Agent-Based Spectrum Management Scheme in Satellite Communication Systems

Feng Li, *Member, IEEE,* Kwok-Yan Lam, *Senior Member, IEEE,* Zhengguo Sheng, *Senior Member, IEEE,* Weidang Lu, *Member, IEEE,* Xin Liu, *Senior Member, IEEE,* and Li Wang

***Abstract*—Efficient spectrum management has always been an important issue due to the scarcity of satellite spectral resource, especially with the ever-increasing broadband demand. This paper proposes a market-driven technique to improve spectrum efficiency. In practice, spectrum resources are typically allocated in bulk to terrestrial agents which in turn will resell the bandwidth to end users of satellite communications. This paper explores the important role of terrestrial agents which serve as spectrum sales agents in satellite communications systems. The proposed approach aims to provide an incentive scheme for the agents to participate in the spectrum optimization process so as to result in maximizing the benefit of the agents as well as the satellite systems. We propose a dynamically optimal cooperation scheme between terrestrial agents and satellite systems, which is based on a stochastic process and optimal contract principle. By taking into consideration the satellite system's marginal cost related to transmission capacity in the given bandwidth, terrestrial agent's effort and the impact of market volatility, we designed an optimal incentive model which allows the satellite systems to determine a threshold value for paying sales commission to terrestrial agents or triggering contract termination if spectrum utilization is inefficient. Numerical results are presented to evaluate the performances of satellite systems' profits in changing spectrum market and agency cost undertaken by satellite systems.**

***Index Terms*—Satellite communication systems, spectrum management, resource optimization**

I. Introduction

SATELLITE users are increasingly dissatisfied with traditional satellite applications of voice, short message and location positioning. The demands for broadband satellite services including video streaming, Internet of Things applications and cloud-based access etc., are undergoing an explosive growth, which calls for a large number of satellite bands along with efficient satellite resource management strategy to fit in [1]-[3].

Remarkable research efforts on enhancing spectrum efficiency in satellite communications systems have been conducted in recent years [4][5]. Multibeam antenna technology are applied to fulfill spectrum reuse between various cells in which inter-cell interference restraining is a key factor [6]. Each beam's wireless resource should be allocated adaptively according to heterogeneous traffic density. In time division multiplex satellite systems, rational time-slot and transmit power resource allocation are essential [7]. Besides, dynamic spectrum access and sharing between satellite systems and terrestrial networks help realize efficient use of idle satellite spectrum [8][9].

Despite research in efficient resource allocation in satellite communication systems has received growing interests in recent years, it still requires deeper investigated. As resource allocation in communication systems always needs to balance the benefits of different participants, marketed-driven scheme consisting of auction-based or pricing-based approaches have been explored. In this connection, however, most of the existing works mainly focus on investigating spectrum sharing from the perspectives of dynamic dealing or bargaining between satellite systems and satellite users [10]-[12]. Very few research focuses on exploring the role of terrestrial agents in spectrum management. In practical situations, satellite spectrum are typically leased to terrestrial agents which in turn resell the spectrum to end subscribers. The terrestrial agents can play a key role in enhancing spectrum efficiency in that, in order to maximize their profits, they will design sales strategy spectrum and trading schemes to maximize bandwidth available for use by subscribers. Therefore, a key issue is to design spectrum management schemes that can incentivize the participation of terrestrial agents while optimizing the profits of the satellite communications systems.

In addition, it is worth noting that though a previous work [10] also focus on improving the efficiency of spectrum management in satellite communication systems, the specific technical approach and key objectives are very different. [10] only investigated optimal spectrum pricing between satellite systems and satellite users, whereas this paper discusses the use of optimal incentive mechanism among terrestrial agent and the satellite systems. Besides, unlike [10], which achieves optimal spectrum sharing by adopting game theory as a mathematical tool to achieve pricing bargaining, this paper proposed the use of general convex optimization method as

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore under its Strategic Capability Research Centres Funding Initiative. Also, this work was supported by the National Natural Science Foundation of China under Grant 61871348 and Natural Science Foundation of Zhejiang Province under Grant LY19F010009 and LY19F010008. (Corresponding author: Xin Liu.)

