SCIENCE CHINA
Information Sciences

• LETTER •

February 2019, Vol. 62 029307:1–029307:3
https://doi.org/10.1007/s11432-017-9440-x

Energy-efficient task offloading, load balancing, and resource allocation in mobile edge computing enabled IoT networks

Shulei LI[1*], Daosen ZHAI[2], Pengfei DU[3] & Ting HAN[4]

[1] *Tianyuan Ruixin Communication Technology Co. Ltd., Xi'an* 710071*, China;*
[2] *School of Electronics and Information, Northwestern Polytechnical University, Xi'an* 710071*, China;*
[3] *The 10th Institute of China Electronics Technology Group Corporation (CETC), Chengdu* 610036*, China;*
[4] *The 504th Institute of China Space Technology, Xi'an* 710199*, China*

Received 20 December 2017/Revised 10 March 2018/Accepted 3 May 2018/Published online 30 November 2018

Citation Li S L, Zhai D S, Du P F, et al. Energy-efficient task offloading, load balancing, and resource allocation in mobile edge computing enabled IoT networks. Sci China Inf Sci, 2019, 62(2): 029307, https://doi.org/10.1007/s11432-017-9440-x

Dear editor,

The constraints on energy supply for smart mobile devices (SMDs) have obstructed the development of IoT. Mobile edge computing (MEC) [1] is a promising way to overcome the abovementioned challenge, whereby MEC servers (MECSs) can provide computing capabilities to SMDs with superior computing capabilities and thus reduce the energy consumption (EC) for SMDs [1].

Computation offloading and resource allocation are two key points in MEC research. The authors in [2] investigated a delay minimizing computation offloading problem for a single-SMD-based MEC system. An adaptive task offloading framework with an SMD and multiple MECSs was proposed in [3], and by offloading tasks to different MECSs, the weighted average cost of processing delay and EC was minimized. The authors in [4] further considered a system comprising multiple SMDs, multiple long term evolution eNB-based access point, and a cloud server. By transmit power optimization, the total EC is minimized.

We investigate the computation offloading and transmit power control in a multiple-SMDs-multiple-MECS environment to decrease the system EC and thus prolong the battery life of SMDs. We then decouple the joint optimization into two subproblems and devise a low complexity algorithm called joint offloading, load balancing, and power allocation algorithm (OLP) to solve it. In OLP, first offloading decisions are obtained using a channel gain and threshold-based heuristic algorithm. Then using fractional programming, we transform the transmit power control subproblem into a convex programming problem whereby the closed-form solution is obtained.

System model. We investigate an MEC system comprising N SMDs and M MECSs. Let $\mathcal{N} = \{1, \ldots, N\}$ and $\mathcal{M} = \{1, 2, \ldots, M\}$ represent the set of SMDs and MECSs, respectively. The MECSs are of different types and there is no coupling between them. Each SMD has only one inseparable energy-intensive task to be processed locally or offloaded to one of the MECSs. The task of SMD n, $n \in \mathcal{N}$ can be expressed in $\Psi_n = \{D_n, C_n\}$, where D_n represents the size of input data (in bits) and C_n denotes the calculation amount (in CPU cycles). It is assumed that D_n and C_n are known in advance, and the program of the task Ψ_n with size C_n is backed up in each MECS.

When SMD n adopts local processing, the EC is

* Corresponding author (email: savearmy@163.com)

$E_n^{\rm local} = p_n^{\rm local}\frac{C_n}{f_n^{\rm local}}$, where $f_n^{\rm local}$ and $p_n^{\rm local}$ indicate the local computing capability (in CPU cycles/s) and power consumption (in watt) of SMD n, respectively.

In mobile edge computing fashion, suppose SMD n offload its task Ψ_n to MECS m. Let the transmit power and radio bandwidth of SMD n be $p_{n,m}$ and $B_{n,m}$, and the wireless channel gain between SMD n and MECS m be $g_{n,m}$. Then the wireless transmit rate of SMD n is $r_{n,m} = B_{n,m}\log_2(1+p_{n,m}g_{n,m})$. Let $p_n^{\rm idle}$ represent the idle power of SMD n and denote the computation capability allocated to SMD n as $f_{n,m}$. Then the EC of SMD n in MEC mode is $E_{n,m}^{\rm mec} = p_{n,m}\frac{D_n}{r_{n,m}} + p_n^{\rm idle}\frac{C_n}{f_{n,m}}$. In this study, the computation capability F_m of each MECS m is allocated evenly among all its serving SMDs.

