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Computing Energy Efficiency for a Cognitive Heterogeneous Satellite Network Based on Interference Management

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Abstract—**Presently, due to emergence of new generation of wireless telecommunication networks, some appropriate capacity and coverage have been provided for end-users by new hybrid terrestrial-satellite networks, consisting of two or more satellites in different orbits and terrestrial equipment. Today, due to the lack of spectral resources, a method, such as cognitive radio is used to allow for coexistence of spectrum between different nodes. Therefore, in this paper, spectral coexistence method between two satellites was applied over a common region based on cognition link to manage energy efficiency. Also, for mitigating interferences between satellites in downlink channel, the Stackelberg game was exploited. According to simulation results, the proposed algorithm for a primary satellite system with a main node had more energy efficiency compared to the other algorithms, such as sequential convex approximation (SCA)-based precoding, multi-beam interference mitigation (MBIM), and zero-forcing (ZF)-based precoding.**

Keywords-Stackelberg game; Convex optimization; power; interference;Energy efficiency

I. INTRODUCTION

Today, with advent of new generation of telecommunication systems, the need to develop terrestrial infrastructure to increase coverage and capacity as an important factor in the fifth -generation (5G) wireless mobile communications has received a great deal of interest by telecommunications engineers [1]. Presently, a satellite system has an important role to provide limited resources to any end-user in rural remote regions. For this reason, one of the proposed structures is the use of multi-beam satellite systems based on frequency reuse (FR) technique together with other ground equipment, which have been introduced as a hybrid terrestrial-satellite telecommunication structure. There are two types of multi-beam structures based on FR; one of them is a conventional multi-beam satellite system, which uses partial FR in time domain to enhance the total rate. This type is impractical to mitigate interference because there is excessive interference between beams. Another model is a beam hopping satellite, which uses full FR in time domain based on beam hopping pattern [2-4]. This type is practical to mitigate interference, due to the fact that there is an opportunity to reuse full frequency by another satellite system in the same time slot. Also, this kind of communication network has limitations in spectrum resource and frequency bands because of the need to develop heterogeneous satellite network (HSN) that includes one or many satellites in different orbits and band frequencies based on their application accompanying terrestrial infrastructure. One of the

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methods, which have been newly evaluated for management of spectrum resource in hybrid satellite-terrestrial systems, is cognitive radio to share spectrum between two or more satellites and terrestrial equipment [5-7]. Today, there are several space projects, such as cooperative and cognitive architecture for satellite networks (CoSAT) [8], spectrum management and interference mitigation in cognitive radio satellite networks (SeMIGod), [9], and cognitive radio for satellite communications (CoRaSat) [10-11]. In a previous study [12], a system model including Ka band multi-beam satellite, terrestrial equipment, and a cognition link was provided. This structure has two main units including spectrum awareness and hybrid terrestrial-satellite network management. In this regard, in a research [13], an optimization strategy was presented for a typical multi-beam satellite system with respect to quality indicators determined in space service level agreement (SSLA), to assign spectrum portions and polarizations to each beam. In another research [14], firstly, the use of cognitive radio was discussed in hybrid satellite-terrestrial communication networks by 5G approach. Secondly, a spectrum sensing technique was provided. Furthermore, with development of hybrid satellite-terrestrial networks, power control between satellites and terrestrial equipment was raised as a major challenge in various frequency bands, such as Ka and Ku. In this way, in a study [15], three types of interference mitigation in a spectral coexistence situation were introduced including distance detection, data exchange based on traffic model ,and power control based on radio cognitive. In a study [16], a hybrid cognitive satellite-terrestrial network in Ka-band was introduced involving fixed-satellite service (FSS) terminals as primary users (PUs) and fixed service microwave links as secondary users (SUs). In this proposed system model, beam forming technique and carrier allocation based on signal-to-interference-plus-noise ratio (SINR) threshold is a package solution to analyze interference and maximize the total rate in downlink in order to improve beam availability. Finally, in development of satellite- integrated terrestrial networks, with the increase in the number of non-geostationary (NGEO) satellites, the use of spectral coexistence with other existing satellites, such as geostationary (GEO) has become irrevocable. For this purpose, in a previous research [17], types of in-line space interference of composite satellite networks including GEO and NGEO, especially, equatorial territory, were provided. In a study [18], a traffic model was presented for a satellite-integrated terrestrial network to allocate space resources, such as transmission power and gain in the worst weather conditions.

