Optimal Power Control in Cognitive Satellite Terrestrial Networks with Imperfect Channel State Information

Shengchao Shi, Kang An, Guangxia Li, Zhiqiang Li, Hongpeng Zhu, and Gan Zheng

***Abstract*—To address the spectrum scarcity in future satellite communications, employing the cognitive technique in the satellite systems is considered as a promising candidate, which leads to an advanced architecture known as cognitive satellite terrestrial networks. Power control is a significant research challenge in cognitive satellite terrestrial networks, especially when the perfect channel state information (CSI) of satellite or terrestrial links is unavailable because of the estimation error or feedback delay. In this context, we investigate the impact of imperfect CSI of both desired satellite link and harmful terrestrial interference link on the power control scheme in cognitive satellite terrestrial networks. By adopting a pilot-based channel estimation of satellite link and a back-off interference power constraint of terrestrial interference link, a novel power control scheme is presented to maximize the outage capacity of the satellite user while guaranteeing the communication quality of primary terrestrial user. Extensive numerical results quantitatively demonstrate the effect of various system parameters on the proposed power control scheme in cognitive satellite terrestrial networks with imperfect CSI.**

***Index Terms*—Power control, imperfect channel state information, cognitive satellite terrestrial networks, outage capacity.**

I. Introduction

COMPARED with terrestrial networks, satellite systems exhibit a prominent superiority in broadcasting, disaster relief, and navigation for their inherent broadcast nature and high reliability [1] [2]. However, the continuous growth of the traffic demand and radio devices has resulted in the spectrum scarcity in satellite communications. Employing cognitive radio (CR) technology in satellite communications is considered as an efficient technique to enhance the spectrum efficiency in the context of coexistence of heterogeneous networks [3] [4].

The incorporation of CR techniques in satellite terrestrial networks can be applied in different approaches [5]. From a cognitive resource allocation perspective, efficient power control schemes should be carefully designed to guarantee the implementation of CR approaches in satellite terrestrial networks. Specifically, the power allocation with quality of service (QoS) constraints was investigated for the downlink cognitive satellite terrestrial network in [6]. In the uplink case, a novel power control scheme was presented to maximize the ergodic capacity of the satellite user in [7], where the terrestrial cellular system served as the primary system. When the fixed-service terrestrial microwave system operated as the primary system, the power allocation scheme was proposed for the fixed satellite service system in [8]. Considering the delay-sensitive service, two optimal power control schemes were presented in [9], which optimized the delay-limited capacity and outage capacity, respectively. Nevertheless, all these previous works were based on the assumption of perfect channel state information (CSI). In practice, however, due to channel estimation errors, mobility and feedback delay, the exactly perfect CSI in cognitive satellite terrestrial networks is commonly unavailable, and thus all the aforementioned analytical results are not sufficient to deal with the imperfect CSI cases [10]. Under this situation, it is an urgent research challenge to investigate the effect of imperfect CSI on the power control scheme in cognitive satellite terrestrial networks.

Considering the effect of imperfect CSI of both satellite link and terrestrial interference link, we propose a novel power control scheme, where a pilot-based channel estimation and a back-off interference power constraint are adopted for the satellite link and terrestrial interference link, respectively. Moreover, we derive the closed-form expression for the outage probability of the satellite user. Extensive numerical results evaluate the performance of the proposed power control scheme.

II. System Model

Fig. 1 depicts the architecture of uplink cognitive satellite terrestrial network adopted in this letter. In the considered network, the terrestrial cellular network (e.g. UMTS or LTE) is considered to be the primary system, whereas the satellite system (e.g. DVB-SH) corresponds to the secondary system [7]. Herein, the underlay technique is adopted as the spectrum sharing approach, where the satellite user is allowed to utilize the same spectral resources with the primary terrestrial user simultaneously without deteriorating its communication quality [6] [7]. Furthermore, the channel gains of the desired satellite link and the terrestrial interference link are denoted as g_S and g_I, respectively. The weak interference from primary terrestrial user to the satellite can be negligible because of the large distance [11]. The free space loss of the secondary link and interference link are denoted as L_s and L_p, respectively. $G_t(\theta)$ corresponds to the transmit antenna gain at the satellite user for secondary link, which can be obtained as [8]

