IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received May 17, 2020, accepted June 10, 2020, date of publication June 16, 2020, date of current version June 25, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3002834

Resource Allocation in Satellite-Based Internet of Things Using Pattern Search Method

FENG LI[1,2], **(Member, IEEE), KWOK-YAN LAM**[2], **(Senior Member, IEEE), XIN LIU**[3], **(Member, IEEE), AND LI WANG**[4]
[1]School of Information and Electronic Engineering, Zhejiang Gongshang University, Hangzhou 310018, China
[2]School of Computer Science and Engineering, Nanyang Technological University, Singapore 639798
[3]School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China
[4]College of Marine Electrical Engineering, Dalian Maritime University, Dalian 116026, China

Corresponding author: Feng Li (fengli2002@yeah.net)

This work was supported in part by the National Research Foundation, Prime Minister's Office, Singapore, through its Strategic Capability Research Centres Funding Initiative, in part by the Natural Science Foundation of Zhejiang Province under Grant LY19F010009 and Grant LY19F010008, and in part by Zhejiang Provincial Key Laboratory of New Network Standards and Technologies, Zhejiang Gongshang University, under Grant 2013E10012.

ABSTRACT The emergence of Internet of Things (IoT) and high throughput satellite communication networks enables the capability of anytime, anywhere environment monitoring and sensing. A key challenge of satellite-based IoT is to enhance spectrum and energy efficiency so as to meet the ever-increasing demand for satellite bandwidth and dynamic access of a massive number of IoT terminals. In this paper, we propose a novel power control algorithm for IoT terminals being deployed in satellite-based IoT systems where some terrestrial base station is available to acquire IoT devices' information as well as to perform resource management. We adopted the Poisson point process (PPP) theory to formulate the model for this power optimization problem. The PPP theory is applied to evaluate the distance distribution of random IoT devices in this satellite-based networks. Optimal power control scheme can be obtained by taking into consideration user distribution and signal interference plus noise ratio (SINR) demand for various IoT terminals. In addition, due to the complexity of the objective function of power control deduced by the PPP theory, we utilize the pattern search method to identify an optimal solution in global area. Furthermore, we provide numerical results from various perspectives including user rates and energy efficiency to testify the performances of our power proposal.

INDEX TERMS Internet of Things, power control, pattern search method, satellite networks.

I. INTRODUCTION

With the rapid development of low cost electronics and wireless communications, Internet of Things (IoT) has received extensive attention of the research community and enabled many cyber-physical applications [1]–[3]. IoT based on terrestrial network techniques has become more mature, yet it is still a challenge to meet the growing bandwidth demands of wireless communications for application scenarios where sensing and actuation functions in remote and isolated geographic areas are required. For instance, in the field environment of off-shore marine monitoring, large scale and real-time maritime information gathering will not be possible without the involvement of satellite networks. Besides, when IoT devices are being deployed to mission-critical system, cybersecurity and privacy preservation mechanisms will be needed, which almost invariably lead to data expansion, hence putting on pressure on bandwidth demand.

Satellite-based IoT has real world demand and wide application potential [4], [5]. However, as current IoT standards, technology and references are mainly based on the cellular communication networks in terrestrial circumstances, research in satellite-based or space-based IoT is in its early stage. The convergence of traditional satellite and space technology with IoT communications, and by integrating cloud and big data analytics, researchers are expecting the emergency of an era of Internet of Everything supported by next-generation networks.

Satellite communications play a critical role in the three-layer framework of IoT systems: sensing layer, network

---

The associate editor coordinating the review of this manuscript and approving it for publication was Jenny Mahoney.

layer and application layer. In [6], the authors analyzed the importance and feasibility of combining satellite communication and industry IoT, and characteristics of space-based IoT applications. In [7], the authors concluded the current status and trend of IoT, and proposed a multibeam modulation technique for M2M communications in space-based IoT.

To realize the full potential of satellite communications in IoT systems, wireless communication techniques such as MIMO, beaming, cognitive radio, edging computing, artificial intelligent and big-data analysis have been extensively investigated. Especially, as a key part of 6G communications, the closely coupled interoperation of satellite technology and other terrestrial networks has become a trend in recent years. In this connection, a key issue is to address the growing demand on spectrum resource and energy efficiency with the anticipated number of IoT terminals that require dynamic access to satellite-based communications. This issue has attracted more and more research interest from the industry and academia [8]–[11]. In [8], from the perspective of ensuring the communication quality of authorized satellite users, the paper analyzed the location range of ground cognitive users, and studied the influence of the location information of ground base station, the fading degree of ground interference link and the antenna mode of satellite users on the performance of authorized satellite network. In [9], for the uplink communication link of cognitive satellite network, a resource allocation scheme combining power and carrier was proposed to maximize the system capacity of cognitive network. For the downlink communication link of cognitive satellite network, a joint beamforming and carrier allocation method was proposed. In [10], In the millimeter wave communication scenario, the authors analyzed the distribution of the non geostationary satellite and the ground network with single and multiple antennas as the protection area of the cognitive network that can access the authorization system of the geostationary satellite to ensure the interruption performance of the authorization network. In [11], the joint allocation of power and carrier was discussed. Compared with the traditional satellite resource allocation technology, the simulation showed that the power gain, spectral efficiency, throughput and other indicators are significantly improved, but the interference level will also rise. In [12], the authors constructed a novel mathematical model to find the best trade-off for power resource allocation in satellite-based IoT equipped with multi-beam technique. In addition, as cognitive radio has been widely investigated in satellite networks for the enhancement of energy efficiency [13], [14], related promising techniques can be referenced for the satellite-based IoT. Other useful novel methods proposed in recent years also provides references [15]–[20].