Let $s_{n,m} = \{0,1\}$, $n\in\mathcal{N}$, $m\in\mathcal{M}_{\rm ex} = \mathcal{M}\bigcup\{M+1\}$ denote the offloading strategy of SMD n, where $s_{n,M+1}=1$ indicates that task Ψ_n is processed locally, and $s_{n,m}=1$, $m\in\mathcal{M}$ represents that the task Ψ_n is executed by MECS m. Then, the offloading strategy matrix of all SMDs is denoted by $\boldsymbol{S} = \{s_{n,m}\}_{N*(M+1)}$, and the EC of SMD n is $E_n = E_n^{\rm local}s_{n,M+1} + \sum_{m\in\mathcal{M}} E_{n,m}^{\rm mec}s_{n,m}$.

We intend to minimize the total EC of all SMDs by jointly optimizing the transmit power and offloading strategy, with load balancing assured. The problem can be modeled by

$$
\begin{aligned}
(\mathcal{P}_1):\ & \min_{\boldsymbol{S},\boldsymbol{P}} \sum_{n\in\mathcal{N}} E_n \\
\text{s.t. } & (\text{C1}): s_{n,m}=\{0,1\},\ \forall n\in\mathcal{N},\ \forall m\in\mathcal{M}_{\rm ex},\\
& (\text{C2}): \sum_{m\in\mathcal{M}_{\rm ex}} s_{n,m} = 1,\ \forall n\in\mathcal{N},\\
& (\text{C3}): \sum_{n\in\mathcal{N}_m} s_{n,m} \leqslant \zeta_m,\ \forall m\in\mathcal{M},\\
& (\text{C4}): 0\leqslant p_{n,m}\leqslant p_n^{\max},\ \forall n\in\mathcal{N},\ \forall m\in\mathcal{M},
\end{aligned}
$$

where $p_n^{\max}$ is the maximum transmit power of SMD n; (C1) and (C2) confines each task to be processed in one place; (C3) ensures that the number of served SMDs do not exceed the capacity of each MECS; (C4) is the transmit power constraint. Problem $(\mathcal{P}_1)$ is a mixed integer and nonlinear programming problem, which is generally NP-hard [5]. To reduce complexity, we propose a joint algorithm referred to as OLP, which divides $(\mathcal{P}_1)$ into two subproblems to solve.

Adaptive offloading strategy making. When offloading, the input data of each task should first be transmitted to an MECS via a wireless channel and then the task will be processed by the MECS. Intuitively, when the wireless channel is good, less EC can be enough for data transmission in offloading, thus MEC mode may be a wise choice. Inspired by this, we proposed a low complexity channel gain and threshold based heuristic algorithm to obtain the offloading policy $\boldsymbol{S}$, while ensuring load balancing between multiple MECSs.

The main idea of the heuristic algorithm includes the following. (i) Each SMD n obtains its offloading strategy according to the wireless channel gain $g_{n,m}$, $m\in\mathcal{M}$, where the MECS m^* with the highest channel gain is selected and set to $s_{n,m^*}=1$. (ii) To maintain the load among multiple MECSs, we set a capacity constraint ζ_m for each MECS. If the number of accepted tasks exceeds ζ_{m^*}, MECS m^* will be infeasible for SMD n; then, the MECS with the highest channel gain among the remaining MECSs is selected as m^*, and set $s_{n,m^*}=1$. The procedure is repeated until (1) no MECS is selected, in which case, the task will be processed locally or (2) an MECS m^* is found, in which case, the task will be offloaded to MECS m^*. (iii) We set a threshold ${\rm Thre}_n$, $n\in\mathcal{N}$ for each SMD n to ensure a good wireless channel condition in offloading. Only when the highest channel gain is higher than ${\rm Thre}_n$, the above point (ii) will be performed and an m^* may be selected, for which we set $s_{n,m^*}=1$; otherwise, we let $s_{n,M+1}=1$.