F. Li is with School of Information and Electronic Engineering, Zhejiang Gongshang University, Hangzhou, 310018, China. F. Li is also at School of Computer Science and Engineering, Nanyang Technological University, 639798, Singapore. (fengli2002@yeah.net)

K. Y. Lam is with School of Computer Science and Engineering, Nanyang Technological University, 639798, Singapore. (kwokyan.lam@ntu.edu.sg)

Z. Sheng is with the Department of Engineering and Design, University of Sussex, Brighton BN1 9RH, United Kindom. (z.sheng@sussex.ac.uk)

W. Lu is with College of Information Engineering, Zhejiang University of Technology, Hangzhou, 310023, China. (luweid@zjut.edu.cn)

X. Liu is with School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China. (liuxinstar1984@dlut.edu.cn)

L. Wang is with College of Marine Electrical Engineering, Dalian Maritime University, Dalian, 116026, China. (liwang2002@dlmu.edu.cn)

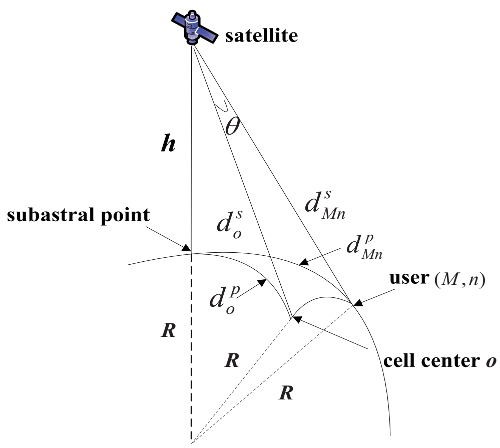

Fig. 1. Oblique projector

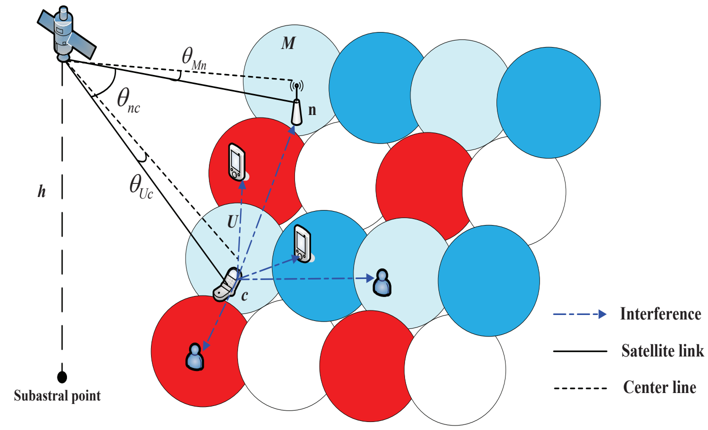

Fig. 2. Spectrum reuse in multibeam satellite systems

the basis of the incentive schemes.

In this paper, an agent-based spectrum optimization scheme for satellite communication systems is proposed. Our goal is to achieve an optimal cooperative mechanism between satellite systems and terrestrial agent to encourage the agent to maximize satellite spectrum benefits with the allocated bandwidth. We investigate the mechanism for achieving a balance between the marginal cost on transmission capacity of the satellite systems and the incentive payment to terrestrial agent. Specifically, the satellite systems need to find an optimal condition such that, while encouraging terrestrial agent to devise better schemes to cater for stochastic user demand, they will not be exposed to excessive unpredictable market risk. We firstly describe the dynamic process of terrestrial agent's revenue, then discuss the incentive condition of optimal spectrum leasing contract. Finally, the differential equations required to be met by satellite systems are defined. The performance of the systems' profits which can be affected by various market volatility and incentive strategy which are testified in simulation part. The rest of this paper is organized as follows. The system model for the proposed agent-based satellite spectrum management scheme is given in Section II. Then, the cooperative mechanism of spectrum trading between satellite systems and terrestrial agent is presented in Section III. In Section IV, numerical results are provided to evaluate the proposal's performances. Last, we conclude this paper in Section V.

