

Economics of Dynamic Spectrum Access

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Abstract—Dynamic Spectrum Access (DSA) was introduced to enhance spectral efficiency as a result of increasing demand for the use of the radio spectrum and to combat the inefficiencies associated with static spectrum allocation. However, it is envisaged that the DSA would result in a drop in revenue, increase in operational costs and could leads to congestion of the network as a result of interference imposed due to secondary usage of the spectrum. Moreover, there is also a need to reduce the energy consumption of the system which could combat the climate change. This therefore, necessitates, the need to examine the social-economic aspect of the DSA systems. The paper investigates the appropriateness of an auction process in DSA networks. Game theory was used to propose a model that helps solving the pricing challenges expected of an auction-based DSA network. The results presented show that, if properly implemented, the DSA can help in congestion management, increase in revenue generation, decrease in operational costs and reduction in in energy consumption. .

Keywords—Dynamic Spectrum Access; Game theory; Spectrum Auction; Spectrum Pricing

I. INTRODUCTION

The radio spectrum is a precious natural resource that lies in the electromagnetic band from 2 Hz up to 300 GHz. Across the globe, different regulatory authorities allocate different parts of the band to a range of wireless technologies. However, in the last decade, the demand for the radio spectrum is facing an unprecedented growth. This is mainly as a result of the increased number of devices seeking access to the radio spectrum. The number of devices seeking access is expected to be over 100 billion by 2020 (Mukherjee, et al., 2015) which also translates to a tremendous increase in data traffic on the radio spectrum. The data traffic is expected to increase 100 fold by 2020 (Mukherjee et al., 2015). This tremendous increase is putting some pressure on the available radio spectrum, thus, necessitating the need for efficient usage of the radio spectrum. A search to accommodate the increase in traffic has led to concepts like Cognitive Radio (CR), Licensed Shared Access (LSA), Authorised Shared Access (ASA), heterogeneous and small cell networks among others Gad & Digham (2010); Hoydis, et al., (2011); Khun-Jush, et al., (2012) ; Parcu, et al., (2011). Most of these concepts are based on the concept of Dynamic Spectrum Access as examined in Gad & Digham, (2010); Song, et al., (2012).

Generally, DSA allows secondary access to the radio spectrum, and the aim is to use the radio spectrum more efficiently. However, ensuring the quality of service of secondary users while satisfying the interference constraint of the primary users is the top challenge of DSA. Furthermore, for effective implementation of DSA, there is a need to use price as a regulatory mechanism. Pricing and economics principle has an important role to play because of the dynamic nature of the wireless environment Jiang, et al., (2015). This is by helping to manage the traffic, examine the value obtained by the users for using the radio resources efficiently and maintaining an equilibrium in the system. Economic incentives have been used to manage vehicular traffic in congested cities around the world such as London and Paris where drivers weigh the options and consequences to either drive or use other means while travelling along the congested zones.

Energy consumption is another important aspect of DSA. There is an urgent need to reduce the amount of energy consumed by wireless networks because of its effect on climate change and to reduce the cost associated with the energy consumed (Rehan & Grace, 2013). The cost of energy consumed forms a significant value in the operational cost of a wireless network. As the demand increases, this is also expected to increase if not properly managed. Tytgat et al., (2011) studied the economic balance as a result of the added cost associated with the introduction of DSA. The paper developed a model that derives the viability of spectrum sensing regarding the added cost and the reliability that comes with it. The paper concluded that the use of Wi-Fi in DSA is viable and it improves the reliability of the network while the case is not same for Zigbee. Jiang et al., (2015) examined the economics behind DSA while examining the simultaneous and sequential auction using game theory however, the paper did not examine the issue of energy usage. Sengupta & Chatterjee, (2009) proposed a knapsack based auction model that allocates spectrum in a manner that maximises revenue and spectrum using game theory. The paper used price as an incentive for upgrading the network It also showed that it is in the best interest of the Wireless Service Provider (WSP) to adhere to the price and channel threshold. Niyato & Hossain, (2008) examined the economics of spectrum trading by introducing a market-equilibrium based spectrum trading mechanism. This mechanism uses the spectrum demand and supply of the primary and secondary users to estimate the price of the radio spectrum. However, the issues dealing with energy consumption was not considered in the paper.