Transmit power control. After we have obtained the offloading strategy, $(\mathcal{P}_1)$ degenerates to the transmit power optimization for the SMDs choosing the MEC mode as follows:

$$(\mathcal{P}_2):\ \min_{\boldsymbol{P}\in(\text{C4})} \sum_{n\in\mathcal{N}}\sum_{m\in\mathcal{M}} E_{n,m}^{\rm mec}.$$

Since there's no coupling, each MECS works independently. Denote the set and number of SMDs served by MECS m as $\mathcal{N}_m$ and $N_m = |\mathcal{N}_m|$ and denote the transmit power of SMDs in $\mathcal{N}_m$ as $\boldsymbol{p}_m = \{p_{1,m},\ldots,p_{N_m,m}\}$, $(\mathcal{P}_2)$ can be decoupled to the optimization among each $\mathcal{N}_m$ as follows:

$$(\mathcal{P}_3):\ \min_{\substack{\boldsymbol{p}_m\in(\text{C4})\\ n\in\mathcal{N}_m}} \sum_{n\in\mathcal{N}_m} p_n^{\rm idle}\frac{C_n}{f_{n,m}} + p_{n,m}\frac{D_n}{r_{n,m}},$$

where $p_n^{\rm idle}\frac{C_n}{f_{n,m}}$ is a constant that is neglected in the following. Then $(\mathcal{P}_3)$ can be simplified as

$$(\mathcal{P}_4):\ \min_{\substack{\boldsymbol{p}_m\in(\text{C4})\\ n\in\mathcal{N}_m}} \sum_{n\in\mathcal{N}_m} p_{n,m}\frac{D_n}{B_{n,m}\log_2(1+p_{n,m}g_{n,m})}.$$

As the power control policy of each SMD is independent from that of the others, the transmit power of SMD n served by MECS m can be obtained by solving

$$(\mathcal{P}_5):\ \min_{p_{m,n}\in(\text{C4})} \frac{D_n p_{n,m}}{B_{n,m}\log_2(1+p_{n,m}g_{n,m})}.$$

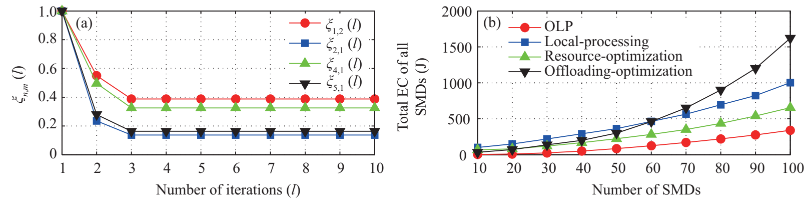

Figure 1 (Color online) (a) Convergence of the iterative transmit power control algorithm; (b) total EC of all SMDs vs. N.

As the objective is a fractional function, $(\mathcal{P}_5)$ is generally non-convex. However, we can resort to nonlinear fractional programming theory [6] to reformulate it. Denote the optimal solution and optimal value of $(\mathcal{P}_5)$ as $\{p^*_{n,m}\}$ and $\xi^*_{n,m}$, we have $\xi^*_{n,m} = \min_{p_{m,n}\in(\mathrm{C4})} \frac{p_{n,m}D_n}{B_{n,m}\log_2(1+p_{n,m}g_{n,m})} = \frac{p^*_{n,m}D_n}{B_{n,m}\log_2(1+p^*_{n,m}g_{n,m})}$.

Theorem 1. The optimal transmit power $p^*_{n,m}$ is achieved if and only if

$$\min_{p_{m,n}\in(\mathrm{C4})}\left[p_{n,m}D_n - \xi^*_{n,m}B_{n,m}\log_2(1+p_{n,m}g_{n,m})\right]$$
$$= p^*_{n,m}D_n - \xi^*_{n,m}B_{n,m}\log_2(1+p^*_{n,m}g_{n,m}) = 0.$$