II. System Model

In this paper, a high-throughput multibeam satellite systems comprising of N beams to serve a specific area is considered. The satellite systems are supposed to operate in Ka-band. Since the scenario involves flexible resource management, it is assumed that the satellite payload is equipped with necessary modules, such as multiport amplifiers, flexible traveling wave tube amplifiers, etc.

In this spectrum management model, several key factors including satellite systems' investment in spectrum band and profits, terrestrial agent's work and reward, market impact will be involved in. Satellite systems' investment means marginal cost when they authorize certain amount of satellite band leased to terrestrial agent. The marginal cost is related to bandwidth and spectrum quality which is related to internet interference and frequency characteristics. In this paper, we take into account the oblique projection in multibeam satellite communications as shown in Fig. 1. The angle θ describing the deviation angle between user $(\alpha, 1)$ and center point o of cell α can be expressed as

$$\theta = \arccos\left(\{(d_o^s)^2 + (d_{Mn}^s)^2 - 2R^2[1-\cos(d_{Mn}^o/R)]\}\right.\\ \left.\times (2d_o^s d_{Mn}^s)^{-1}\right), \tag{1}$$

where d_o^s denotes the distance between cell center and the satellite as shown in Fig. 1. d_{Mn}^s denotes the distance between user (M, n) and the subastral point, d_{Mn}^o denotes the distance between user (M, n) and cell center o, and R means the earth radius. Besides, the spectrum reuse and inter-cell interference in multibeam satellite systems are considered. As shown in Fig. 2, we assume user n at cell M will suffer interference from user c at cell U where the cells in same color share same spectrum band. Then, for the uplink channel, the receiving power at the satellite from user n at cell M can be expressed as

$$P_r = \frac{p_n g_n(\alpha_n) G_M(\theta_n^M)}{(t\pi d_n/\lambda)^2 f_n(\alpha_n)}, \tag{2}$$

where p_n is the transmit power of satellite user n, $g_n(\alpha_n)$ is the antenna gain of satellite user n at direction α_n. θ_n^M denotes the derivation angle of user n to the central line of cell M. $G_M(\theta_n^M)$ denotes the antenna gain of satellite cell M in direction θ_n^M. d_n denotes the straight-line distance between n and the satellite system. λ is the wavelength, and $f_n(\alpha_n)$ is the channel fading for user n in direction α_n. Besides, inter-cell interference during the spectrum reuse can be expressed as

$$I = \sum_{U=1}^{k} \frac{p_c g_c(\alpha_c) G_U(\theta_c^U)}{(4\pi d_c/\lambda)^2 f_c(\alpha_c)} \mu_c \rho_U^M \tag{3}$$

where μ_c denotes the active factor of user c at cell U which is related to the user's service type. ρ_U^M is the polarization isolation factor between cell M and U.

Then, for satellite user (M, n), the transmission capacity with unit bandwidth can be expressed as

$$C_{Mn} = \log_2(1+ \frac{\rho_{Mn} g_{Mn}(\varepsilon_{Mn}) G_M(\varphi_{Mn})}{d_{Uc}^2 f_{Mn}(\varepsilon_{Mn}) \sum_{U=1}^{l} \frac{\rho_{Uc} g_{Uc}(\varepsilon_{Uc}) G_U(\varphi_{Uc}) \mu_{Uc} \rho_U^M}{(4\pi d_{Uc}/M)^2 f_{Uc}(\varepsilon_{Uc})} + N_0(\varepsilon_{Mn})}), \tag{4}$$

where ρ_{Mn} is the transmit power of user (M, n), $N_0(\varepsilon_{Mn})$ denotes the noise, g_{Mn} and G_M denote the antenna gain and d_{Uc} denotes the straight-line distance from user Uc to the satellite system. User Uc locating in adjacent cell shares the same band with Mn.