In this article, we investigate the power optimization scheme for IoT terminals in the environment of satellite-based IoT networks. When satellite communications are integrated with terrestrial IoT networks, the network model is different from that of traditional IoT. In our proposed model, we formulate the optimal power control by introducing the mathematical tool of Poisson point process (PPP) which is suitable for describing random user distribution. For a specific IoT topology characteristics, the optimization objective of power control can be attained by taking into account the users' distances to terrestrial center and the setting of signal interference plus noise ratio (SINR). Also, we introduce the intelligent optimization algorithm—pattern search method to find the global optimal solution.

The main contributions of this paper can be highlighted as following:

- A novel power optimization algorithm is devised to meet the needs of satellite-based IoT.
- A Poisson point process is introduced to model the stochastic node distribution in satellite-based IoT to achieve the statistic probability of nodes' distances to IoT centers.
- Pattern search method is adopted to ascertain the globally optimal solution for the power optimization.

For the reminder of this article, in Section II, the basic network model of this satellite-based IoT is given. In Section III, we identify the optimal function of node's power allocation in various wireless channels and solve it through applying intelligent optimization algorithm. Then, we provide the numerical results in Section IV to show the performances of our proposal. At last, the paper is concluded in Section V.

II. SYSTEM MODEL

In this article, we consider the system model for satellite-based IoT as shown in Fig. 1, where terrestrial IoT is deployed in remote areas without the coverage of cellar networks. Thus, satellite networks are needed to assist the IoTs relaying sensing data to core networks. In this scenario, a terrestrial IoT base station is essential to fulfill the integration and interoperation of IoT and satellite networks. Furthermore, we suppose that the terrestrial base station will collect all the information then forward to the satellite. This is because normal terrestrial terminals cannot communicate with the satellite directly. The proposed power optimization algorithm will be performed in the terrestrial base station, and power allocation instructions will be sent by the base station. Then, we formulate the power control optimization in this scenario for uplink transmission.

In the network model as shown in Fig. 1, we assume that the IoT cell number is M and terminal number is N in the given areas. We further assume that the distributions of terrestrial IoT center and terminals complying with PPP distribution Φ_f and Φ_d, and the corresponding PDF should be λ_f and λ_d. Then, the mathematical sets for terrestrial IoT center and devices can be given as $\Phi_f = \{fP_1, fP_2, \ldots, fP_M\}$ along with $\Phi_d = \{D_1, D_2, \ldots, U_N\}$.

In this case, the effects of fading channels are considered in this uplink communications. For a given IoT terminal $D_i \in \Phi_D$, under the condition of large-scale fading channels, we use $r_i^{-\alpha}$ to express the path loss in which r_i means the distance from user D_i to the IoT center, and α is the fading parameter. In addition, the background noise power is set to

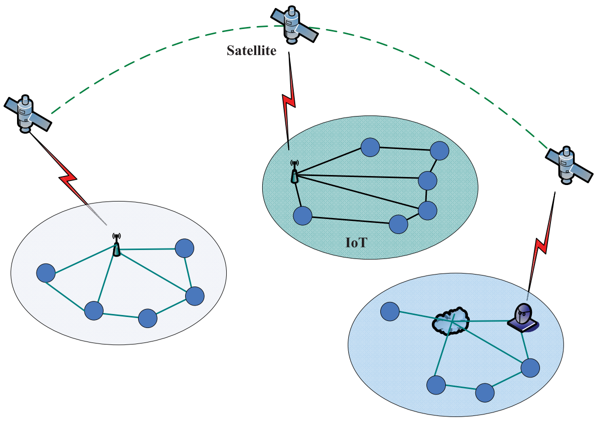


FIGURE 1. Network model for satellite-based IoT.

be σ^2. The SINR for the uplink transmission case can be expressed as

$$SINR_i = \frac{p_i h_i r_i^{-\alpha}}{\sigma^2 + \sum_{j \neq i} p_j h_j r_j^{-\alpha}} = \frac{p_i h_i r_i^{-\alpha}}{\sigma^2 + \hat{I} - p_i h_i r_i^{-\alpha}} \quad (1)$$

where $\hat{I} = \sum_{k=1}^{K} \sum_{D_l \in \Phi_{dl}} P_k h_l r_l^{-\alpha}$.

