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Queue-aware energy-efficient scheduling and power allocation with feedback reduction in small-cell networks

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In small cell networks (SCNs), the path loss becomes smaller, and energy efficiency could be improved. If plenty of small base stations (BSs) are deployed, the energy consumption of each BSs can be small enough to make the total energy remain the same or even less. However, because of the cost of deployment and maintenance, operators often choose to install BSs which are not small enough. Thus the total energy consumption in SCNs still increases.

In [1], it is showed that queue state information (QSI) could be used to promote energy efficiency. Most of the existing researches of queue-aware scheduling focus on single cell scenario, including the optimization of sum rate [2], delay [3] and energy [1]. Besides, they did not consider BS selection and inter-cell interference. Most of the existing researches of user scheduling and resource allocation in multiple cells concentrate on enhancing throughput and do not consider QSI, such as [4]. Authors in [5] studied energy saving, but QSI was not considered.

In this paper, we concentrate on minimizing the total energy consumption in all slots in SCNs with resource reuse among cells by queue-aware user scheduling and resource allocation. The accomplishments of the study are as follows.

- QSI and channel state information (CSI) are jointly considered for user scheduling and power allocation to save the total energy consumption in coordinated multi-cell SCNs with resource reuse among cells, where interference exists among adjacent cells. A heuristic algorithm (HA) is proposed, and the performance of HA is similar to that of exhaustive search algorithm (ESA).
- A distributed feedback algorithm jointly utilizing QSI and CSI to lessen CSI feedback is proposed. To the best of authors' knowledge, the joint consideration of QSI and CSI to lessen CSI feedback could not be found in existing researches.

System model and problem formulation. Figure 1 shows the scenario of user assignment and power allocation in SCNs, where interference exists among adjacent cells using the same radio resource. N BSs and K mobile stations (MSs) exist in the cellular system. Downlink transmission is considered. MSs access BSs in time division multiple access (TDMA) fashion. Data for MSs are cached separately in the central controller. In each slot, the central controller uses both QSI and CSI to make a decision of joint user scheduling and power allocation. It is assumed that the central controller already has the CSI prediction of this slot from previous measurement and feedback from

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the MSs.

$s_{ij}(t) \in \{0,1\}$ is the indicator of user scheduling. When MS_j is assigned to BS_i in slot t, $s_{ij}(t) = 1$. Otherwise, $s_{ij}(t) = 0$. In later discussions, the notation t will be left out if it does not affect the readability. In each slot, each MS can be assigned to not more than one BS, and each BS can serve not more than one MS. Denote $a_j(t)$ as the stochastic process of data arrival of MS_j in slot t. Denote the value of $b_j(t)$ as the data conveyed of MS_j in slot t. $Q_j(t)$ represents the queue length of MS_j at the beginning of slot t and it could be calculated as

$$Q_j(t+1) = \max\left[Q_j(t) - b_j(t), 0\right] + a_j(t). \quad (1)$$

Denote $p_i(t)$ as the transmitting power of BS_i in slot t. As all the BSs use the same spectrum, some BSs could cause strong interference to MSs which are not served by them. The problem is to find an optimal strategy of user assignment s_{ij} and power allocation p_i to minimize the mean of total power expenditure in all slots. At the same time, the queues of MSs are supposed to be mean rate stable[1)]. Keeping the traffic queue mean rate stable can make sure that all the traffic data can be conveyed in time [1]. Then we get a stochastic control optimization problem as in (2):

$$\begin{aligned}
\min_{s_{ij}(t),p_i(t)} \quad & \lim_{T\to\infty} \frac{1}{T} \sum_{t=0}^{T-1} \sum_{i=1}^{N} \sum_{j=1}^{K} s_{ij}(t) p_i(t) \\
\text{s.t.} \quad & \text{(i)} \ \sum_{i=1}^{N} s_{ij}(t) \leqslant 1, \forall j, t, \\
& \text{(ii)} \ \sum_{j=1}^{K} s_{ij}(t) \leqslant 1, \forall i, t, \qquad (2) \\
& \text{(iii)} \ s_{ij}(t) \in \{0,1\}, \forall i, j, t, \\
& \text{(iv)} \ 0 \leqslant p_i \leqslant p_i^m, \forall i, t, \\
& \text{(v)} \ Q_j(t) \text{ is mean rate stable}, \forall j, t.
\end{aligned}$$

In problem (2), constraint (i) ensures one user in each slot can be assigned to not more than one BS; constraint (ii) ensures each BS in each slot can serve not more than one user; constraint (iv) ensures the transmitting power of BS_i can not exceed p_i^m and ensures the transmitting power is positive; constraint (v) ensures all the data can be transmitted.