The management model consists of risk-neutral satellite systems and terrestrial agent. Satellite systems own the spectrum resource, while terrestrial agent takes the charge of it and uses the satellite band for leasing. Suppose cumulative selling process A_t meets the differential equation as below

$$dA_t = a_t \mu dt + \sigma B_t, \quad t \geq 0, \tag{5}$$

where $\sigma > 0$ is the volatility of A_t, $B = \{B_t : 0 \leq t < \infty\}$ which means the Brownian motion in given probability space denoting as $(\Omega, \digamma, P)$. In spectrum selling process, the terrestrial agent's effort level's $a_t \in [0, 1]$ apparently impacts satellite systems' return rate. Terrestrial agent pays more effort to selling spectrum, then a_t is bigger which leads higher systems' return rate. Meanwhile, terrestrial agent's private benefit will decrease due to less private time for other activities.

It is considered the profits of satellite systems are proportional to bandwidth number leased. The actual profits can be expressed as

$$dY_t = (\pi^n - U_t)dA_t - K_t(\epsilon dt + \upsilon dN_t), \tag{6}$$

where K_t denotes the overall investment of the satellite systems poured into this trading until time t. The investment means marginal cost for the systems which can be given by

$$K = \eta C, \tag{7}$$

where C given in (4) denotes the transmission capacity based on given bandwidth. It should also be noted that the capacity will be affected by many factors such as satellite fading channel, users' transmit power and inter-cell interference. Besides, in (6), $\pi^n \in \{\pi^h, \pi^l\}$ is a two-dimensional Markov transformation process which denotes the change of spectrum selling. U_t denotes the terrestrial agent's remuneration. ϵ denotes linear growth rate, and υ is a given constant. Due to the probability of this kind of market change, we use Poisson stochastic process $N = \{N_t\}_{t \geq 0}$ to represent the number of times at clock t, $\{T_k\}_{k \geq 1}$ denotes the time of kth accident, A_t denotes the density of accident happened. In actual operation of spectrum selling, satellite systems and terrestrial agent have to confront market risk, such as significant volatility of satellite users' demand and policy. Suppose the damage induced by significant market volatility is proportional to satellite systems' investment on bandwidth number released which can be expressed by υK_t.

In the proposed model, satellite systems pay the terrestrial agent according to the benefits they earned. When the agent makes lots of efforts and enable satellite systems to reap more profits, high remunerations are expected despite its additionally private incomes and time decrease. Therefore, it's a balance for terrestrial agent to choose which kind of effort level it should pay. Also, satellite systems require to balance the remunerations they pay to the agent and their own profits. Thus, there exists an optimal cooperative mechanism $\phi = (I, U, \tau)$ for this agent-based spectrum trading. This mechanism needs to assign satellite systems' spectrum investment decision I_t, terrestrial agent's remuneration U_t which is its utility function, and the termination time of this cooperation τ.

The mechanism requires to inspire the agent for better sales, and maximize satellite systems' benefits meanwhile. The agent's effort level depends on the remuneration it achieved, and it's labor cost must be paid with non-decreasing U_t. According to terrestrial agent's effort level $a_t \in [0, 1], (0 \leq t \leq \tau)$, its utility function can be given as

$$\begin{aligned} W(\Phi) = \max_{a_t} E[\int_0^\tau e^{-\gamma t}(dU_t + \lambda(1 - a_t)\mu K_t dt \\ + I_{a_t < 1} \triangle \alpha K_t b dt)], \end{aligned} \tag{8}$$