$$G_t(\theta) = \begin{cases} G_{t,\max}, & 0^\circ < \theta < 1^\circ \\ 32 - 25\log\theta, & 1^\circ < \theta < 48^\circ \\ -10, & 48^\circ < \theta < 180^\circ \end{cases}, \qquad (1)$$

where θ is the elevation angle. $G_t(\theta')$ denotes the equivalent transmit antenna gain for terrestrial interference link with off-axis angle $\theta' = \arccos(\cos(\theta)\cos(\phi))$ and ϕ denotes the angle between the over horizon projected main lobe of the

This work of S. Shi, K. An, G. Li, Z. Li and H. Zhu was supported by National Natural Science Foundations of China (No. 61571464, 61601511, 91338201, 91438109 and 61401507). The work of G. Zheng was supported by the UK EPSRC under grant number EP/N007840/1.

S. Shi, K. An, G. Li, Z. Li and H. Zhu are with the College of Communications Engineering, PLA Army Engineering University, Nanjing, China (e-mail: shishengchao88@gmail.com; ankang@nuaa.edu.cn; satlab_13905177686@163.com; uuulzq@163.com; hongpengzhu@126.com).

G. Zheng is with the Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, U.K. (e-mail:g.zheng@lboro.ac.uk).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LWC.2017.2752160, IEEE Wireless Communications Letters

satellite user and the BS. Besides, G_{BS} is the receive antenna gain at the BS, and $G_r(\varphi)$ denotes the receive antenna gain at the satellite, which can be calculate as [1]

$$G_r(\varphi) = G_{r,\max}\left(\frac{J_1(u)}{2u} + 36\frac{J_3(u)}{u^3}\right)^2, \tag{2}$$

with $J(\cdot)$ being the Bessel function and $u = 2.07123\frac{\sin\varphi}{\sin\varphi_{3\mathrm{dB}}}$. $G_{r,\max}$ represents the maximum gain at the onboard antenna boresight, φ is the angle between the satellite user and the antenna boresight, and $\varphi_{3\mathrm{dB}}$ is the 3-dB angle [1] [12]. For simplicity, we denote $G_S{=}L_sG_t(\theta)G_r(\varphi)$ and $G_I{=}L_pG_t(\theta')G_{BS}$ in the rest of the derivation.

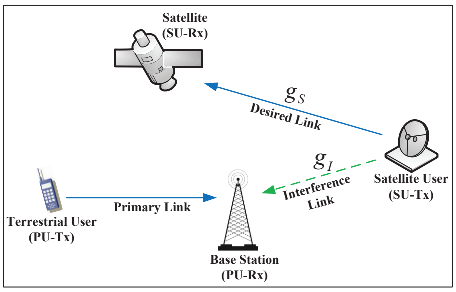

Fig. 1: Uplink cognitive satellite terrestrial network.

III. Channel Estimation

In this section, we consider that only imperfect CSI of both desired satellite link and terrestrial interference link is known at the cognitive satellite user. Thus, imperfect channel gains need to be determined before the proposal of new power control scheme.

A. Cognitive Satellite Link

Without loss of generality, we consider that the satellite user is a mobile/portable terminal and adopt the well-accepted Shadowed Rician (SR) fading model in [13]. In practice, the exact CSI of satellite uplink are obtained by employing return training where the satellite user transmits pilots to the satellite for channel estimation, and then satellite estimates the uplink channel and sends the estimated value over the downlink. Herein, we employ a channel estimation method, by jointly processing the training symbols and data symbols, which can improve the SNR comparing with decoupled detection [10]. When the satellite user transmits data symbols d or L training symbols s_i with transmit power P_T, the signals received at the satellite are z and r_i correspondingly as