III. OPTIMAL POWER CONTROL IN SATELLITE-BASED IoT

In this article, our goal is to devise an optimal power control method for the satellite-based IoT environment for maximizing network capacity. Since the internet interference along with power optimization have obvious relation with users' distribution and terrestrial center's position, we require to investigate the topology characteristics of the satellite-based IoT then identify the power optimization objective function.

In this scenario, stochastic geometry theory is used to formulate the user distribution of IoT terminals in the satellite-based IoT. During the course, the specific network scenario is modeled to be a PPP. Generally, point process theory is a kind of statistics tool to describe the target objects' space distribution characteristics. In this case, we use PPP method to formulate the stochastic IoT terminals' positions.

$$P\{\Phi(A_1)=n_1, \ldots, \Phi(A_k)=n_k\}=\prod_{i=1}^{k}(e^{-\wedge(A_i)\frac{\wedge(A_i)^{n_i}}{n_i!}}) \quad (2)$$

where $k = 1, 2, \ldots, A_i$, $i = 1, 2, \ldots, k$, and $\wedge$ is the measuring density of PPP Φ. k denotes the IoT user and n is a given value. Furthermore, there are two basic properties as following

(i) The distribution of point number is subject to Poisson distribution: In point process Φ, the point number contained in bounded set B complies with Poisson distribution with average value $\lambda \nu_d(B)$ wherein λ is constant. We have

$$P(\Phi(B) = m) = \frac{\mu^m}{m!} \exp(-\mu), \quad m = 0, 1, 2, \ldots \quad (3)$$

where $\mu = \lambda \nu_d(B)$.

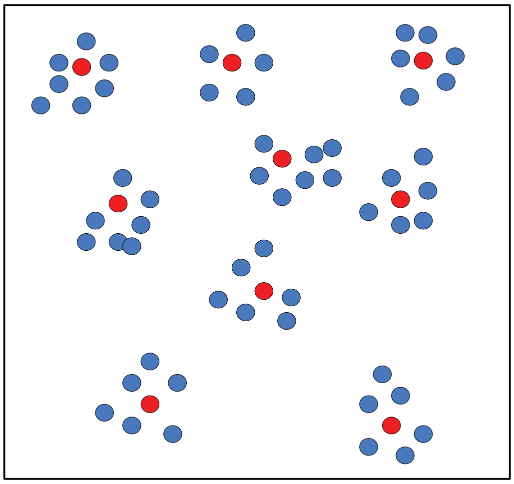


FIGURE 2. Stochastic IoT node distribution.

(ii) Independent scattering property: For any given k, in point process Φ, the point number of k disjoint Borel set will form k independent stochastic variables.

Thus, it should be noted that the position distribution is random while various Poisson points are independent in this case. To simulate the actual IoT network topology, the space distribution of terrestrial base station and other devices should be assumed to be stochastic. In addition, to specifically formulate the situation, more detailed information of many IoT points should be given. Therefore, we use a classic PDF of Palm distribution probability to model the position distribution. Then, we have the following expression

$$P(\Phi \subset \Omega || x) = P(\Phi \subset \Omega | x \in \Phi) \quad (4)$$

As shown in Fig. 2, we suppose the scheme of spectrum reuse in the cells are adopted to improve spectrum usage. In this case, proper power control is required to balance inter-cell interference and enhance network capacity. Then, we have the optimization objective function for terminal's power control as

$$\max_{P(n,m)} = \sum_{n=1}^{N} \sum_{m=1}^{M} R(n, m)$$
$$s.t. \sum_{n=1}^{N} |Y(n_P, n, m)|^2 P(n, m) + \sigma^2(n_P, m) \leq I_{max} \quad (5)$$

where I_{max} is the maximal interference threshold, Y is the parameter of channel fading, N denotes the device number in IoT, M is the sub-carrier number in the given OFDM mode. In addition, the PDF of IoT devices can be given as

$$P(N(B) = x) = (\lambda \nu_d(B))^x \exp \frac{(-\lambda \nu_d(B))}{x!} \quad (6)$$

where $N(B)$ denotes the terminal number complying to PPP distribution in average value of $\lambda \nu_d(B)(\lambda > 0)$. λ denotes the average number of IoT devices in unit area. Y denotes the

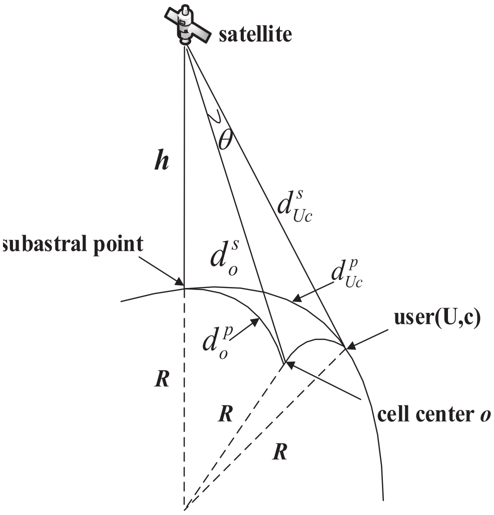


FIGURE 3. **Oblique projector in satellite communications.**

internet interference expressed as

$$Y_{TiS} = \sum_{j=1}^{N} r_{TiSj}^{-m} H_{TS} Q_{TS} X_{TiSj} \tag{7}$$

where X_{TiSj} is the interference suffering from cell S to terminal i in cell T. r_{TiSj}^{-m} is the path loss between user i to user j, in which r_{TiSj} denotes the distance from user i to user j. Furthermore, m denotes the loss coefficient. Then, $H_{TS} = \sqrt{2/\pi R_{ij}}$ describes the Rayleigh fading, where we have