where the second item denotes the private income of terrestrial agent when it choose $a_t < 1$. K, I denotes total bandwidth number and the ratio of leased band, γ denotes the discount rate of terrestrial agent, λ is the monetary coefficient. $E(\cdot)$ means mathematical expectation. For terrestrial agent, the payment it receives should not be less than the revenue of other opportunities, i.e., $W_t > 0, \forall t > 0$. Then, Based on the proposed cooperative mechanism $\Phi = (I, U, \tau)$, the satellite systems' utility function can be expressed to be

$$F(K_0, W_0, \pi^n) = \max_{\Phi} E[\int_0^\tau e^{-rt} dY_t + e^{r\tau} l K_\tau - \int_0^\tau e^{-rt} dU_t], \tag{9}$$

To guarantee the integral existence, we have $E(\int_0^\tau e^{-\gamma s} dU_s)^2$ and $E[\int_0^T (e^{-rt} K_t)^2 dt] < \infty$.

III. Cooperative Mechanism of Spectrum Trading

According to the requirements of optimal contract between satellite systems and terrestrial agent, we aims to investigate the dynamic process of the agent's utility function so as to ascertain the optimal incentive conditions and achieve the differential equation met by satellite systems.

Based on the cumulative information of spectrum trading, the utility function of terrestrial agent at time t can be expressed as

$$W_t(\Phi) = E_t[\int_t^\tau e^{-\gamma(s-t)} dU_s]. \tag{10}$$

To maintain incentive effect which makes terrestrial agent to choose $a_t = 1$, we have the essential condition as

$$a_t = 1 \Longleftrightarrow \beta_t \geq \lambda, \quad h \geq b, t \geq 0, \tag{11}$$

where $h = \frac{H}{K}$. We assume the satellite systems' benefits is in direct proportion to the spectrum they leased, which means

$$F(K, W, \pi^n) = K f_n(\omega), \tag{12}$$

where $f_n(w)$ denotes the benefits reaped by satellite systems in per band, $W = \frac{W}{K}$ denotes the corresponding discount value in unit band. Thus, we can degrade the optimal contract problem with two state variables K, W_t to objective function with single variable $w = \frac{W}{K}$.

Besides, satellite systems can choose to pay terrestrial agent U_o in one-time cash or in delayed way. When there is

$$f_n(\omega) \geq f_n(\omega - U_o) - U_o, \tag{13}$$

which means $f'(\omega) \geq -1$, thus the agent's marginal payment cost dose not exceed the payment cost of one-time cash. In this case, the one-time payment will not adopted. Furthermore, defining ω^1 as the threshold of delayed payment, we have

$$f'_n(\omega^1) = -1, \quad f''_n(\omega^1) = 0. \tag{14}$$

It can be defined $U_o = \max(\omega - \omega^1, 0)$, wherein in case of $\omega_t > \omega^1$, terrestrial agent can reap cash payment of $\omega_t - \omega_1$ and there is $f(\omega_t) = f(\omega_1) - (\omega_t - \omega_1)$. When $\omega_t \in [b, \omega^1]$, the agent's remuneration will be delayed to pay with $U_o = 0$. Therefore, in our optimal incentive contract model, when $\omega \in [b, \omega^1]$, the discount value ω in unit spectrum should meet the following equation

$$\begin{aligned} d\omega_t =& (\gamma - i + \delta)\omega_t dt + \lambda\sigma dB_t - b(\alpha dt - dN_t) + \\ & \psi_{mn}(\omega)(dM_t - \xi^n dt), \end{aligned} \tag{15}$$

where λ is the parameter of private benefit for terrestrial agent, σ is the market's volatility rate. Satellite systems' benefits in unit spectrum satisfies