$$z = d\sqrt{G_S}g_S + w, \tag{3}$$

$$r_i = s_i\sqrt{G_S}g_S + n_i, (i = 1, 2, 3..., L), \tag{4}$$

where w and n_i are the additive white Gaussian noise (AWGN) with zero mean and variance N_S. By employing the maximum likelihood detector, the estimated channel gain $\widehat{g}_S$ can be calculated as

$$\widehat{g}_S = \frac{d^*z + \sum\limits_{i=1}^{L} s^*r_i}{L+1}. \tag{5}$$

According to [10, eq.(12)], the instantaneous received SNR at the satellite can be written as

$$\gamma = \frac{P_TG_Sh_S}{N_S\left(1+\frac{1}{L+1}\right)}, \tag{6}$$

where $h_S = |g_S|^2$ denotes the channel power gain of the satellite link. As can be observed, the received SNR would be degraded compared with the perfect CSI scenarios. Combining (6) with [13, eq.(6)], we can get the probability density function (PDF) of estimated power gain $\hat{h}_S = h_S/\left(1+1/\left(L+1\right)\right)$ as

$$f_{\widehat{h}_S}(x){=}\alpha\exp\!\left(-\left(1{+}\frac{1}{L+1}\right)\beta x\right)\!{}_1F_1\!\left(m_S,1,\left(1{+}\frac{1}{L+1}\right)\delta x\right), \tag{7}$$

where ${}_1F_1(\cdot,\cdot,\cdot)$ denotes the confluent hypergeometric function [14] and $\alpha = \left(2b_Sm_S/\left(2b_Sm_S+\Omega_S\right)\right)^{m_S}/\left(2b_S\right)$, $\beta = 1/\left(2b_S\right)$, $\delta = \Omega_S/\left(2b_S\left(2b_Sm_S+\Omega_S\right)\right)$, with $2b_S$ being the average power of the scatter component, Ω_S the average power of the line-of-sight (LOS) component and m_S the Nakagami fading parameter. For simplicity, we suppose that m_S takes integer values. Under this situation, we adopt [12, eq.(41)], and thus (7) can be rewritten as (8).

B. Terrestrial Interference Link

As for the terrestrial interference link between the satellite user and the base station (BS), Nakagami fading distribution is considered, in which the channel power gain $h_I = |g_I|^2$ follows the PDF given by [6]

$$f_{h_I}(x) = \frac{\varepsilon^{m_I}x^{m_I-1}}{\Gamma(m_I)}\exp(-\varepsilon x), \tag{9}$$

where $\Gamma(\cdot)$ is the Gamma function [14], m_I is the Nakagami fading parameter, Ω_I is the average power and $\varepsilon = m_I/\Omega_I$.

When the perfect CSI of the interference link is unavailable[1], the conventional interference power constraint can no longer guarantee the communication quality of the primary terrestrial user. We use the model for two correlated Nakagami-m random variables in [15] to describe the relation between perfect and imperfect CSI of terrestrial interference link. From [15, eq. (9.398)], the joint PDF of the perfect channel gain h_I and its imperfect estimation $\widehat{h}_I$ is given by (10), where $I_n(\cdot)$ is the nth-order modified Bessel function of the first kind and $\rho \in [0, 1]$ denotes the correlation coefficient between h_I and $\widehat{h}_I$. Specifically, $\rho{=}1$ indicates that the CSI is perfect.

To ensure the communication quality of the primary terrestrial user, the interference power should not exceed the interference power constraint Q_m, i.e., the transmit power of the satellite user should be set to $P_T = Q_m/\widehat{h}_I$. The actual interference at the primary terrestrial user I_p equals to $Q_mh_I/\widehat{h}_I$. That is to say, due to the imperfect CSI, I_p may exceed Q_m. To characterize the interference at primary terrestrial user, the interference probability of primary terrestrial user P_I is defined as the probability that I_p is higher than Q_m. The scenario with estimated channel gain would lead to an overestimation or underestimation of the received interference at the primary terrestrial user. In this regard, we adopt a back-off power control which replaces Q_m with a new value $\widehat{Q}_m = \mu Q_m$, where $\mu \in [0, 1]$ [16]. Then the actual power control can be adjusted to $\widehat{P_T} = \mu Q_m/\widehat{h}_I$. The new interference probability $\widehat{P}_I$ can be calculated as (11), where ${}_2F_1(\cdot,\cdot;\cdot;\cdot)$ is the Gaussian hypergeometric function [14].