Game theory has been widely used in the analysis of conflict and cooperation between intelligent players with decisions to make. Cuzanauskas & Anskaitis, (2015) described different possibilities of game theory for wireless networks. Wu, et al., (2011) used a Stackelberg game to study joint pricing and power allocation for DSA networks. This was achieved by using the game to the benefit of the primary and secondary users while sharing the radio spectrum. The paper showed that primary users could benefit by selecting multiple secondary users to share their channel with, provided that mutual

interference from the secondary user is limited. The paper highlighted the drawback from the interference caused by the secondary user.

This work, takes into consideration the interference from the secondary users to examine how a game model can be used in modelling the price of the energy consumed in a DSA based wireless network. The paper formulates the reasons behind an auction process and suggest why the preference for this techniques to determine the valuation of the user to maximize revenue intake of the service provider. The economic aspect of DSA is also examined because the operators of secondary wireless access face some challenges such a revenue generation, operational cost reduction, congestion management, among others. To reduce operational cost, the cost of energy used must be taking into consideration. Furthermore, the work considers a model with multiple wireless service providers (WSP) such that where we assume end users connects to any of the WSP of their choice. Based on the concept of DSA, the WSP's in this paper are assumed to be secondary users of the radio spectrum. Hence, they are constrained by the amount of interference that the primary users can endure. The main contribution of this paper is in twofold. Firstly, the paper proposes a game theoretical framework in determining the optimal price for the energy used based on the concept of DSA. Secondly, the work shows how an auction process gives the best result in allocation resources with an unknown value.

II. GAME ANALYSIS

The proposed model, considered a game with N secondary WSP's in the system and N_f users sharing the same channel in adjacent cells. Each WSP is granting access to w secondary end users. However, for the purpose of understanding and without loss of generality, it is assume that $w = 1$ for all WSP's. Hence, we can interchangeably use WSP and user as they mean the same thing. We assume the presence of primary users in the system, however, the users in our proposed model are secondary users with fractional frequency reuse factor . Furthermore, p_i is the amount of energy resources that is consumed by user i . ($i = 1, 2, 3 \dots N$) then, energy resources consumed by all users sharing the same channel in the system is:

$$P = \sum_{i=1}^{N_f} p_i \quad p_i \in [0, \infty] \quad (1)$$

Each user has a varying level of used energy resources which is independent of any other users in the system. However, there is a maximum allowable transmit power ($p_{i_{max}}$) for any user in this system that would allow for the maximal use of the network by both the primary and the secondary users in the systems. However, a user can choose to transmit above $p_{i_{max}}$ hence the infinity in equation (1). It is assumed that there are three components of payments made by the secondary users as demonstrated using the utility expression in equation (2): the payment per unit of energy resources consumed, the fixed price paid to the primary user for secondary access and a varying charge depending on the level of interference experienced by the primary user. The third part of the payment is introduced because,

with DSA, a secondary user is not only sharing the radio spectrum with the primary user but with other secondary users in adjacent cells. Since the users are sharing a common radio spectrum, the activity of one user on the radio spectrum affects others using the same spectrum band. A selfish user transmitting with excessive transmit power diminishes a shared spectrum band for others.

In the formulated game, every user must decide how much it should pay for the energy consumed. The utility of each user is formulated as:

$$U(p_1, \dots, p_i, \dots, p_N) = p_i[s_i(p_i) - b_i] - \int_0^p c(\sum_{f=1}^{N_f} p_f) dp_i \quad (2)$$

where $s_i(p_i)$ is the expected gain of user i , for using transmitting power p_i . b_i is the unit price for the energy consumed by user i . The amount of energy consumed by the user depends on the application as each application has a varying level of transmitting power required. The transmit power required by each application is represented by P_a . When $p_i > p_{max}$, then $s_i=0$. This means that the users are causing so much interference and rendering the system unusable. Otherwise the system is stable. Furthermore, the value of the expected gain varies from one user to the other. Hence, $s_i(p_i) \neq s_j(p_j)$. c is the cost of interference on the system and p_f is power of the interference caused by user i to users both in same cell and in adjacent cells. We assume that the WSP are granted secondary access to the radio spectrum, hence, interference to both the primary users and the other users sharing the same band in adjacent cell is of a significance. The level of interference that can be tolerated on the network varies from one user to the other. However, P_c is the level of interference that the primary user can tolerate. $P_c - P_j$ is the value of interference above P_j that the primary user can tolerate. It is assumed that the users are also charged based on the level of interference they cause to the primary user. This cost for interference is shared by all interfering secondary user. The more the number of secondary users causing interference, the lower the value paid by each user. The total interference from user i is represented as:

$$P_j = \sum_{f=1}^{N_f} p_f \quad (3)$$

For any WSP, when $p_i > p_{i_{max}}$ then the variation in expected gain caused by a single user consuming additional unit of energy is zero. That is,

$$\frac{\partial s}{\partial p} = 0 \quad (4)$$

Therefore:

$$\begin{cases} \frac{\partial c}{\partial p_j} > 0 & 0 < P_j < P_c \\ \frac{\partial c}{\partial p_j} = 0 & P_j = P_c \end{cases}$$

Also the above can be written as

$$\begin{cases} \frac{\partial c}{\partial p_j} < 0 & P_c < P_j < P_{\max} \\ \frac{\partial c}{\partial p_j} = 0 & P_{\max} \leq P_j \end{cases}$$

where $P_{\max}$ is the maximum transmit power that allow the successful transmission at the primary and secondary users . In order to maximize the utility of the users we find the derivative of equation (2) with respect to p_i

$$\frac{\partial U_i}{\partial p_i} = s_i(b_i) - b_i + p_i S'_i(p_i) - c_i(P_j) = 0 \quad (9)$$

substituting equation (4) into equation (9), equation (10) is obtained

$$\frac{\partial U_i}{\partial p_i} = s_i(p_i) - b_i = c_i(P_j) \quad (10)$$

$$s_i(p_i) = c_i(p) + b_i \quad (11)$$

while the second derivative is

$$\frac{\partial^2 U_i}{\partial p_i^2} = -\frac{\partial c_i}{\partial P_j} \quad (12)$$

To get the optimal price, the marginal benefit must be equal to the marginal gain. Based on the equation, it can also be seen that a user in the system cannot be better off without making another user sharing same channel worse off. Hence, the equilibrium is defined as Pareto optimization. The equilibrium is Pareto because we have a non-cooperative game. The alternative would be to have a cooperative game where the users would distribute the profit. To examine the Nash equilibrium, the game can be described as:

Case 1: when derived benefit is always above the cost paid.

$$s_i(p_i) > C_i \left(p_{i_{\max}} + \sum_{f=1, f \neq i}^{N_f} p_f \right) \quad (13)$$

Hence, Case 1 optimization of equation (2) would be for the user to transmit almost at maximum power $p_i \approx p_{\max}$. This is because no matter the transmit power the derived benefit is above the cost. Therefore, in this case, the optimal value of b_i is given as

$$b_i^* = S_i p_{i_{\max}} - C_i \left(p_{i_{\max}} + \sum_{f=1, f \neq i}^{N_f} p_f \right) \quad (14)$$

Case 2: When the benefit derived is greater than the cost of interference to other users but less than the marginal cost.

$$c_i \sum_{f=1, f \neq i}^{N_f} p_f < S_i p_i < C_i \left(p_{i_{\max}} + \sum_{f=1, f \neq i}^{N_f} p_f \right) \quad (15)$$

In this case, the optimal value to pay for unit of energy consumed is

$$b_i^* = S_i p_i^* - C_i(p_i^* + \sum_{f=1, f \neq i}^{N_f} p_f) \quad (16)$$

Case 3: The benefit derived is always less than the cost incurred. Therefore no matter the amount for unit of energy consumed the cost is always higher than the gain.

$$s_i(p_i) < C_i \left(p_{i_{max}} + \sum_{f=1, f \neq i}^{N_f} p_f \right) \quad (17)$$

Interference to other users is, therefore, a factor that must be taken into consideration. Hence, to maximize benefit the level of interference in the system must be carefully chosen. To maximize equation (1) all the users in the system must pick their choice of interference level that would allow for the system to be useable. We assume h_i to be the cost of unit of energy consumed by user i which is causing interference to others in same and adjacent cell.

$$U = \int c_i(p_i + \sum_{f=1, f \neq i}^{N_f} p_f) - p_i \max[-h_i, S_i(p_i)] \quad (18)$$