$$\begin{aligned} r f_n(\omega) = & \max_{i,h,\beta,\psi} \{\mu\pi^n - \alpha\upsilon - \epsilon + f_n(\omega)(i - \delta) - \omega f'_n(\omega) \\ & \times (i - \delta) + f'_n(\omega)(\gamma\omega + h\alpha - \psi_{mn}\xi^n) + \frac{1}{2} f''_n(\omega)\sigma^2\beta^2\}, \end{aligned} \tag{16}$$

which is subject to

$$\begin{cases} \beta = \lambda, & h = b; \\ f'_n(\omega^1 = -1), & f''_n(\omega^1 = 0); \\ f(b) = l, \end{cases} \tag{17}$$

where $(m, n) \in \{(h, l), (l, h)\}$, $\psi_{nm} = \frac{\Psi_{nm}}{K}$, $i = \frac{I}{K}$. When $\omega \in [0, b]$, the cooperation is terminated. Satellite systems receive liquidation value wherein $f(\omega = l)$. When $\omega \geq \omega^1$, terrestrial agent receives profits $\omega^1 - \omega$ and systems' utility function in unit spectrum will be $f(\omega_t) = f(\omega_1) - (\omega_t - \omega_1)$. Then, the optimal spectrum investment rate i and terrestrial agent's adjusting cost satisfy the following equations

$$i_n(\omega) = \frac{f_n(\omega) - \omega f'(\omega) - 1}{\theta} \tag{18}$$

$$f'(\omega) = f'_m(\omega + \psi_{nm}(\omega)), \tag{19}$$

where $\omega + \psi_{nm}(\omega) \geq b$. Otherwise $\psi_{nm}(\omega) = b - \omega$, the trading cooperation terminates.

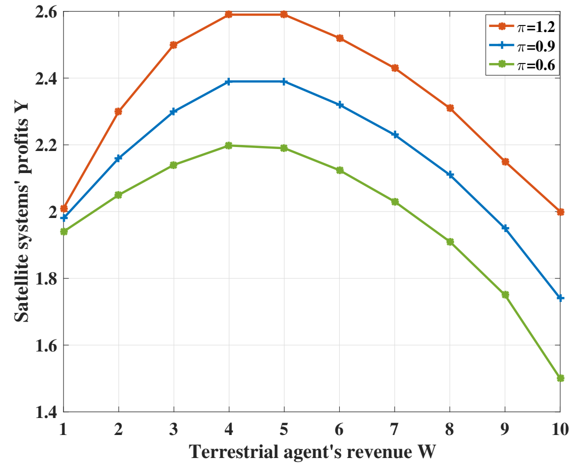

Fig. 3. System profits with various π

IV. Numerical Results

In this section, we evaluate the impacts of agency cost and market volatility on systems' profits. In this circumstance, the satellite systems are supposed to work in channelized TDM mode with spectrum reuse between various beams to enhance spectrum efficiency. External interference caused by other satellite systems are ignored.

In Fig. 3, we give the performances of satellite systems' profits in unit spectrum with changing cost paid to terrestrial agent. In this test, transforming coefficient π is changing from 0.6 to 1.1. Furthermore, $\eta = 1$, $C = 4$, $\epsilon = 1.5$, $\upsilon = 1$, $\sigma = 0.2$, $\lambda = 0.2$. As shown in Fig. 3, with the increase of terrestrial agent's revenue paid by satellite systems, systems' profits can reap proportional growth at the initial stage because proper remuneration is essential for the agent to keep incentive effects. Meanwhile, when terrestrial agent's revenue continues increasing, systems' profits begin to decrease which denotes the agent's cost affects the overall benefits of satellite systems in turn. Thus, the marginal effects of raising agent's revenue reduce or the terrestrial agent has paid all its available time on spectrum selling. It is a key point for satellite systems to balance the payment for inspiring terrestrial agent and their own benefits. In addition, with the decrease of sale transforming parameter π which means more market risk or degrading user demands, the satellite systems' profits is affected apparently.