[1] In practical scenarios, due to channel estimation errors or feedback delay, the CSI of h_I is imperfect, especially the CSI from another system under spectrum sharing environment.

$$f_{\widehat{h}_S}(x)=\alpha\exp\left(-\left(1+\frac{1}{L+1}\right)(\beta-\delta)x\right)\sum_{k=0}^{m_S-1}\frac{(-1)^k(1-m_S)_k\left(\left(1+\frac{1}{L+1}\right)\delta x\right)^k}{(k!)^2} \tag{8}$$

$$f_{h_I,\widehat{h}_I}(x,y)=\frac{\varepsilon^{m_I+1}}{(1-\rho)\Gamma(m_I)}\left(\frac{xy}{\rho}\right)^{(m_I-1)/2}\exp\left(-\frac{\varepsilon(x+y)}{1-\rho}\right)I_{m_I-1}\left(\frac{2\varepsilon\sqrt{\rho xy}}{1-\rho}\right) \tag{10}$$

$$\hat{P}_I=\left(\frac{\mu}{1+\mu}\right)^{m_I}\sum_{i=0}^{m_I-1}\binom{m_I+i}{i}\left(\frac{1-\rho}{1+\mu}\right)^i\left[\frac{m_I}{m_I+i}{}_2F_1\left(\frac{m_I+i}{2},\frac{m_I+i+1}{2};m_I;\frac{4\rho\mu}{(1+\mu)^2}\right)-\frac{\rho}{1+\mu}{}_2F_1\left(\frac{m_I+i+1}{2},\frac{m_I+i+2}{2};m_I+1;\frac{4\rho\mu}{(1+\mu)^2}\right)\right] \tag{11}$$

$$P_T^*=\begin{cases}\frac{N_S\left(2^{R_{th}/B}-1\right)}{G_S\widehat{h}_S}, & \widehat{h}_S\geq\frac{N_S\left(2^{R_{th}/B}-1\right)}{G_SP_m}\text{ and }\widehat{h}_I\leq\frac{G_S\widehat{h}_S\widehat{Q}_m}{G_IN_S\left(2^{R_{th}/B}-1\right)}\\ 0, & \text{others}\end{cases} \tag{13}$$

$$P_{out}=1-\int_{\frac{N_S\left(2^{R_{th}/B}-1\right)}{G_SP_m}}^{\infty}\underbrace{\int_0^{\frac{G_S\widehat{h}_S\widehat{Q}_m}{G_IN_S\left(2^{R_{th}/B}-1\right)}}f_{\widehat{h}_I}(x)\,dx}_{I_1}f_{\widehat{h}_S}(y)\,dy, \tag{14}$$

$$P_{out}=1-\alpha\sum_{k=0}^{m_S-1}\frac{(-1)^k(1-m_S)_k\left(\left(1+\frac{1}{L+1}\right)\delta\right)^k}{(k!)^2}\left\{\underbrace{\int_{\frac{N_S\left(2^{R_{th}/B}-1\right)}{G_SP_m}}^{\infty}y^k\exp\left(-\left(1+\frac{1}{L+1}\right)(\beta-\delta)y\right)dy}_{I_2}\right.$$
$$\left.-\sum_{m=0}^{m_I-1}\frac{1}{m!}\left(\frac{\varepsilon G_S\widehat{Q}_m}{G_IN_S\left(2^{R_{th}/B}-1\right)}\right)^m\underbrace{\int_{\frac{N_S\left(2^{R_{th}/B}-1\right)}{G_SP_m}}^{\infty}y^{m+k}\exp\left(-\left(\left(1+\frac{1}{L+1}\right)(\beta-\delta)+\frac{\varepsilon G_S\widehat{Q}_m}{G_IN_S\left(2^{R_{th}/B}-1\right)}\right)y\right)dy}_{I_3}\right\}. \tag{16}$$