S_i is cost of interference which is a factor of the energy transmitted and it is also an odd function. Hence, $s_i(-p_i) = -s_i p_i$. To check for maximization we differentiate equation (18)

$$\frac{\partial U}{\partial p_i} = -c_i(P) - \max[-h_i, S_i(p_i)] = 0 \quad (19)$$

$$c_i(P) = -\max[-h_i, S_i(p_i)] \quad (20)$$

To determine the optimal value we have two scenarios

Scenario 1: The price paid by user i for an interference level is less than the expected gain for using p_i amount of energy.

$$-h_i > S_i(p_i) \quad (21)$$

In this scenario equation (21) can be simplified as

$$h_i = c_i(P) \quad (22)$$

Scenario 2: The price paid by user i for an interference level is higher than the expected gain for using p_i amount of energy

$$-h_i < S_i(p_i) \quad (23)$$

Hence,

$$h_i = -S_i(p_i) \quad (24)$$

Based on (21) to (24), the optimal price paid for acceptable inference level is

$$h_i^* = \begin{cases} C_i(p_i + \sum_{j=1, j \neq i}^n p_j, \text{ if } h_i > S_i(p_i)) \\ S_i(p_i^*) \text{ if } h_i < S_i(p_i) \end{cases} \quad (25)$$

It can also be seen from equation (25) that amount a user is ready to pay depends on the category it belongs to. A user with a high level of interference requirement can accept high price provided the benefit derived is higher than cost while those who are not sensitive to high interference can accept much interference and pay less for energy usage. This shows that the Nash equilibrium satisfies the condition that marginal cost must be equal to marginal benefit. Combining all the cases, we obtain the Nash Equilibrium.

$$\sum S_i(p_i^*) + \max[-h_i, S_i(p_i^*)] > \sum c_i(P) \quad (26)$$

For the Nash equilibrium to be achieved, the cooperation of all users in the form of a coalition is required. Furthermore, to determine which category a user belongs to, having the internal knowledge of all the users is required. Hence, an auction pricing model would be appropriate. This would allow the users to express their valuation. Therefore, the use of an auction process is proposed since it removes uncertainty in the system by defining the strategy to be used by all the users and the allocation and payment procedure. This is done by assuming that the characteristics of the players are drawn from probability distribution which is a common knowledge to all users.

There are different types of auction models, the adopted one depending on a number of factors. However, based on revenue equivalent theorem, we should expect that all auction models should provide the same amount of revenue. Therefore, different auction models are examined in this paper.

III. AUCTION MODEL

An auction is a process where bids are taken from interested parties, and a winner is determined based on some established criteria. According to Dictionary (2014) "an auction involves the public sale of a good to the highest bidder". It can be used as the centralized market mechanism for allocating the radio resources. An auction usually involves a single seller and multiple buyers. This pricing scheme is quite interesting and can help to determine the appropriate market price or valuation for commodities.

In any auction process, there are three rules that must be made very clear before an auction begins which are the bidding rule, the allocation rule and the payment rule. The bidding rule informs all the

potential buyers of how the bids are carried out either an open or closed bid, or if it is open, it can be increasing/decreasing auction. The allocation rule states what each bidder gets if they emerge victorious and the payment rule states the amount to be paid. These rules determine the auction schemes. Auctions can also be categorised either as single item auction or multiple item auctions. In a single item auction, only one item is up for sale while multiple items are up for sale in a multi-item auction. An auction process is prone to sellers and buyers acting selfishly as they tend to maximise each other's benefit.

A. Auction Theory for DSA

Auction theory deals with the economics behind an auction. There are different models of auction, some of which are explained below.

a) First Price Sealed Bid Auction

This is a simple auction process where the highest bidder wins and pays the bid value submitted. This is usually carried out in a concealed fashion. It is widely used in wireless communication because it requires less computation complexity Eraslan, et al, (2011).

b) Vickrey Auction

This is a kind of auction where the highest bidder is allocated the item on auction, but the highest bidder pays the price offered by the second highest bidder. Vickrey auctions are usually carried out using the sealed bid auction process. This encourages bidders to put forward bid which shows their true valuation of the radio spectrum. This method is disadvantageous if more than one winner emerges from the auction process. It also does not allow for price discovery and cannot maximise profit (it might even generate zero revenue to the auctioneer). The Vickery auction model was adopted in Yongle, et al, (2008) to capture the interaction between end users and spectrum brokers.