$$R_{ij} = \sqrt{G_I^2 + G_Q^2} \tag{8}$$

where $G_I, G_Q \sim N(0, 1), Q_{MS} = \exp(\nu G_j) \sim LN(0, \nu^2)$. It is assumed that all the transmission signals in the given satellite-based IoT environment are independent, then we have

$$X_{TiSj} = B\cos\theta_j + \tilde{j}B\sin\theta_j \tag{9}$$

where B is the signal envelope. Besides, θ_j denotes the stochastic phase in the region $[0, 2\pi]$.

As shown in Fig. 3, we take into account the effects of oblique projector of satellite communications. Then, for the uplink transmission, the receiving power at satellite can be expressed as

$$C = \frac{p_{Uc} g_{Uc}(\alpha_{Uc}) G_U(\theta_{Uc}^U)}{(4\pi d_{Uc}/\lambda)^2 f_{Uc}(\alpha_{Uc})} \tag{10}$$

where p_{Uc} means the transmit power of IoT terminal c at cell U. α_{Uc} denotes the elevation angle from device c at cell U to the satellite. $g_{Uc}(\alpha_{Uc})$ denotes the antenna gain for device c in the direction of α_{Uc}. θ_{Uc}^U represents the derivation angle from device c to the central line at cell U. Besides, $f_{Uc}(\alpha_{Uc})$ denotes channel fading for user c and λ denotes the wavelength.

Furthermore, the inter-cell interference can be given as

$$I = \sum_{M=1}^{k} \frac{p_{Mn} g_{Mn}(\alpha_{Mn}) G_M(\theta_{Mn}^M)}{(4\pi d_{Mn}/\lambda)^2 f_{Mn}(\alpha_{Mn})} \mu_{Mn} \rho_M^U \tag{11}$$

Then, the network capacity can be obtained to be

$$R = W\log_2(1 + \frac{Y_c C}{I + Wn_0}) \tag{12}$$

where n_0 represents the background noise. Replacing R by equation (12), we have

$$\begin{aligned} \max_{P(n,m)} &= \sum_{n=1}^{N}\sum_{m=1}^{M} W\log_2(1 + \frac{Y_c C}{I + Wn_0}) \\ s.t. &\sum_{n=1}^{N} |Y(n_P, n, m)|^2 P(n, m) + \sigma^2(n_P, m) \le I_{max} \end{aligned} \tag{13}$$

Then, based on Jesesen inequality, we further achieve

$$\begin{aligned} \tilde{R}_i &= E[\ln(1 + SINR_i)] \\ &\ge E[\ln(SINR)_i] \\ &\ge \ln(p_i h_i r_i^{-\alpha}) - \ln(E[\tilde{I}] + \sigma^2 - p_i h_i r_i^{-\alpha}) \end{aligned} \tag{14}$$

Then, in light of PPP distribution function, we have

$$f(r_1, r_2, \ldots, r_N) = e^{-\eta_k \lambda_k r_N^2}(2\lambda\pi)^n r_1 \cdots r_N \tag{15}$$

Based on the stochastic geometry theory, the expectation value of $\tilde{I}$ is

$$\begin{aligned} E(\tilde{I}) &= \sum_{k=1}^{k} \underset{\{h_l, r_l\}}{E} (\sum_{U_l \in \Phi_{uk}} P_k h_l r_l^{-\alpha}) \\ &= \sum_{k=1}^{K} \underset{r_l}{E} (\sum_{U_l \in \Phi_{uk}} P_k r_l^{-\alpha}) \\ &= \sum_{k=1}^{K} \int_{r_N} \cdots \int_{r_1} P_k r_l^{-\alpha} f(r_1, \ldots, r_N) dr_1 \ldots dr_N \end{aligned} \tag{16}$$

Since the optimization function for power control in this proposed method is relatively complex as shown in (13) where the complexity will rise with increasing N, we cannot solve the problem by using general convex optimization method. In this case, we use pattern search method – one of the intelligent algorithm to identify the proposed power solution. The searching pattern of the search method is given in Fig. 4. Also, the diagram of the pattern search method is given in Fig. 5.

The basic steps of pattern search method are as follows.

(1) Given initial point $X_1 \in R^n$, n coordinate point $e_1, e_2, \cdots, e_n$. Set the initial step length σ, acceleration factor $\alpha \ge 1$, reduction rate $\beta \in (0, 1)$, tolerance BER $\varepsilon > 0$. Set $Y_1 = X_1, k = 1, j = 1$.