II. Main Contribution

Based on the previous references, such as books or papers reviewed above, the main contributions of this paper are provided as follows:

1. A HSN system model including two satellites in different orbits that use spectrum coexistence to increase the total rate based on beam hopping technique and a terrestrial network is proposed in the present study. In this system model, the primary satellite has more beams than the secondary one in common region.

2. In this system model, Stackelberg game is used to determine cost of interference by each of satellite systems (primary or secondary) [19]. Thus, interference level for any satellite system can be controlled via transmission power and interference threshold level in downlink. Each satellite system can transmit the maximum power by increasing interference tolerance. Optimizing energy efficiency (EE) in terrestrial wireless systems has already been evaluated. In this paper, this parameter is obtained at optimal power and interference threshold level for any primary or secondary satellite systems. In this paper, EE can be decreased compared to other pervious works [20-21]. Therefore, it is noteworthy that there is interference management for this type of structure in the 5G and beyond. Although, interference management mechanism has already been studied and modeled in other proposed structures, computing EE based on interference management for a cognitive HSN in cognitive radio has not been studied for satellite communications (CoRaSat) used in 5G satellite networks. In a previous study [22], variation in satellite antenna angle in downward direction was investigated to calculate the sum rate and interference price according to the predicted limits for the transmitted satellite power and acceptable interference values. Also, EE and traffic matching based on satellite antenna angle were assessed for a HSN. In this type of system models, there is no primary or secondary satellite system based on cognition technique. In a research [23], achievable rate and cost of interference were compared in up and downlinks based on interference management mechanism. Also, bandwidth purchase of the proposed system model was provided according to the game theory. This type of mechanism is according to distance and the number of users in each small cell. Finally, the effect of increasing the number of satellites in the total rate is simulated.

III. System Model

The proposed heterogeneous cognitive satellite network, consisting of two satellites with spectrum coexistence is shown in Fig.1. In the proposed system model, there are a primary satellite (PS) and a secondary satellite (SS). Also, both satellites have a multi-beam structure covering the same geographical region. Moreover, there is a space database for both satellites to adjust transmission data and get beam pattern correctly, since SS only communicates with a small fraction of beams from the total beams. Therefore, the rest of the beams are idle and SS can be the same spectrum in the same time slot in the system model. All of notations used in the proposed system model based on "i" and "j" indexes are shown in Table 1.

TABLE I. LIST OF SOME ACRONYMS IN EQUATIONS BASED ON I AND J INDEXES

Abbreviations	Explanation
$P_P(i,j)$	The power of primary satellite from the ith beam to the jth mobile user
$P_{P-\max}$	Maximum power for primary satellite
$G_{P-MEO}(i,j)$	The gain of primary satellite from the ith beam to the jth mobile user
$G_{mu}(i,j)$	Amount of gain of the ith mobile user in the jth beam
$h_{\text{P-mu}}(i,j)$	Space channel from primary satellite from the ith beam to the jth mobile user
$price_P(i,j)$	Cost of payment by primary satellite from the ith beam to the jth mobile user
$I_{P-\max}$	Maximum interference for primary satellite
$P_S(i,j)$	The power of secondary satellite from the ith beam to the jth mobile user
$P_{S-\max}$	Maximum power for secondary satellite
$G_S(i,j)$	Amount of gain of secondary satellite from the kth beam to the nth mobile user
$h_{\text{S-mu}}(i,j)$	Space channel from secondary satellite from the ith beam to the jth mobile user
$price_S(i,j)$	Cost of payment from secondary satellite from the ith beam to the jth mobile user
$I_{S-\max}$	Maximum interference for secondary satellite
P_n	Noise power