Dynamic scheduling strategy for interference channel. According to Lyapunov optimization theory [1], we can get the following optimization problem for scenario with resource reuse among cells:

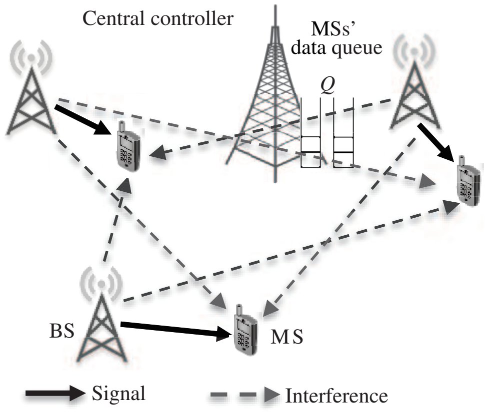

Figure 1 Scenario of multiple user scheduling in SCNs.

$$\begin{aligned}
\min_{s_{ij},p_i} \quad & \sum_{i=1}^{N} \sum_{j=1}^{K} V_{ij} s_{ij} \\
\text{s.t.} \quad & \sum_{i=1}^{N} s_{ij} \leqslant 1, \ \forall j, \quad \sum_{j=1}^{K} s_{ij} \leqslant 1, \ \forall i, \qquad (3) \\
& s_{ij} \in \{0,1\}, \ \forall i,j, \quad 0 \leqslant p_i \leqslant p_i^m, \ \forall i,
\end{aligned}$$

where $V_{ij} = -Q_j r_{ij} + V p_i$ and r_{ij} (bits/s) is the data rate from BS_i to MS_j. Denote h_{ij} as the complex channel gain[2)]. According to Shannon capacity theory, it can be calculated as

$$r_{ij} = B \log_2 \left(1 + \frac{p_i |h_{ij}|^2}{1 + \sum_{k\neq i} p_k |h_{kj}|^2} \right) s_{ij}. \quad (4)$$

In problem (3), user scheduling s_{ij} and power allocation p_i are coupled together, which makes the problem very difficult to solve. Since the mixed combinatorial problem is NP-hard [6], we propose a heuristic iteration algorithm. In the algorithm, we try to decouple the the process of user scheduling and the process of power allocation. First, we assume there is no inter-cell interference and the transmitting power is given with $p_i = \hat{p}_i$. Take $\hat{p}_i$ into problem (3), then we get a generalized assignment problem (GAP), where $V_{ij} = -Q_j B \log_2(1 + \hat{p}_i |h_{ij}|^2) + V \hat{p}_i$. Second, assume user scheduling is given and try to find the optimal power allocation. Denote the optimal user scheduling of the GAP as $\hat{s}_{ij}$ and take $\hat{s}_{ij}$ into problem (3). Then we get a non-convex optimization problem of power allocation:

$$\begin{aligned}
\min_{p_i} \quad & \sum_{i=1}^{N} \sum_{j=1}^{K} \left[-Q_j r_{ij} + V p_i\right] \hat{s}_{ij} \\
\text{s.t.} \quad & 0 \leqslant p_i \leqslant p_i^m, \quad \forall i.
\end{aligned} \qquad (5)$$

[1)] $Q(t)$ is mean rate stable, if $\lim_{t\to\infty} \frac{\mathbb{E}[Q(t)]}{t} = 0$ [1].

[2)] Assume $h_{ij}(t)$ is normalized by noise power. If MS_j receive no signal from BS_i, h_{ij} is assumed to be zero.