$$I_2=\left(\left(1+\frac{1}{L+1}\right)(\beta-\delta)\right)^{-k-1}\Gamma\left(k+1,\left(1+\frac{1}{L+1}\right)(\beta-\delta)\frac{N_S\left(2^{R_{th}/B}-1\right)}{G_SP_m}\right), \tag{17}$$

$$I_3=\left(\left(1+\frac{1}{L+1}\right)(\beta-\delta)+\frac{\varepsilon G_S\widehat{Q}_m}{G_IN_S\left(2^{R_{th}/B}-1\right)}\right)^{-(m+k+1)}\Gamma\left(m+k+1,\left(\left(1+\frac{1}{L+1}\right)(\beta-\delta)+\frac{\varepsilon G_S\widehat{Q}_m}{G_IN_S\left(2^{R_{th}/B}-1\right)}\right)\frac{N_S\left(2^{R_{th}/B}-1\right)}{G_SP_m}\right). \tag{18}$$

When $\widehat{P}_I$ is determined, we can calculate μ for the given m_I and ρ according to (11).

Remark 1. *Although (11) is quite complicated that the analytical expression of μ cannot be obtained, we can get the exact value of μ by applying numerical methods such as bisection algorithm because $\widehat{P}_I$ in (11) is a strictly increasing function with respect to μ.*

IV. Optimal Power Control Scheme with Imperfect CSI

In this section, we propose a new power control scheme in cognitive terrestrial networks with imperfect CSI, which aims to maximize the outage capacity of the satellite user. Outage capacity is defined as the maximum achievable rate that can be maintained over the fading blocks for a specific outage probability, which is mathematically equivalent to minimize the outage probability for a given outage capacity R_{th} [17]. To protect the operation of the primary terrestrial user, the interference probability should be carefully regulated below an acceptable threshold. Thus, when only the estimated channel gains are available for both the satellite uplink and the terrestrial interference link, the optimization problem of the power control scheme can be formulated as

$$\begin{aligned}&\min_{P_T} Pr\left\{B\log_2\left(1+\frac{P_TG_S\widehat{h}_S}{N_S}\right)<R_{th}\right\}\\ &s.t.\begin{cases}P_TG_I\widehat{h}_I\leq\widehat{Q}_m & \text{(t1)}\\ P_T\leq P_m & \text{(t2)}\end{cases}\end{aligned} \tag{12}$$

where $Pr\{\cdot\}$ denotes the probability and P_m is the maximum available power for the satellite user. It can be seen that the minimum transmit power required for the satellite user to guarantee the outage capacity R_{th} is $N_S\left(2^{R_{th}/B}-1\right)/G_S\widehat{h}_S$, which is denoted as P_{th}.

In the case of $P_{th}>P_m$, i.e. $B\log_2\left(1+P_mG_S\hat{h}_S/N_S\right)<R_{th}$. The required power to maintain R_{th} for the satellite user is always larger than P_m, which means that the satellite user is in outage all the time. That is to say, the satellite user cannot work normally even with the maximum available power. Thus, from the perspective of saving power, the optimal transmit power $P_T^*=0$.

In the case of $P_{th}\leq P_m$, i.e. $B\log_2\left(1+P_mG_S\hat{h}_S/N_S\right)\geq R_{th}$. The satellite user can work normally with adequate transmit power. However, if $P_{th}>\widehat{Q}_m/G_I\widehat{h}_I$, $P_T^*=0$ due to the same reason as mentioned above. When $P_{th}\leq\widehat{Q}_m/G_I\widehat{h}_I$, the satellite user transmits with $P_T^*=P_{th}$ in order to save power.