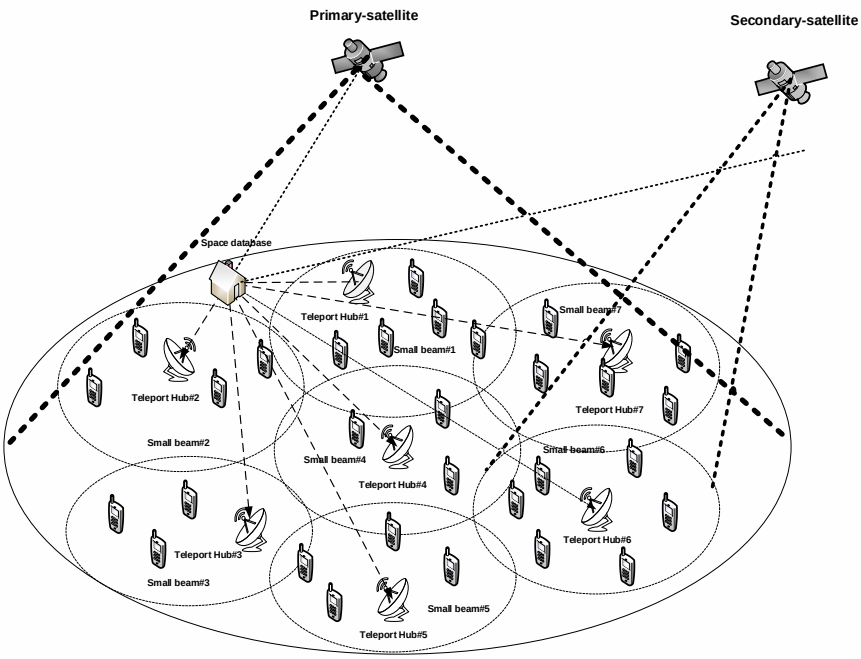

Figure. 1. System model.

Let $i=(1,...,N_b)$, $n=(1,...,N)$, $l=(1,...,L)$. Therefore, 'i' show the number of beams, 'n' show the number of mobile users in each beam, 'l' show the number of ground stations in the system model, respectively. In this system model, space channel coefficients from satellite systems to terrestrial equipment in the down link are Rayleigh distribution [23]. Moreover, constant carrier allocation is assumed for the proposed system model.

A. *Power Control Method Based on Interference-Pricing*

Based on the Stackelberg game theory [18-19], two groups of satellite system are assumed as follows:

1. Follower is a satellite system that is permitted to send data.
2. Leader is a satellite system that is not permitted to send data.

Therefore, this type of game theory has two main roles in the proposed system model as follows:

- The leader and follower must obtain optimal value of transmission power in each beam.
- Cost of interference is proportional to level of interference threshold that will be paid by each satellite to each beam.

Based on the above assumptions, there are two types of interference price as follows:

1. Interference price for PS, which is not allowed to transmit data to a mobile user under territory of another PS beam.
2. Interference price for SS, which is not allowed to transmit data to a mobile user under territory of SS beam.

Based on the literature [23-24], for investigating the effect of interference management on EE, first, there is a need to obtain two crucial factors including transmission power and cost of interference.

B. *Power Control Method of Primary Satellite*

In this section, interference between PS and mobile users is investigated.

In this scenario, interference price must be paid by PS to the mth mobile user in other small cells. In Equation (1), the purpose is maximizing utility function of the PS for the nth mobile user in the ith beam covered by the PS down link. Also, for maximizing utility function of the PS system, the maximum interference threshold is considered as a constraint [22].