In Fig. 4, we evaluate the performances of satellite systems' profits from another aspect in which various monetary transforming coefficients η are applied. When transforming coefficient η is relatively high, more benefits can be reaped by the terrestrial agent. Thus, same satellite bandwidth may means various utilities for different terrestrial users. Besides, heterogeneous user demands may also have an effect on the spectrum trading which is beyond our current research. As shown from Fig. 4, when terrestrial agent receives more rational utility function due to higher transforming coefficient η, it will be well inspired to pay more time on improving spectrum selling. More systems' profits and agent payments

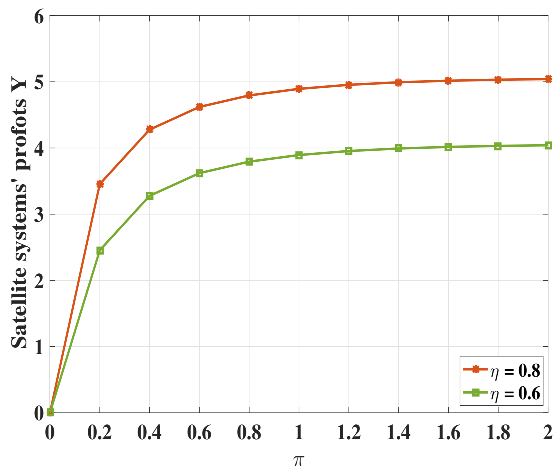

Fig. 4. System profits with various η

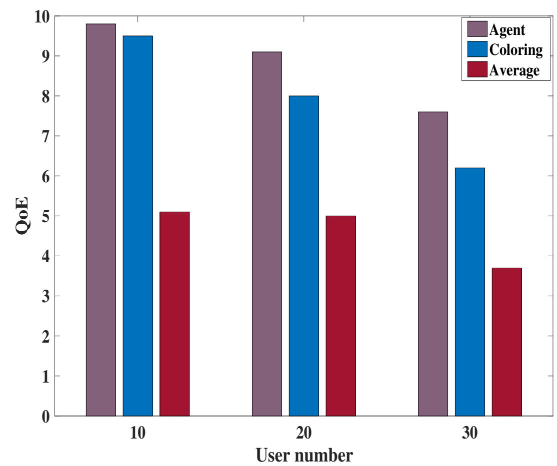

Fig. 6. Quality of Experience

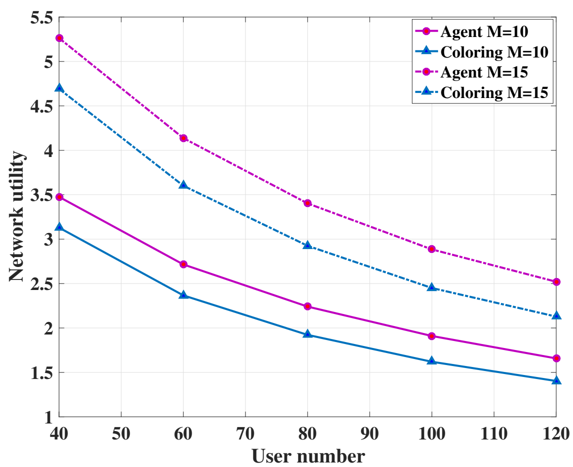

Fig. 5. Network utility

will be realized in this case.

In Fig. 5 and Fig. 6, we give the numerical results of simulation tests that compare between the proposed agent-based method and other traditional solutions including coloring and average spectrum management methods. In coloring-based management method, terrestrial agent is not adopted and the satellite spectrum will be reused and allocated in a balanced way without large variance. In the comparison tests, we divide the satellite spectrum into uniform sub-channels for leasing. As shown in Fig. 5, when stimulating terrestrial agent to optimize the spectrum usage, more network utilities can be attained. Besides, in Fig. 6, the performance of average Quality of Experience (QoE) for satellite users is presented. Wherein, for average spectrum allocation strategy, the satellite spectrum is scheduled to terrestrial users in a fixed and uniform manner which likely leads to low QoEs of hot terminals.