(2) If the fitness function $f(Y_j + \sigma e_j) < f(Y_j)$, let $Y_{j+1} = Y_j + \sigma e_j$ and go to Step (4); Otherwise, carry out Step (3).

(3) If $f(Y_j - \sigma e_j) < f(Y_j)$, let $Y_{j+1} = Y_j - \sigma e_j$ and go to Step (4); Otherwise, let $Y_{j+1} = Y_j$, carry out Step (4).

(4) If $j < n$, set $j := j + 1$, then go to Step (2); Otherwise, carry out Step (5);

(5) If $f(Y^{n+1}) < f(X_k)$, go to Step (6); Otherwise, carry out Step (7);

(6) Set $X_{k+1} = Y_{n+1}$ and $Y_1 = X_{k+1} + \alpha(X_{k+1} - X_k)$. Let $k = k + 1, j = 1$, then go to Step (2);

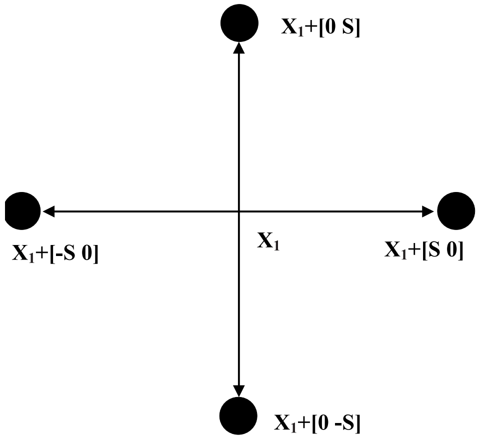


FIGURE 4. Searching pattern of pattern search method.

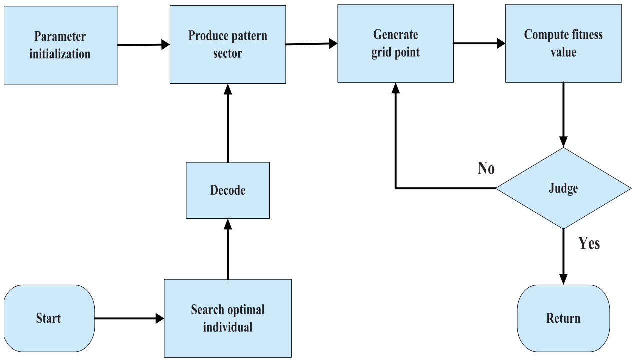


FIGURE 5. Diagram of pattern search method.

(7) If $\sigma \leq \varepsilon$, stop iteration. Otherwise, let $\sigma = \beta\alpha$, $Y_1 = X_k$, $X_{k+1} = X_k$. Let $k : k + 1, j = 1$, go to Step (2).

IV. NUMERICAL RESULTS

In Fig. 2, the IoT terminals' distribution is given. Related parameters are $\gamma^{tar} = 8$, $f_{Uc} = 0.1$, $f_{Mn} = 0.2$, and $P_d \in [0, 1000](mW)$ for IoT device's power, $N = 20$ for device number. The initial parameter values of pattern search method are set as: initial step length $\delta_0 = 10^{-3}$, contraction factor $\beta = 0.1$ and the minimal step length $\gamma = 10^{-7}$.

The stop criteria for the pattern search method are as: 1) The threshold of constantly successful search $d = 0.01$; 2) Minimal distance of two constant objective function $D_min = 0.001$; 3) The threshold of computation time 10^7; 4) The threshold of iteration times 10^6.

In Fig. 6, IoT terminals' optimal power allocations have been given. In this case, IoT terminals' transmit powers are subject to $P_t \in [0, 1000](mW)$. We can obtain from the figure that the terminals' transmit power can converge after various iterations. As the iteration times are relatively few, the complexity of our proposal is low and suitably to be performed in distributed manner. In Fig. 6, various power levels mean the IoT terminals can make different power choices. When the power control is conducted more specific, the optimal power is lower.

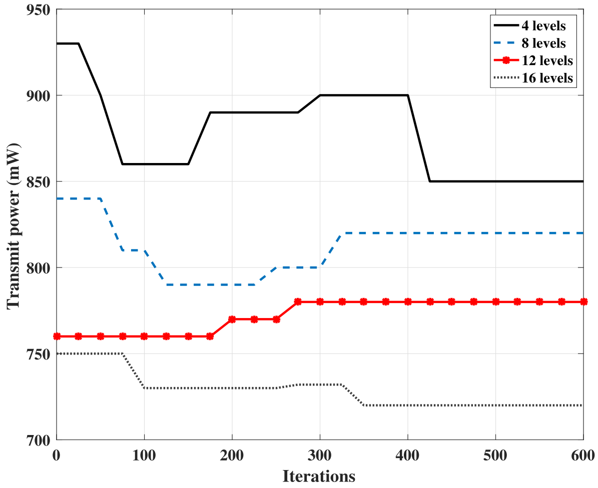


FIGURE 6. Average transmit power.