$$Utility_{\mathrm{P}}(i,n)=\sum_{i=1}^{N_P}\log_2\left(1+\frac{P_{\mathrm{P}}(i,n)\times G_{\mathrm{P}}(i,n)\times G_{mu}(i,n)\times|h_{\text{P-mu}}(i,n)|^2}{I1+P_n}\right)-Price_{\mathrm{P}}(i,m)\times P_{\mathrm{P}}(i,m)\times\sum_{m=1,m\neq n}^{N}|h_{\text{P-mu}}(i,m)|^2. \quad (1)$$

$$\mathbf{I1}=\sum_{j=1}^{n_s}P_{\mathrm{S}}(j,n)\times G_{\mathrm{S}}(j,n)\times G_{mu}(j,n)\times|h_{\text{S-mu}}(j,n)|^2+\sum_{l=1,l\neq i}^{N_P}P_{\mathrm{P}}(l,n)\times G_{\mathrm{P}}(l,n)\times G_{mu}(l,n)\times|h_{\text{P-mu}}(l,n)|^2,$$

$$\mathbf{A1}=G_{\mathrm{P}}(i,n)\times G_{mu}(i,n)\times|h_{\text{P-}mu}(i,n)|^2.$$

Where N_p is the number of beams used for PS. In this equation, **I1** shows the unwanted interference caused by the jth beam from SS and the lth beam from PS to the nth mobile user under territory of the ith PS beam. Also, P_n is additive noise power in this system model. In the proposed system model, for obtaining optimum power and maximization of the utility function of the ith PS beam for the nth mobile user, which is an active beam, two sub-games must be provided [18]. Sub-game (1) is considered as a follower game to obtain optimum power of ith PS system. Thus, i^{th} PS system acts as a follower. Thus, sub-game (1) is defined as:

$$\underset{P_{P-MEO}(i,n)}{Max}\ Utility_{\mathrm{P}}(i,n) \quad s.t.\quad 0\le P_P(i,n)\le P_{P-\max}. \quad (2)$$

As we know, second derivation of $(Utility_{\text{Primary-MEO}}(i,n))$ vs. $P_{P-MEO}(i,n)$ is less than zero. Thus, this type of function is concave. Hence, maximization of concave function is a convex optimization problem [22-24] and [25]. Finally, optimum $P^*_{P-MEO}(i,n)$ can be obtained as follows [23]:

$$P^*_P(i,n)=\frac{1}{ln2\times\mathbf{B1}}-\frac{\mathbf{I1}}{\mathbf{A1}}. \quad (3)$$

$$\mathbf{B1}=Price_{\mathrm{P}}(i,m)\times\sum_{m=1,m\neq i}^{N}|h_{\text{P-mu}}(i,m)|+\lambda_1.$$

Also, sub-game (2) is defined by calculation of interference price that will be paid by the ith beam of PS system, which has undesirable interference to the mth mobile user. Thus, this sub-game is written as:

$$\underset{Price_P(i,m)}{Max}\ Price_P(j,n)\times P^*_P(i,m)\times\sum_{m=1,m\neq n}^{N}|h_{\text{P-mu}}(i,m)|, \quad (4)$$

$$s.t.\quad P_P(i,m)\times\sum_{m=1,m\neq n}^{N}|h_{\text{P-mu}}(i,m)|\le I_{P-\max}.$$

The objective function in Eq. (4) is a convex function. Based on the literature [26-27], the objective function can turn into the concave function or a minimization problem. After simplification and problem solving, optimum $price_P(i,m)$ can be obtained as follows:

$$Price^*_P(i,m)=\sqrt{\frac{\mu_1\times\mathbf{A1}}{\ln 2\times\sum_{m=1,m\neq n}^{N}|h_{\text{P-mu}}(i,m)|\times\mathbf{I1}}}-\frac{\lambda_1}{\sum_{m=1,m\neq n}^{N}|h_{\text{P-mu}}(i,m)|}. \quad (5)$$

C. *Power Control Method of Secondary Satellite*

In this section, it was assumed that interference price is identical for active and inactive beams.

