SCIENCE CHINA
Information Sciences

• LETTER •

June 2021, Vol. 64 169306:1–169306:2
https://doi.org/10.1007/s11432-020-3091-6

Fairness-improved and QoS-guaranteed resource allocation for NOMA-based S-IoT network

Jian JIAO[1,2], Shiyi LIAO[1,2], Yunyu SUN[1], Shaohua WU[1*] & Qinyu ZHANG[1,2]

[1]*Harbin Institute of Technology (Shenzhen), Shenzhen* 518055*, China;*
[2]*Peng Cheng Laboratory, Shenzhen* 518055*, China*

Received 8 July 2020/Revised 4 October 2020/Accepted 16 October 2020/Published online 26 April 2021

Citation Jiao J, Liao S Y, Sun Y Y, et al. Fairness-improved and QoS-guaranteed resource allocation for NOMA-based S-IoT network. Sci China Inf Sci, 2021, 64(6): 169306, https://doi.org/10.1007/s11432-020-3091-6

Dear editor,

Recently, the satellite-integrated Internet of Things (S-IoT) has supported many emergent IoT applications [1], such as smart agriculture, remote healthcare, and environmental monitoring [2]. To make full use of the broadband access ability of S-IoT, nonorthogonal multiple access (NOMA) techniques are used to simultaneously support multiple terrestrial user terminals (UTs).

Satellites have limited onboard power and storage resources; therefore, optimal resource allocation for NOMA is critical for improving the S-IoT network utility. Thus, through the Lyapunov theoretical framework, an optimized resource allocation scheme for power and storage is proposed [3], wherein the satellite inclines to allocate maximum power to the UTs that have "good" channel gains. Meanwhile, the UTs with "bad" channel gains tend to be allocated little or no power. Then, the S-IoT can achieve maximum long-term network utility. However, this resource allocation scheme would be unfair to the UTs that could not receive their data packets in time because of bad channel conditions. Consequently, this resource allocation scheme is not capable of guaranteeing quality of service (QoS) for all UTs.

Therefore, we propose a fairness-improved and QoS-guaranteed resource allocation for the S-IoT NOMA downlink network. Further, we study the trade-off between fairness and energy efficiency. For working out the joint optimization problem, we exploit the Lyapunov framework to break down the non-convex joint optimization problem into a sequence of individual sub-problems. The decomposed sub-problems are extremely complicate to find in a closed-form solution; therefore, we use the particle swarm optimization (PSO) algorithm to solve the proposed sub-problems and obtain a sub-optimal solution named NOMA-QoS scheme. The simulation results prove that our NOMA-QoS scheme outperforms the existing benchmark schemes.

Problem formulation. We consider an S-IoT NOMA downlink network that includes a satellite S and multiple terrestrial UTs in its multi-beam coverage. To avoid inter-beam interference, we assume that resource allocation is a hybrid multiple access system, where S serves different beams in an orthogonal multiple access (OMA) manner and performs the NOMA technique for the UTs in each beam. To evaluate the long-term system performance, we construct three virtual queues $Q_i(\varsigma)$, $X_i(\varsigma)$, and $Y(\varsigma)$ to derive the queue backlog, transmission delay, and power consumption, respectively. Thus, we have

$$Q(t+1) = \max\{Q_i(\varsigma) - b_i(\varsigma), 0\} + a_i(\varsigma), \tag{1}$$

where ς denotes the current time slot, $a_i(\varsigma)$ is the data arriving rate at the queue $Q_i(\varsigma)$, and $b_i(\varsigma)$ is the data departing rate.

To maintain network stability and prevent data overflow, the following network stability constraint must be satisfied [4]:

$$\lim_{\varsigma\to\infty} \frac{\mathrm{E}[Q_i(\varsigma)]}{\varsigma} = 0. \tag{2}$$

For the transmission delay $X_i(\varsigma)$, let D_i denote the long-term QoS constraint of UT_i, which is the average transmission delay that cannot exceed D_i. Therefore, according to Little's theorem [5], the following condition needs to be satisfied:

$$\frac{\lim_{\Upsilon\to\infty} \frac{1}{\Upsilon}\sum_{\varsigma=0}^{\Upsilon-1} \mathrm{E}[Q_i(\varsigma)]}{\lim_{\Upsilon\to\infty} \frac{1}{\Upsilon}\sum_{\varsigma=0}^{\Upsilon-1} \mathrm{E}[b_i(\varsigma)]} \leqslant D_i, \tag{3}$$

where Υ is the number of total transmission slots.