Therefore, the optimal transmit power of (12) can be summarized as (13). Substituting (13) into (12), we can further express the outage probability as (14), where by using [14, eq.(3.351.1)], we first get I_1 as

$$I_1=\frac{1}{\Gamma(m_I)}\gamma\left(m_I,\frac{\varepsilon G_S\widehat{Q}_m\widehat{h}_S}{G_IN_S\left(2^{R_{th}/B}-1\right)}\right), \tag{15}$$

where $\gamma(\cdot,\cdot)$ is lower incomplete Gamma function [14]. Then,

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LWC.2017.2752160, IEEE Wireless Communications Letters

substituting (15) into (14) along with [14, eq.(8.352.1)], we can further have (16). In order to derive (16), we have employed [14, eq.(3.351.2)] and obtained the analytical results of I_2 and I_3 as (17) and (18), respectively, where $\Gamma(\cdot,\cdot)$ is upper incomplete Gamma function [14].

V. Numerical Results

To evaluate the performance of the proposed scheme, numerical results are presented in this section. Herein, we consider B=10MHz,θ=10°,ϕ=50°,$G_{r,\max}=52.1$dB,$G_{t,\max}=42.1$dB,$G_{BS}=0$dB, noise temperature T=300K and $R_{th}=35$Mbps are assumed unless otherwise stated [1] [8]. Moreover, the Average Shadowing (AS) scenario (m_S=10, $b_S=0.126$, Ω_S=0.835) is assumed for satellite link [13]. Besides, Monte Carlo simulations are also given with 10^6 realizations.

Fig. 2 depicts the outage probability of the satellite user versus L for different ρ. It can be observed that the simulation results match well with the analytical results, which shows the correctness of our theoretical derivation. We can see that the outage probability decreases with the increasing of L. This is because the channel estimation error of the satellite link become smaller with the increasing of L. Moreover, the smaller outage probability corresponds to the larger ρ for a given L. This means that the growing of the determinacy for terrestrial interference link is helpful to improve the performance of the satellite user. In addition, it can be inferred that the performance with perfect CSI provides a tight upper bound for the power control scheme.

Fig. 3 shows the outage probability of the satellite user versus ρ for different $\widehat{P}_I$ and m_I. It can be found that when ρ increases to 1, the outage probability of the satellite user gradually decreases and then reaches a certain saturated value. Moreover, with the increasing value of $\widehat{P}_I$, the outage performance of the satellite user would be significantly improved, because larger $\widehat{P}_I$ means the looser constraint for the transmit power of the satellite user. Interestingly, the performance of satellite user in good terrestrial interference link quality (i.e. large m_I) scenario is superior to that of bad terrestrial interference link quality (i.e. small m_I). This phenomenon displays that the more deterministic the terrestrial link is, the better performance of satellite user can be achieved.

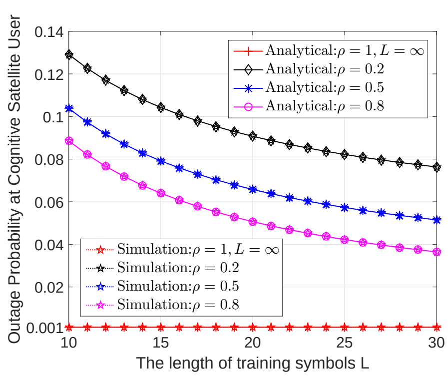

Fig. 2: Outage probability at cognitive satellite user versus L for different ρ with $m_I=3$ and $\widehat{P}_I=0.1$.

VI. Conclusions

In this letter, we proposed a novel power control scheme in cognitive satellite terrestrial networks with imperfect CSI, which aims to maximize the outage capacity of the satellite user without degrading the communication quality of the primary terrestrial user. To alleviate the impact of imperfect CSI and guarantee the operation of primary terrestrial network, we employ a pilot-based channel estimation and a back-off interference power constraint for the satellite link and the terrestrial interference link, respectively. Extensive numerical results demonstrate the impact of various system parameters on the proposed power control scheme.