$$Utility_S(k,n) = \sum_{k=1}^{N_S} \log_2\left(1+\frac{P_S(k,n)\times G_S(k,n)\times G_{mu}(k,n)\times|h_{S\text{-}mu}(k,n)|^2}{\mathbf{I2}+P_n}\right) - Price_S(k,m)\times P_S(k,m)\times \sum_{m=1,m\neq n}^{N}|h_S(k,m)|^2. \quad (6)$$

$$\mathbf{I2} = \sum_{l=1}^{n_p} P_P(l,n)\times G_P(l,n)\times G_{mu}(l,n)\times|h_P(l,n)|^2 + \sum_{j=1,j\neq k}^{N_S} P_S(j,n)\times G_S(j,n)\times G_{mu}(j,n)\times|h_S(j,n)|^2,$$

$$\mathbf{A2} = G_S(k,n)\times G_{mu}(k,n)\times|h_{S\text{-}mu}(k,n)|^2.$$

Where N_s is the number of beams used for SS. In this equation, **I2** shows the unwanted interference caused by the lth beam from PS and the jth beam from SS to n^{th} mobile user under territory of the kth SS beam. Now, achievement of optimal value of the transmission power and maximization of utility function of the kth SS are both considered in two sub-games. Sub-game (3) is regarded as a follower game to identify optimum power of kth SS, the kth SS beam acts as a follower. Therefore, sub-game (3) is defined as:

$$\underset{P_S(k,n)}{Max}\, Utility_S(k,n) \quad (7)$$
$$s.t. \quad 0 \le P_S(k,n) \le P_{S-\max}.$$

Thus, optimum $P^*_S(k,n)$ can be obtained as follows:

$$P^*_S(k,n) = \frac{1}{ln2\times\mathbf{B2}} - \frac{\mathbf{I2}}{\mathbf{A2}}^{+}. \quad (8)$$
$$\mathbf{B2} = Price_S(k,m)\times\sum_{m=1,m\neq n}^{N}|h_{S\text{-}mu}(k,m)| + \lambda_2.$$

Also, sub-game (4) is considered as a leader game in calculation of interference price that will be paid by the kth beam from SS, which has undesirable interference to the mth mobile user. Thus, sub-game (4) is written as:

$$\left(\begin{array}{l} \underset{Price_S(k,m)}{Max}\; Price_S(k,m)\times \\ P^*_S(k,m)\times\sum_{m=1,m\neq n}^{N}|h_{S\text{-}mu}(k,m)|, \\ s.t.\quad P_S(k,m)\times\sum_{m=1,m\neq n}^{N}|h_{S\text{-}mu}(k,m)| \le I_{S-\max} \end{array}\right). \quad (9)$$

The objective function in Eq. (9) is a convex function. Similar to the previous section, optimum $price_P(i,m)$ can be obtained by minimizing Eq. (9). Therefore, optimum $price_S(k,m)$ can be obtained as follows:

$$Price^*_S(k,m) = \sqrt{\frac{\mu_2\times\mathbf{A2}}{\ln 2\times\sum_{m=1,m\neq n}^{N}|h_{S\text{-}mu}(k,m)|.\times\mathbf{I2}}} - \frac{\lambda_2}{\sum_{m=1,m\neq n}^{N}|h_{S\text{-}mu}(k,m)|.}. \quad (10)$$

Similar to the previous relationships Eqs. (4-5), optimum power and price of the SS can be obtained. Finally, the total rate of PS and SS is shown as follows [28]:

$$Utiliy_{Total} = Utility_P(i,n) + Utility_S(k,n). \quad (11)$$

Hence, EE is an important parameter for evaluating hybrid terrestrial-satellite performance. This parameter is defined based on the SINR value divided by optimum satellite power consumption determined in the previous sections (PS or SS) [20].

$$\sum_{i=1}^{N_b}\sum_{n=1}^{N}(Utility_P(i,n))/(P^*_P(i,n)), \quad (12)$$
$$\sum_{i=1}^{Ns}\sum_{n=1}^{N}(Utility_S(k,n))/(P^*_S(k,n)).$$

IV. Simulation Results

In this section, numerical results are presented for performance evaluation. Based on the previous studies [20] and [28], the maximum transmission power of PS and SS, the user antenna gain, the number of beams for PS, the number of beams for SS are equal to 32.75 dBW,41.7 dBi,7 and 3, respectively.