c) Sealed-bid Auction

In sealed bid auctions, the bids of the users are submitted in a concealed fashion. The submitted bids are then compared, and the winner emerges depending on the auction model adopted. A sealed bid auction model cannot be applied in isolation. It has to be implemented in conjunction with other models such as the first or second price auction. This auction model guards against collusion among users and it is widely used in spectrum allocations because it allows users to simultaneously submit their bids thereby reducing delay in the system Coppinger, et al, (1980). This is because the delay is an important factor in any wireless communication system.

d) Simultaneous Ascending Auction (Dutch auction)

This method involves bidding in rounds. The auctioneer specifies the minimum bid increment, and the bidder increases their bids above the minimum increment. This method can be time-consuming. In this auction process, the buyers might resolve to the "live and let live" situation. This is where, in the early stages of the auction process when prices are low, buyers collude to allow everyone to win a band and tactically agree to stop pushing prices up.

e) The Reserve Price Auction

This is a type of auction that guarantees that the sellers only sell above a minimum price. If a buyer bids below the specified minimum price, the sellers can refuse to sell. The reserve price can be public or private knowledge. However, usually the reserve price is not always announced, but it must be realistic. If a realistic reserve price is not set, it could impact negatively on the auction.

f) Homogeneous Sealed Bid Auction

This type of auction is a multiple bid auction in which the buyers submit their bid in a vector format $(b_1, b_2, b_3, \dots, b_n)$. where each bid stands for the amount, the buyer is willing to pay for a particular commodity. The maximum total amount the bidder is willing to pay for all the commodities is the sum of $b_1, b_2, \dots, b_n$. In this type of auction, the buyer puts in a bid for different commodities such as different bands of the radio spectrum. Using this auction process, the bidder might lose some of the items it bids for and win some Hailu & Thoyer (2006).

g) Uniform Pricing Scheme

A uniform pricing scheme is an auction process where all the winning bidders pay the same amount. This scheme is popular for a multi-unit auction. In this scheme, the auctioneer might be the one to determine the clearing price that maximises the auctioneer's revenue based on the average bid submitted. This scheme can also be implemented with the winners paying an amount which is the lowest offered price of all the winning bids. This type of pricing scheme prone to collusion among bidders and it is less fair in creating an unsettled market Mezzetti, Pekeč, & Tsetlin (2008) .

IV. PROPOSED MODEL WITH RESULTS AND DISCUSSIONS

A DSA system using a sealed bid auction process and a reserve price is proposed. A sealed bid auction is combined with a reserve price because of the benefits as outlined in the previous section. The users in the system pick a satisfaction level that would satisfy their requirement based on an infrastructure-based uplink scenario. This work is based on the hexagonal cell structure with a fixed frequency reuse factor as specified in the parameters table. The channel assignment scheme is based on the least interfered channel. A session arrival according to a Poisson distribution process with

arrival rate (λ) and inter-arrival described as exponential distribution is assumed. Each of the users who want to transmit at each auction round submits a sealed bid to the spectrum broker.

Figure 1 shows the blocking probability of the system against the traffic load. When a utility value of above 60% is required, it can be seen that more blocking occurs in the system compared to a user satisfaction of 20 and 40 percent. Our proposed model has the least blocking probability, and this is about 50% which shows a great improvement over the work without proposed constraint threshold. The proposed model provides a better blocking probability because the users who value the spectrum more are allowed when the traffic in the system is high. Figure 2 shows the average energy consumed per unit price against traffic load. From figure 2, it can be seen that the energy consumed increases with traffic load.