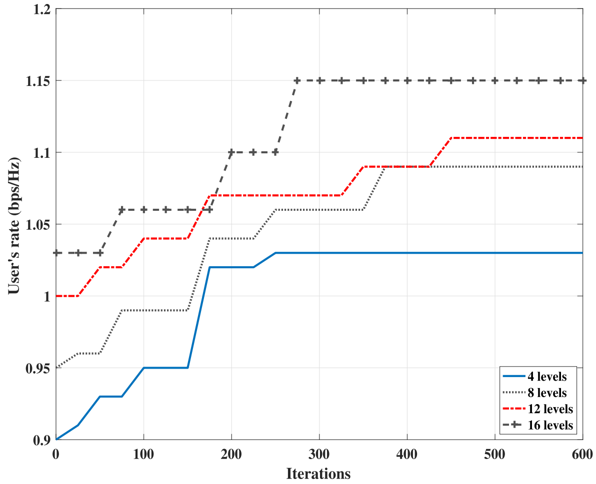


FIGURE 7. IoT terminal's average rates.

In Fig. 7, IoT terminal's average rates have been shown with various power classification. Similar to Fig. 6, more detailed power classification will lead to apparent difference for transmit power and corresponding user rates. Besides, in Fig. 8, the energy efficiency of this proposal is given in which we can obtain that the energy efficiency is also affected by power classification.

Furthermore, in Fig. 9, the sum of IoT users' rates has been given. We can get from Fig. 9 that the network capacity will generally decrease with the rising of IoT user' number. In addition, the overall network capacity will rise to the top when the number of IoT devices reaches about 50, which means excessive network load can decrease network performances.

At last, as shown in Fig. 10, we give the performances of the change of user's transmit power with various background noise changing from 0 to $3 \times 10^{-11} mW$. The three solid lines represent the performances of our solution which varies from user number 10 to 30. With the increase of network

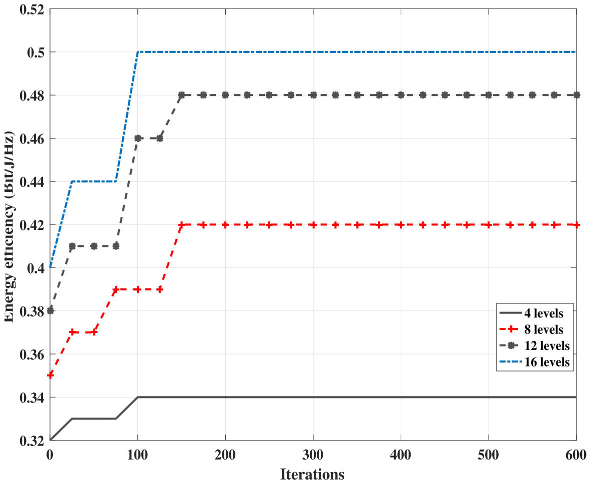


FIGURE 8. Energy efficiency.

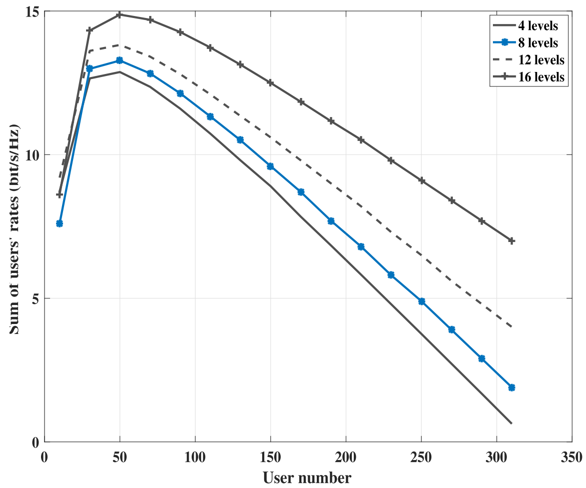


FIGURE 9. Sum of users' rates.

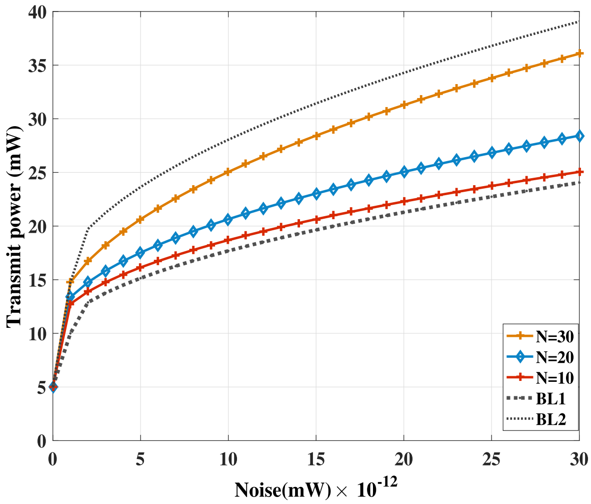


FIGURE 10. Transmit power in various background noise.