The normalized additive noise power was set to 1[1]. As in shown in Fig.2., EE was decreased with the increase in interference tolerance because PS beams can be transmitted with more the transmission power. Therefore, based Eq.(12), EE decreases when optimum transmission PS increases.

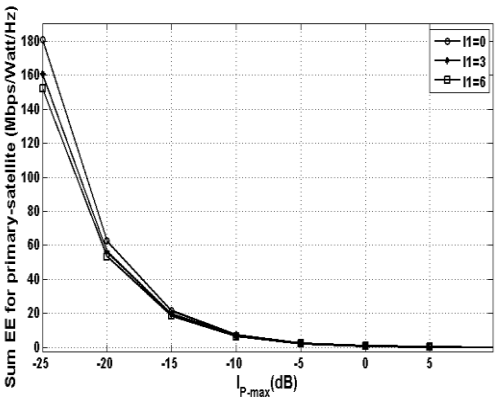

Figure. 2. Energy efficiency for the primary satellite vs. interference tolerance.

As demonstrated in Fig.3, EE was decreased with the increase in interference tolerance because SS beams can be transmitted with more power.

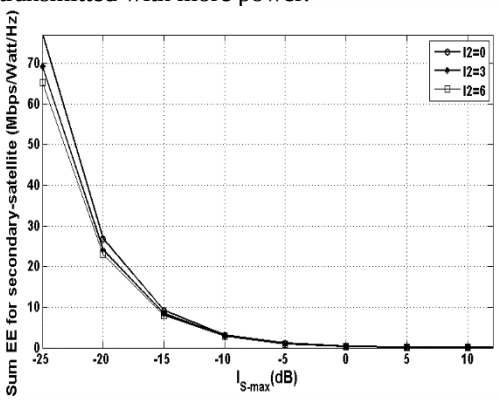

Figure. 3. Energy efficiency for the secondary satellite vs. interference tolerance.

[1] Most of the simulation parameters were provided by the European Space Agency (ESA) in [20].

As depicted in Fig.4, EE was increased with the increase in the number of SS beams and interference tolerance.

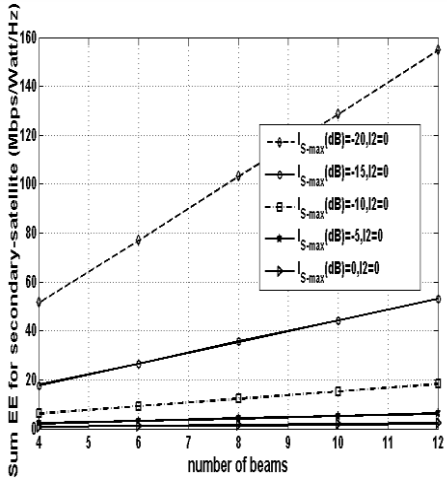

Figure. 4. Sum of energy efficiency vs. different number of beams for the secondary satellite and interference tolerance.

Fig. 5 shows the total rate for HSN including PS and SS with active beams in the same region based on cognition link.

Totally, with the increase in interference tolerance, utility function for PS and SS increases.

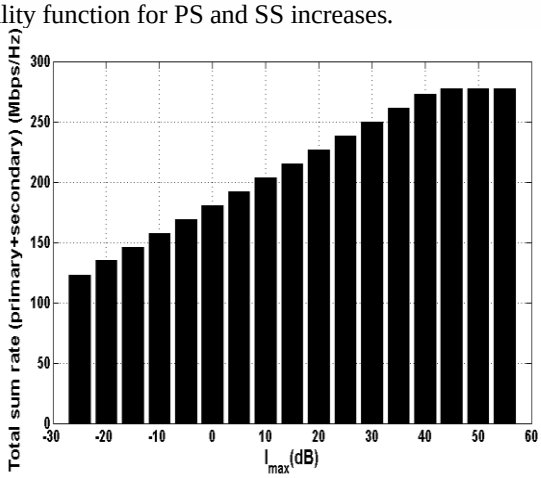

Figure. 5. Total rate for primary satellite and secondary satellite.