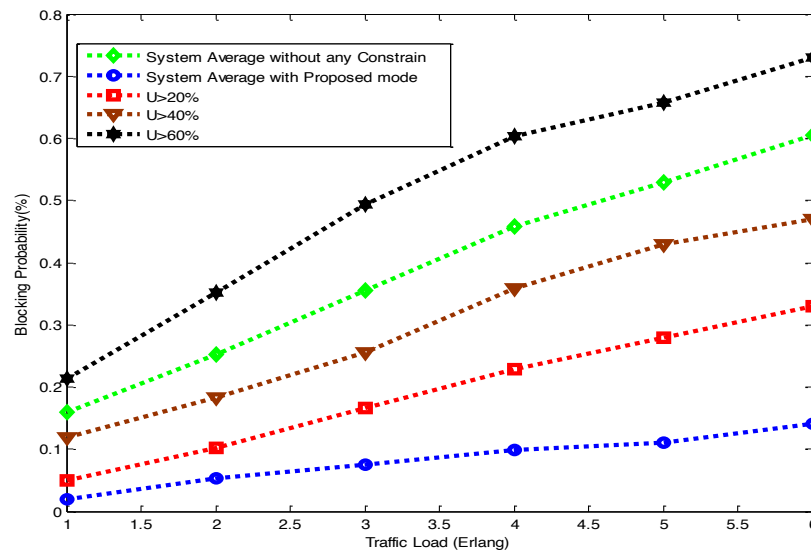


Figure 1. Blocking probability against traffic load for proposed model, without constrains and, utilities of above 20, 40 and 60%.

It can also be seen that when a target of above 60% is set as utility values for the users gives the least amount of energy consumed. This is because users without a utility value less than 60 percent are not considered.

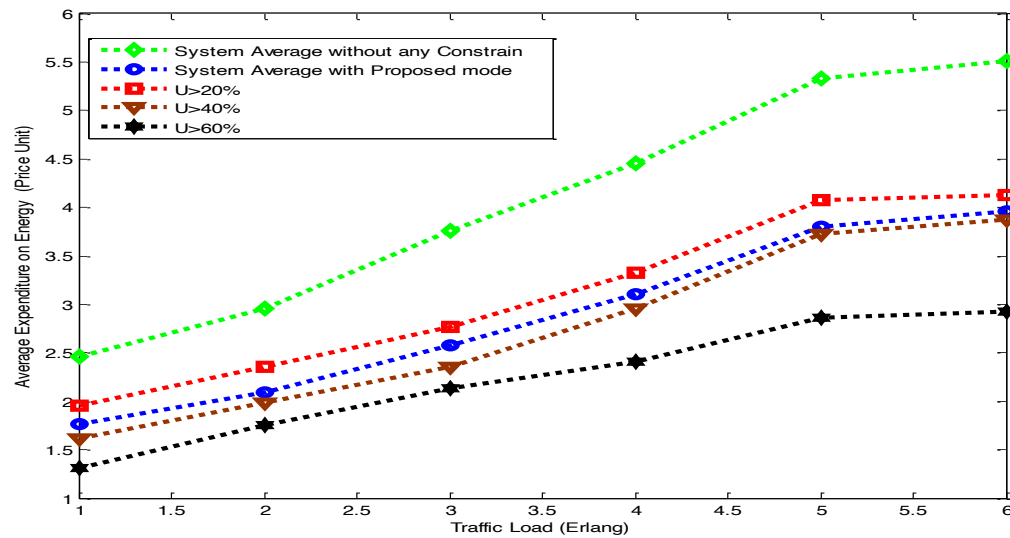


Figure 2. Average energy against traffic load

This is followed by utility value of above 40% and the reason is same. The result also shows that the proposed model performed better than a model with no constraints. Looking at this result alone, one would imagine that having a utility value set to 60% is better than values below it. However, from figure 3, it can be seen that a utility value set as high as 60 percent yields lower throughput when compared to that of 40 percent for all traffic load examined. This is also similar when the utility is set to 20% compared to that of 40%. The result also shows that the proposed model gives the best throughput possibly because the users are allowed to express themselves using the auction process.