Last, for the power consumption $Y(\varsigma)$, let P_{ave} denote the average value of the power that S can support. $Y(\varsigma)$ is the overdraft power consumption, and we have

$$Y(\varsigma+1) = \max(Y(\varsigma) - P_{\mathrm{ave}}, 0) + \sum_{i=1}^{\psi} p_i(\varsigma) + P_c, \tag{4}$$

where ψ is the number of UTs, and P_c is the circuit power consumption in the system, which is usually a constant.

The energy efficiency at UT_i can be expressed as the ratio of the data arriving rate $a_i(\varsigma)$ to the overall power consumption [6]. Then, the long-term average value of energy

* Corresponding author (email: hitwush@hit.edu)

efficiency at UT_i is denoted as $\overline{\text{EE}}_i$, which can be expressed as follows:

$$\overline{\text{EE}}_i = \frac{\lim_{\Upsilon\to\infty} \frac{1}{\Upsilon}\sum_{\varsigma=0}^{\Upsilon-1} \text{E}[a_i(\varsigma)]}{\sum_{i=1}^{\psi} \lim_{\Upsilon} \to \infty \frac{1}{\Upsilon}\sum_{\varsigma=0}^{\Upsilon-1} \text{E}[p_i(\varsigma)] + P_c}. \quad (5)$$

Furthermore, to measure a specified level of fairness among the UTs with different channel gains, we introduce a widely used fairness indicator $f(b_i(\varsigma))$, that is, Jain's index [7]; $f(b_i(\varsigma))$ is expressed as the ratio of the square of the sum of the data departing rate $b_i(\varsigma)$ to the sum of the squares of $b_i(\varsigma)$. We have

$$f(b_i(\varsigma)) = \frac{[\sum_{i=1}^{\psi} b_i(\varsigma)]^2}{\psi\sum_{i=1}^{\psi} b_i(\varsigma)^2}. \quad (6)$$

Thus, the value of $f(b_i(\varsigma))$ ranges from $1/\psi$ to 1, where $1/\psi$ reflects no fairness at all, and 1 means perfect fairness. Then we can formulate our joint optimization problem as follows:

$$\max \text{EU} = \ln(\overline{\text{EE}}) \quad (7a)$$

$$\text{s.t. C1}: \sum_{i=1}^{\psi} p_i(\varsigma) + P_c \leqslant P_{\max}, \quad (7b)$$

$$\text{C2}: \lim_{\Upsilon\to\infty} \frac{1}{\Upsilon}\sum_{\varsigma=0}^{\Upsilon-1} \text{E}\left[\sum_{i=1}^{\psi} p_i(\varsigma)\right] + P_c \leqslant P_{\text{ave}}, \quad (7c)$$

$$\text{C3}: 0 \leqslant a_i(\varsigma) \leqslant a_{\max}, \quad (7d)$$

$$\text{C4}: \lim_{\varsigma\to\infty} \frac{\text{E}[Q_i(\varsigma)]}{\varsigma} = 0, \quad (7e)$$

$$\text{C5}: \frac{\lim_{\Upsilon\to\infty} \frac{1}{\Upsilon}\sum_{\varsigma=0}^{\Upsilon-1} \text{E}[Q_i(\varsigma)]}{\lim_{\Upsilon\to\infty} \frac{1}{\Upsilon}\sum_{\varsigma=0}^{\Upsilon-1} \text{E}[b_i(\varsigma)]} \leqslant D_i, \quad (7f)$$

$$(7g)$$

$$\text{C6}: \begin{cases} p_1(\varsigma) \geqslant \{\Gamma_1 = \max(\Gamma_1^1(\varsigma), \Gamma_1^2(\varsigma))\}, \\ \cdots \\ p_\psi(\varsigma) \geqslant \{\Gamma_i = \max(\Gamma_i^1(\varsigma), \Gamma_i^2(\varsigma))\}, \\ \quad \text{for } i = 2, 3, \ldots, \psi. \end{cases} \quad (7h)$$

where $P_{\max}$ is the maximum short-term power in a time slot on S, $a_{\max}$ is the upper bound of $a_i(\varsigma)$, $\Gamma_i^1(\varsigma)$ is the minimum power threshold to enhance the probability of the successive interface cancellation (SIC) decoding success [3], and $\Gamma_i^2(\varsigma)$ is the minimum power threshold to guarantee the QoS requirement.