load, the average transmit power for a given user has to be raised to battle the background noise. The change of transmit power is relatively linear. In addition, we give the performance comparison of our proposal with that of the SINR (Signal Interference plus Noise Ratio) balanced power control method which can be given as

$$p_i^{(k+1)} = \gamma_i^{tar}\left(\frac{p_i^{(k)}}{\gamma_i^{(k)}}\right) \tag{17}$$

As given in (17), the renown SINR balanced power control solution is an iterative method which can converge within very few iterations and is suitable to be applied in distributed network scenario such as IoT environment. By given a fixed SINR threshold as γ^{tar}, the transmit power can reach a minimal level merely satisfying the SINR demand. As shown in Fig. 10, the dotted line marked BL1 presents the performance in condition of user number 10. Another dotted line marked BL2 shows the performance in user number 40. Thus, from Fig. 10, we can achieve that the performance of our solution approaches that of the SINR balanced method. Since the optimal solution identified by pattern search method has little vibration, the outcomes from the intelligent algorithm will has certain biases. Yet, with proper parameter settings for the optimization theory, the optimal power control solution returned by our proposal is relatively accurate.

V. CONCLUSION

In this article, we proposed a power control method in satellite-based IoT environment where PPP mathematical model has been introduced to formulate stochastic IoT users' distribution. The main contribution of this paper is that we devised a novel power control method for IoT scenarios where the IoT networks need satellite systems to relay their signal in remote and isolated geographic areas. When using the PPP model to describe user distribution in satellite-based IoT, we can acquire basic information of the IoT users at terrestrial base station. Then, users' power optimization and internet interference control will be performed to improve network capacity and energy efficiency. Comparison analysis tests were also given to evaluate the overall performances of our proposal and that of traditional power control method of SINR balanced algorithm. The results showed that the performances of our proposal can closely approach the optimization solution.

ACKNOWLEDGMENT

This article was presented in part at the ICAIIC 2020.

REFERENCES

[1] F. Li and K.-Y. Lam, "Resource optimization in satellite-based Internet of Things," in *Proc. Int. Conf. Artif. Intell. Inf. Commun. (ICAIIC)*, Fukuoka, Japan, Feb. 2020, pp. 6–11, doi: 10.1109/ICAIIC48513.2020.9065200.

[2] F. Li, K.-Y. Lam, N. Zhao, X. Liu, K. Zhao, and L. Wang, "Spectrum trading for satellite communication systems with dynamic bargaining," *IEEE Trans. Commun.*, vol. 66, no. 10, pp. 4680–4693, Oct. 2018.

[3] G. Gui, F. Liu, J. Sun, J. Yang, Z. Zhou, and D. Zhao, "Flight delay prediction based on aviation big data and machine learning," *IEEE Trans. Veh. Technol.*, vol. 69, no. 1, pp. 140–150, Jan. 2020, doi: 10.1109/TVT.2019.2954094.

[4] M. Liu, J. Yang, and G. Gui, "DSF-NOMA: UAV-assisted emergency communication technology in a heterogeneous Internet of Things," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 5508–5519, Jun. 2019.

[5] F. Li, K.-Y. Lam, X. Li, X. Liu, L. Wang, and V. C. M. Leung, "Dynamic spectrum access networks with heterogeneous users: How to price the spectrum?" *IEEE Trans. Veh. Technol.*, vol. 67, no. 6, pp. 5203–5216, Jun. 2018.

[6] Z. Lv and Z. Deng, "Satellite communications in the Era of Internet of Things and cloud computing," *Int. Space*, vol. 9, no. 1, pp. 32–37, 2013

[7] H. Dong, J. Tang, and D. Yu, "Development status and trend of IoT communication technology," *Commun. Technol.*, vol. 5, no. 11, pp. 1233–1239, 2014.

[8] W. Tang, P. Thompson, and B. Evans, "Frequency sharing between satellite and terrestrial systems in the ka band: A database approach," in *Proc. IEEE Int. Conf. Commun. (ICC)*, London, U.K., Jun. 2015, pp. 867–872.

[9] K. An, T. Liang, G. Zheng, X. Yan, Y. Li, and S. Chatzinotas, "Performance limits of cognitive-uplink FSS and terrestrial FS for ka-band," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 55, no. 5, pp. 2604–2611, Oct. 2019.

[10] C. Zhang, C. Jiang, L. Kuang, J. Jin, Y. He, and Z. Han, "Spatial spectrum sharing for satellite and terrestrial communication networks," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 55, no. 3, pp. 1075–1089, Jun. 2019.

[11] J. Lei and M. A. Vazquez-Castro, "Joint power and carrier allocation for the multibeam satellite downlink with individual SINR constraints," in *Proc. IEEE Int. Conf. Commun.*, May 2010, pp. 1–5.