The problem in (5) is a constrained non-convex optimization problem, and global optimization algorithms [7] could be applied to get $\hat{p_i}$. Then repeat the above process until the iteration gain in the decrease of $F(t) = \sum_{i=1}^{N}\sum_{j=1}^{K}\left[-Q_j r_{ij} + V p_i\right] s_{ij}$ is negligible. The result of simulations shows HA has similar performance as brute-force algorithm, which could be found in Appendix A.

Distributed adaptive feedback strategy. The proposed algorithm above needs full CSI, and the overhead of CSI feedback is quite heavy, when there are a lot of MSs or BSs. Therefore the CSI feedback overhead needs to be compressed. In our previous work [8], a two-step feedback strategy is proposed, and LQ and LKQ feedback algorithms are also presented. In the feedback strategy, the number of channel gains which MS_j reports in each time slot is L_j. In this part, we propose a QSI and CSI based algorithm (LQH), where QSI and CSI are jointly considered to determine L_j. And L_j is defined as

$$L_j = \min\left[L_{\max}, \sum_{i}^{N} \min\left(1, \left\lfloor \frac{Q_j |h_{ij}|^2}{Q_j^{\mathrm{mean}} |h_{\mathrm{mean}}|^2} \right\rfloor\right)\right], \tag{6}$$

where Q_j^{mean} is pre-determined parameter concerning the average queue length of MS_j, h_{mean} is pre-determined parameter concerning the channel state of the system, $L_{\max}$ is the maximum number of feedback channels. For some cross-layer communication systems, Q_j can be acquired from the transport layer. Otherwise, we can use $\hat{Q}_j$ instead of Q_j, where $\hat{Q}_j(t) = \max[\hat{Q}_j(t-1) - b_j(t-1), 0] + \lambda$ and $\hat{Q}_j(t)$ can be regulated in a long time scale. Q_j^{mean} could be updated by the central controller at intervals. Besides, MSs can also calculate Q_j^{mean} locally [8]. Besides, LQH could be extended for the sytem with multipe carriers in [9]. Simulation results in Appendix A verify that LQH algorithm can substantially reduce the overhead of CSI feedback. Besides, LQH could be extended for the sytem with multipe carriers in [9].

Conclusion. This paper jointly considered QSI and CSI to lessen energy consumption of BSs in SCNs, where inter-cell interference exists. User scheduling and power allocation are employed to minimize the total energy consumption in all slots, while keeping the user data queue mean rate stable simultaneously. A heuristic iterative algorithm is presented. In order to diminish the CSI feedback overhead, a distributed CSI feedback algorithm based on QSI and CSI is presented.

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Supporting information Appendix A. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

References

1 Neely M J. Energy optimal control for time-varying wireless networks. IEEE Trans Inf Theory, 2006, 52: 2915–2934
2 Tassiulas L, Ephremides A. Dynamic server allocation to parallel queues with randomly varying connectivity. IEEE Trans Inf Theory, 1993, 39: 466–478
3 Sadiq B, Baek S J, de Veciana G. Delay-optimal opportunistic scheduling and approximations: the log rule. IEEE/ACM Trans Netw, 2011, 19: 405–418
4 Feng W, Wang Y, Lin D, et al. When mmwave communications meet network densification: a scalable interference coordination perspective. IEEE J Sel Areas Commun, 2017, 35: 1459–1471
5 Ge X H, Chen J Q, Wang C X, et al. 5G green cellular networks considering power allocation schemes. Sci China Inf Sci, 2016, 59: 022308
6 Venturino L, Zappone A, Risi C, et al. Energy-efficient scheduling and power allocation in downlink OFDMA networks with base station coordination. IEEE Trans Wirel Commun, 2015, 14: 1–4
7 Ugray Z, Lasdon L, Plummer J, et al. Scatter search and local NLP solvers: a multistart framework for global optimization. INFORMS J Comput, 2007, 19: 328–340
8 Wei H X, Zhong X F, Zhao M, et al. Feedback reduction for queue-aware coordinated multi-user scheduling in small-cell networks. In: Proceedings of the 33rd Annual IEEE Military Communications Conference (MILCOM), Baltimore, 2014. 1562–1567
9 Wei H X, Feng W, Li Y Z, et al. Energy-efficient resource allocation for small-cell networks: a stable queue perspective. China Commun, in press