Using Theorem 1, $(\mathcal{P}_5)$ can be reformulated as

$$(\mathcal{P}_6): \min_{p_{m,n}\in(\mathrm{C4})} p_{n,m}D_n - \xi^*_{n,m}B_{n,m}\log_2(1+p_{n,m}g_{n,m}),$$

which is a convex programming problem about $p_{n,m}$. However, the newly introduced $\xi^*_{n,m}$ is unknown, making $(\mathcal{P}_6)$ still hard to solve. To solve the problem, we replace $\xi^*_{n,m}$ with an update parameter $\xi_{n,m}(l) = \frac{p_{n,m}D_n}{B_{n,m}\log_2(1+p_{n,m}g_{n,m})}$, and $(\mathcal{P}_6)$ is transformed into

$$(\mathcal{P}_7): \min_{p_{m,n}\in(\mathrm{C4})} p_{n,m}D_n - \xi_{n,m}(l)B_{n,m}\log_2(1+p_{n,m}g_{n,m}).$$

Since $\xi_{n,m}(l)$ is a known parameter depending on previous power control, $(\mathcal{P}_7)$ can be solved easily, with its closed-form optimal solution as

$$p^*_{n,m} = \min\left\{\max\left\{\frac{\xi_{n,m}(l)B_{n,m}}{D_n\ln 2} - \frac{1}{g_{n,m}}, 0\right\}, p_n^{\max}\right\}.$$

Performance evaluations. The parameters are set as follows: $M = 2$, $N = 50$, $p_n^{\mathrm{idle}} = 0.005$–$0.008$ W, $p_n^{\mathrm{local}} = 1.5$–$2$ W, $p_n^{\max} = 0.5$–1 W, $D_n = 0.42$ MB, $C_n = 1000$ M CPU cycles, $f_n^{\mathrm{loc}} = 0.1$–0.5 G CPU cycles/s, $\mathrm{Thre}_n = 3$, $\zeta_m = N/2$, $g_{n,m} = 0.3$–10, and F_m is produced from $[10, 15, 20]$ G CPU cycles/s randomly.

In Figure 1(a), we plot $\zeta_{n,m}$, $n \in \mathcal{N}_2$ versus iterations to show the convergence of the iterative power allocation algorithm. We take four SMDs indexed $n = 1, 2, 4, 5$, $n \in \mathcal{N}_2$ as examples, where $\zeta_{1,2}$, $\zeta_{2,1}$, $\zeta_{4,1}$, $\zeta_{5,1}$ indicate that SMD 1 offloads task to MECS 2, and SMDs 2, 4, 5 offload their tasks to MECS 1. As shown, $\zeta_{n,m}$, $n \in \mathcal{N}_2$ converge at the 3rd iteration, which is considerably fast.

Figure 1(b) shows the performance of OLP by comparing it with other algorithms, namely (i) local processing; (ii) resource-optimization, where transmit power control is optimized, and offloading strategy is made randomly; and (iii) offloading-optimization, where offloading strategy is optimized and transmit power is allocated randomly. As shown, with the growth of N, the total EC also increases. However, as a joint optimization, OLP always performs the best.

Conclusion. We investigated an energy-efficient joint computation offloading, load balancing, and transmit power control problem in a multiple-SMD-multiple-MECS system, and then proposed a heuristic algorithm to obtain offloading strategies while guaranteeing load balancing between the multiple MECSs. Using fractional programming, the optimum transmit power of each SMD was obtained. Simulation results demonstrate the performance of OLP in EC reduction.

References

1 Hu Y C, Patel M, Sabella D, et al. Mobile Edge Computing — A Key Technology Towards 5G. ETSI White Paper 11.11. 2015
2 Jia M, Cao J N, Yang L. Heuristic offloading of concurrent tasks for computation-intensive applications in mobile cloud computing. In: Proceedings of IEEE Conference on Computer Communications Workshops, Toronto, 2014. 352–357
3 Wang J Y, Peng J, Wei Y H, et al. Adaptive application offloading decision and transmission scheduling for mobile cloud computing. China Commun, 2017, 14: 169–181
4 Sardellitti S, Scutari G, Barbarossa S. Joint optimization of radio and computational resources for multicell mobile-edge computing. IEEE Trans Signal Inf Process Netw, 2015, 1: 89–103
5 Sheng M, Zhai D S, Wang X J, et al. Intelligent energy and traffic coordination for green cellular networks with hybrid energy supply. IEEE Trans Veh Technol, 2017, 66: 1631–1646
6 Du J B, Zhao L Q, Feng J, et al. Computation offloading and resource allocation in mixed fog/cloud computing systems with min-max fairness guarantee. IEEE Trans Commun, 2018, 66: 1594–1608