[12] Y. Xu, G. Li, Y. Yang, M. Liu, and G. Gui, "Robust resource allocation and power splitting in SWIPT enabled heterogeneous networks: A robust minimax approach," *IEEE Internet Things J.*, vol. 6, no. 6, pp. 10799–10811, Dec. 2019.

[13] Y. Xu and G. Li, "Optimal and robust interference efficiency maximization for multicell heterogeneous networks," *IEEE Access*, vol. 7, pp. 102406–102416, 2019.

[14] M. Jia, X. Zhang, J. Sun, X. Gu, and Q. Guo, "Intelligent resource management for satellite and terrestrial spectrum shared networking toward B5G," *IEEE Wireless Commun.*, vol. 27, no. 1, pp. 54–61, Feb. 2020.

[15] M. Jia, Q. Gao, Q. Guo, X. Gu, and X. Shen, "Power multiplexing NOMA and bandwidth compression for satellite-terrestrial networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 11, pp. 11107–11117, Nov. 2019.

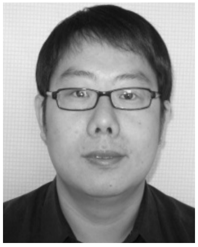
[16] M. Jia, D. Li, Z. Yin, Q. Guo, and X. Gu, "High spectral efficiency secure communications with nonorthogonal physical and multiple access layers," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 5954–5961, Aug. 2019.

[17] M. Takahashi, Y. Kawamoto, N. Kato, A. Miura, and M. Toyoshima, "Adaptive power resource allocation with multi-beam directivity control in high-throughput satellite communication systems," *IEEE Wireless Commun. Lett.*, vol. 8, no. 4, pp. 1248–1251, Aug. 2019.

[18] A. Blanco-Campal, U. Diaz-Orueta, A. B. Navarro-Prados, T. Burke, D. J. Libon, and M. Lamar, "Features and psychometric properties of the montreal cognitive assessment: Review and proposal of a process-based approach version (MoCA-PA)," *Appl. Neuropsychol., Adult*, vol. 12, pp. 1–15, Nov. 2019, doi: 10.1080/23279095.2019.1681996.

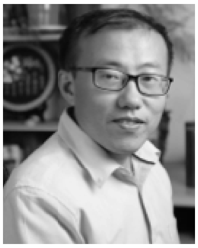
[19] P. Lai, H. Bai, Y. Huang, Z. Chen, and T. Liu, "Performance evaluation of underlay cognitive hybrid satellite–terrestrial relay networks with relay selection scheme," *IET Commun.*, vol. 13, no. 16, pp. 2550–2557, Oct. 2019.

[20] J. Jiao, Y. Sun, S. Wu, Y. Wang, and Q. Zhang, "Network utility maximization resource allocation for NOMA in satellite-based Internet of Things," *IEEE Internet Things J.*, vol. 7, no. 4, pp. 3230–3242, Apr. 2020, doi: 10.1109/JIOT.2020.2966503.

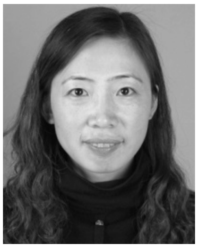


FENG LI (Member, IEEE) received the Ph.D. degree from the Harbin Institute of Technology, Harbin, China, in 2013. He is currently a Full Professor with the School of Information and Electronic Engineering, Zhejiang Gongshang University, Hangzhou, China. He is also with Nanyang Technological University, Singapore. His research interests include power and spectrum allocation for cognitive radio networks, wireless sensor networks, and satellite networks.

KWOK-YAN LAM (Senior Member, IEEE) received the B.Sc. degree (Hons.) from the University of London, in 1987, and the Ph.D. degree from the University of Cambridge, in 1990. He was a Visiting Scientist with the Isaac Newton Institute, Cambridge University, and a Visiting Professor with the European Institute for Systems Security. He has collaborated extensively with law-enforcement agencies, government regulators, telecommunication operators, and financial institutions in various aspects of Infocomm and Cyber Security in the region. He was a Professor with Tsinghua University, China, from 2002 to 2010, and has been a Faculty Member of the National University of Singapore and the University of London, since 1990. He is currently a Renowned Cyber Security Researcher and a Practitioner. He is also a Full Professor with Nanyang Technological University. In 1998, he received the Singapore Foundation Award from the Japanese Chamber of Commerce and Industry in recognition of his research and development achievement in information security in Singapore.



XIN LIU (Member, IEEE) received the B.S., M.S., and Ph.D. degrees from the Harbin Institute of Technology, Harbin, China, in 2006, 2008, and 2012, respectively. He is currently an Associate Professor with the Dalian University of Technology. His research interests include cognitive radio networks, the Internet-of-Things networks, and satellite communication systems.



LI WANG received the B.S. and the M.S. degrees from the Harbin University of Science and Technology, Harbin, China, in 2002 and 2005, respectively, and the Ph.D. degree from the Harbin Institute of Technology, Harbin, in 2013. She is currently an Associate Professor with Dalian Maritime University. Her research interests include optical communication and particle sizing technique.

• • •