Therefore, C1 is the upper bound of the short-term power in a time slot on S. C2 ensures that the average power consumption is less than P_{ave} for a long time. C3 specifies the data arriving rate constraint. C4 guarantees the queue stability. C5 is the long-term average transmission delay constraint. C6 is the joint minimum power threshold constraint, which can enhance the probability of SIC decoding success and guarantee the QoS requirement.

Solution and main simulation results. To solve the above optimization problem, we propose a power allocation scheme, called the NOMA-QoS scheme, which can be summarized in the following steps.

First, we calculate the minimum transmission power threshold Γ_i for all the ψ UTs.

Second, we compare the sum of the minimum transmission power threshold with $P_{\max}$, and then determine whether to continue or interrupt the transmission. If the minimum transmission power threshold is larger than $P_{\max}$, the transmission in the time slot ς becomes an outage. If the minimum transmission power threshold is less than $P_{\max}$, we continue the transmission and calculate the optimal power allocation coefficients according to the NOMA-PSO scheme [3], and the optimal solution is recorded as $\boldsymbol{P}^{\text{opt}} = [p_1^{\text{opt}}, p_2^{\text{opt}}, \ldots, p_\psi^{\text{opt}}]$.

To validate the effectiveness of our proposed NOMA-QoS scheme, we compare its utility and fairness performance with the following benchmark schemes. The NOMA-PSO scheme was introduced in [3]. The NOMA-Q scheme and NOMA-G scheme allocate power according to the queue backlog and the channel gain, respectively. Note that in Figure 1, our proposed NOMA-QoS scheme has the highest fairness among all the five schemes. In particular, the fairness of the NOMA-QoS scheme is 42.9% higher than that of the NOMA-PSO scheme. Moreover, our NOMA-QoS scheme has the second highest network utility; it is only 1.3% less than the NOMA-PSO scheme, as shown in Figure 1. Therefore, our NOMA-QoS scheme achieves better fairness than the NOMA-PSO scheme with a slightly loss in the network utility.

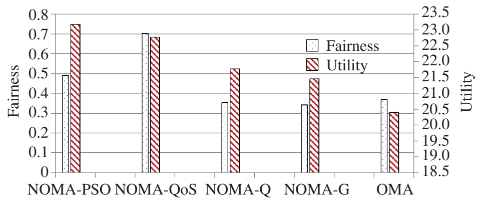

Figure 1 (Color online) Fairness and utility of different schemes.

Conclusion. Our proposed NOMA-QoS scheme outperforms the existing benchmark schemes in fairness performance. In addition, the utility of our proposed NOMA-QoS scheme is slightly lower than that of the NOMA-PSO scheme, which further validates that the trade-off between energy efficiency and fairness.

Acknowledgements This work was supported in part by National Natural Sciences Foundation of China (Grant Nos. 62071141, 61871147, 61831008, 61525103), Shenzhen Basic Research Program (Grant No. ZDSYS201707280903305), Natural Science Foundation of Guangdong Province (Grant Nos. 2020A1515010505, 2018B030322004), and Verification Platform of Multi-tier Coverage Communication Network for Oceans (Grant No. LZC0020).

References

1 Yao H, Wang L, Wang X, et al. The space-terrestrial integrated network: an overview. IEEE Commun Mag, 2018, 56: 178–185
2 Di B, Song L, Li Y, et al. Ultra-dense LEO: integration of satellite access networks into 5G and beyond. IEEE Wireless Commun, 2019, 26: 62–69
3 Jiao J, Sun Y, Wu S, et al. Network utility maximization resource allocation for NOMA in satellite-based Internet of Things. IEEE Internet Things J, 2020, 7: 3230–3242
4 Neely M J. Stochastic network optimization with application to communication and queueing systems. Synth Lect Commun Netw, 2010, 3: 1–211
5 Song Y, Zhang C, Fang Y, et al. Revenue maximization in time-varying multi-hop wireless networks: a dynamic pricing approach. IEEE J Sel Areas Commun, 2012, 30: 1237–1245
6 Fang F, Zhang H, Cheng J, et al. Energy-efficient resource allocation for downlink non-orthogonal multiple access network. IEEE Trans Commun, 2016, 64: 3722–3732
7 Jain R, Chiu D M, Wr H. A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer Systems. Technical Report DEC-TR-301. 1984