D. Comparsion of Different Algorithms Regarding EE

Based on the previous research [20] and [29], EE of a HSN was compared. The first algorithm is a sequential convex approximation (SCA)-based precoding. In this type of algorithm, EE in Eq.(7) will be optimized based on the total transmission power of a multi-beam satellite system.

The second algorithm is zero-forcing (ZF)-based precoding. In this type of algorithm, EE in Eq.(7) will be optimized based on interference among users of a multi- beam satellite system. Third algorithm is multi-beam interference mitigation (MBIM).

In this type of algorithm, EE in Eq.(7) will be obtained by maximizing intra-beam minimum transmission power and minimizing inter-beam interference for a multi-beam satellite system [29].As can be seen in Fig.6, the proposed algorithm can have more or low EE compared to other algorithms based on the maximum interference value from PS or SS systems to end-users in downlink. Comparing different algorithms, it can be concluded that increasing level of interference threshold and consequently, increasing transmission satellite power in our proposed system model can lead to low EE. This behavior is similar to the MBIM algorithm [20]. In this type of algorithm, when transmission power increases from 16 to 22 watt, EE suddenly decreases.

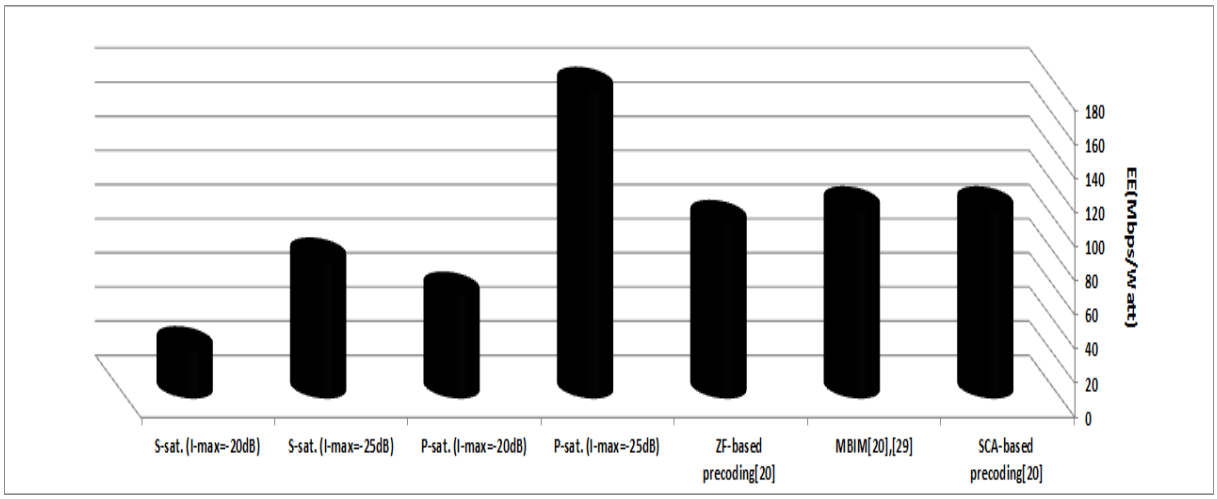

Figure. 6. Comparison of Energy efficiency for four different algorithm methods

V. CONCLUSION

In this paper, a cognitive beam hopping technique was used for HSN, consisting of a PS system and a SS system in spectral coexistence mode. Also, for mitigating interference between beams from PS and SS systems, power control and interference price were evaluated. Based on simulation results, optimum EE can be obtained with respect to optimum transmission power and maximum permissible interference constraints to both PS and SS. The considered problems were solved using convex optimization and game theory based on different sub-games for PS or SS systems. For the future studies, it is suggested to focus on other new solutions regarding pattern of antenna gain and so on.

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