V. Conclusions

In this article, we proposed an optimal cooperation scheme between satellite systems and terrestrial agent to improve satellite spectrum trading. In general, satellite spectrum is always allocated to terrestrial users by leasing at fixed or dynamic mode wherein a terrestrial agent is usually essential to fulfill this trading. The main contribution of this paper is that we designed a proper incentive mechanism for terrestrial agent with the ultimate intention of maximizing satellite systems' profits. When authorizing an agent to perform satellite spectrum selling, a rational contract between participants is critical to combat market risk and achieve win-win results. In our proposal, we ascertain the optimal incentive condition of this spectrum trading cooperation and proper liquidation threshold for satellite systems to reduce damage. Our research reveals not only spectrum pricing but also proper trading contract plays a key role in satellite spectrum optimization. Numerical results show that market volatility and the revenue received by terrestrial agent have apparent impacts on satellite systems' profits.

References

[1] W. Zhong, H. Wang, "Channel estimation based on improved PLS and PLS_ZP algorithm for mobile satellite communication system," *Journal of Sichuan University*, vol. 47, no. 1, Jan. 2015.

[2] Z. Na, Z. Pan, X. Liu, et al., "Distributed routing strategy based on machine learning for leo satellite network," *Wireless Communications and Mobile Computing*, 2018.

[3] C. Han, A. Liu, L. Huo, et al., "A prediction-based resource matching scheme for rentable LEO satellite communication network," *IEEE Communications Letters*, vol. 24, no. 2, pp. 414-417, Feb. 2020.

[4] S. S. Kafiloglu, G. Guer, F. Alagoz, "A Markovian model for satellite integrated cognitive and D2D HetNets," *Computer Networks*, vol. 169, Mar. 2020.

[5] Q. Xu, J. Chen, L. Liu, "Channel allocation algorithm in MF-TDMA GEO satellite system," *Computer Science*, vol. 41, no. 4, pp. 40-43, 2014.

[6] U. Park, H. W. Kim, D. S. Oh and B. J. Ku, Flexible bandwidth allocation scheme based on traffic demands and channel conditions for multi-beam satellite systems, IEEE VTC Fall, pp. 1-5, 2012.

[7] X. Wan, F. Shan, X. Shen, "An optimal algorithm for time-slot assignment in SS/TDMA satellite systems," *International Conference on Computer Communication and Networks*, 2013, pp. 1-6.

[8] X. Xu, K. Tang, Y. Shi, J. Li, S. Yang, "Performance analysis of dynamic bandwidth allocation scheme based on QoS in satellite networks," International Conference on Wireless Communications & Signal Processing, pp. 1-6, 2010.

[9] E. Lagunas, S. K. Sharma, S. Maleki, S. Chatzinotas, B. Ottersten, "Resource allocation for cognitive satellite communications with incumbent terrestrial networks," *IEEE Transactions on Cognitive Communications and Networking*, vol. 1, no, 3, pp. 305-317, 2015.

[10] F. Li, K. Lam, N. Zhao, et al., "Spectrum Trading for Satellite Communication Systems With Dynamic Bargaining," *IEEE Transactions on Communications*, vol. 66, no. 10, pp. 4680-4693, Oct. 2018.

[11] D. H. Jung, M. S. Shin, J. G. Ryu, "Fairness-Based Superframe Design and Resource Allocation for Dynamic Rate Adaptation in DVB-RCS2 Satellite Systems," *IEEE Communications Letters*, vol. 23, no. 11, pp. 2046-2049, Nov. 2019.

[12] A. Fiachetti, M. Fiachetti, A. Pietrabissa, M. Petrone, "Congestion pricing for dynamic bandwidth allocation in satellite networks: a game-theoretic approach," IEEE First AESS European Conference on Satellite Telecommunications, pp. 1-5, 2012.