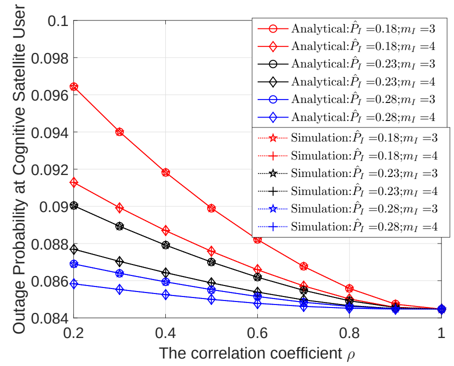

Fig. 3: Outage probability at cognitive satellite user versus ρ for different $\widehat{P}_I$ and m_I with $L=10$.

References

[1] G. Zheng, S. Chatzinotas and B. Ottersten, "Generic optimization of linear precoding in multibeam satellite systems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 6, pp. 2308-2320, June 2012.

[2] M. K. Arti, "Two-way satellite relaying with estimated channel gains," *IEEE Trans. Commun.*, vol. 64, no. 7, pp. 2808-2820, July 2016.

[3] S. K. Sharma, S. Chatzinotas and B. Ottersten, "Cognitive radio techniques for satellite communication systems," in *Proc. IEEE 78th VTC Fall*, Las Vegas, United States, Sept. 2013, pp. 1-5.

[4] K. An, *et al*, "Outage performance of cognitive hybrid satellite-terrestrial networks with interference constraint," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9397-9404, Nov. 2016.

[5] K. Liolis, *et al*, "Cognitive radio scenarios for satellite communications: the CoRaSat approach," in *Proc. Future Network and Mobile Summit*, Lisbon, Portugal, July 2013, pp. 1-10.

[6] S. Vassaki, M. I. Poulakis, A. D. Panagopoulos, *et al*, "Power allocation in cognitive satellite terrestrial networks with QoS constraints," *IEEE Commun. Lett.*, vol. 17, no. 7, pp. 1344-1347, July 2013.

[7] S. Vassaki, M. I. Poulakis and A. D. Panagopoulos, "Optimal iSINR-based power control for cognitive satellite terrestrial networks," *Trans. Emerging Tel. Tech.*, vol. 28, no. 2, pp. 1-10, Feb. 2017.

[8] E. Lagunas, S. Maleki, S. Chatzinotas, M. Soltanalian, A. I. Pérez-Neira, and B. Ottersten, "Power and rate allocation in cognitive satellite uplink networks," in *Proc. IEEE ICC*, Kuala, Malaysia, May. 2016, pp. 1-6.

[9] S. Shi, G. Li, K. An, Z. Li, and G. Zheng, "Optimal power control for real-time applications in cognitive satellite terrestrial networks," *IEEE Commun. Lett.*, to be published in 2017, doi: 10.1109/LCOMM.2017.2684798.

[10] M. K. Arti, "Channel estimation and detection in satellite communication systems," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 10173-10179, Dec. 2016.

[11] S. K. Sharma, S. Chatzinotas *et al*, "Satellite cognitive communications: interference modeling and techniques selection," in *Proc. 6th ASMS and 12th SPSC*, Baiona, Spain, Sept. 2012, pp. 111-118.

[12] K. An, *et al*, "Secure transmission in cognitive satellite terrestrial networks," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 11, pp. 3025-3037, Nov. 2016.

[13] A. Abdi, W. C. Lau, M. S. Alouini, and M. Kaveh, "A new simple model for land mobile satellite channels: first- and second-order statistics," *IEEE Trans. Wireless Commun.*, vol. 2, no. 3, pp. 519-528, May. 2003.

[14] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products (Seventh Edition)*: Elsevier, 2007.

[15] M. K. Simon and M. Alouini, *Digital communication over fading channels*: John Wiley & Sons, 2005.

[16] Y. Huang, *et al*, "Cognitive MIMO relaying networks with primary user's interference and outdated channel state information," *IEEE Trans. Commun.*, vol. 62, no. 12, pp. 4241-4254, Dec. 2014.

[17] X. Kang, *et al*, "Optimal power allocation for fading channels in cognitive radio networks: ergodic capacity and outage capacity," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 940-950, Feb. 2009.