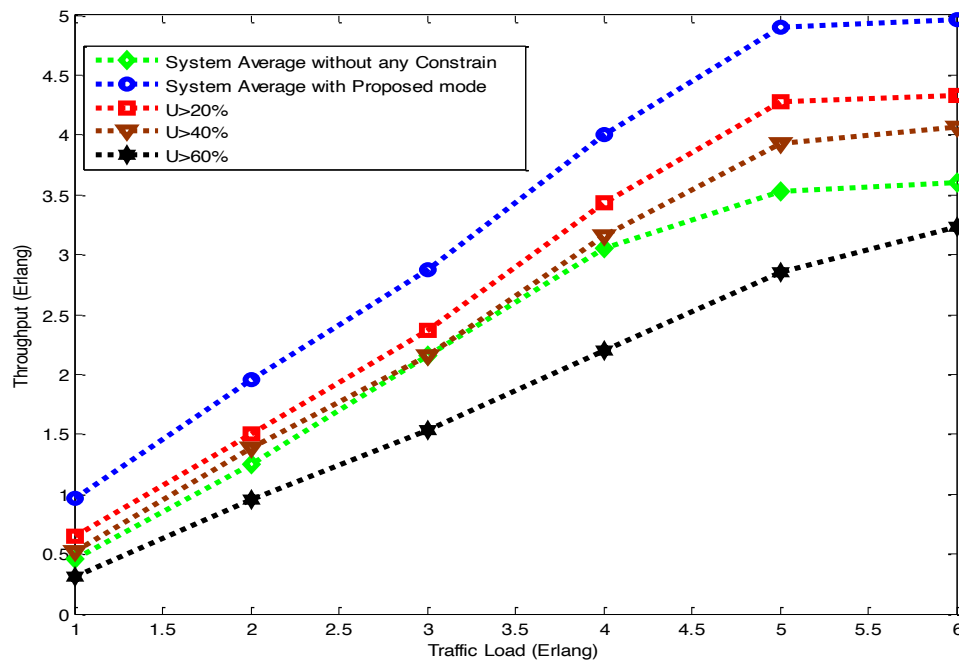


Figure 3. System throughput against traffic load

Figure 4 shows the energy saved against traffic load for the different levels of utility values. It can be seen that the proposed model gives the least amount of energy saving (numerical value should be stated) compared to when the utility value was set to 20, 40 or 60 percent. This is because the higher the utility value the better, however, more energy saving does not correspond to better throughput as seen in figure 3. This shows that energy savings is important but, this must be balanced against other system performance matrices such as the system throughput, interference cancellation. The utility value of 60 percent performs better because it sets higher requirements for the users. This is unlike the proposed model which allows for all the users to express themselves as a result of the auction process.

In order to examine the performance of the proposed model against a non DSA system, this paper compares DSA system with a system with static spectrum allocation which as shown in figure 5. The results show that for all traffic loads examined the DSA system has a better performance. This is as expected because dynamic spectrum access allows for flexible use of the radio spectrum thereby reducing the number of failed attempts.

Figure 6 shows the dropping probability with and without DSA. It can be seen that when the traffic load in the system is low, there is no much difference between the model with DSA and the one without DSA. However as the traffic load increases, the mode with DSA performs better because, in

the proposed DSA model, co-channel and adjacent channel interference are taken into consideration which is not considered in the case of static spectrum allocation

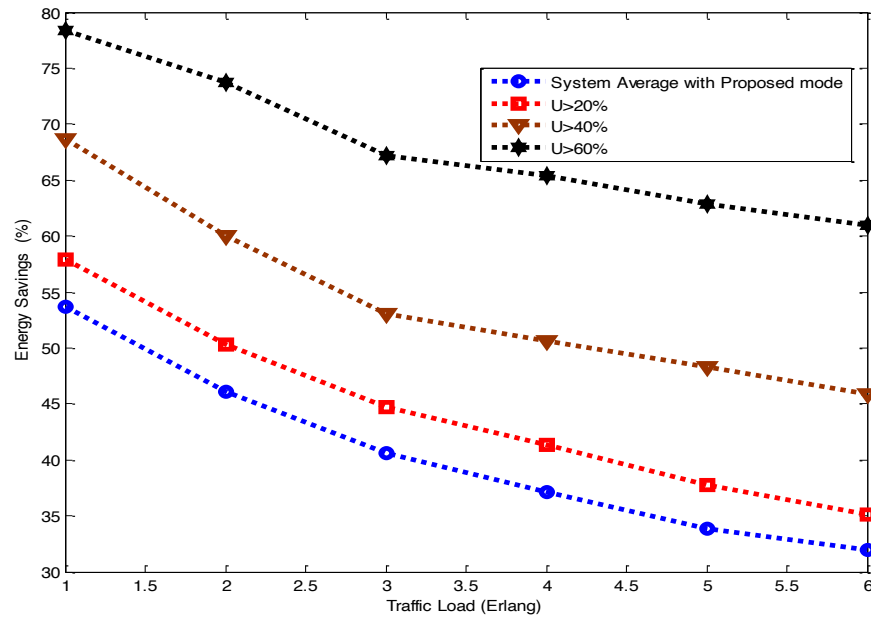


Figure 4. Overall Energy Savings against traffic load

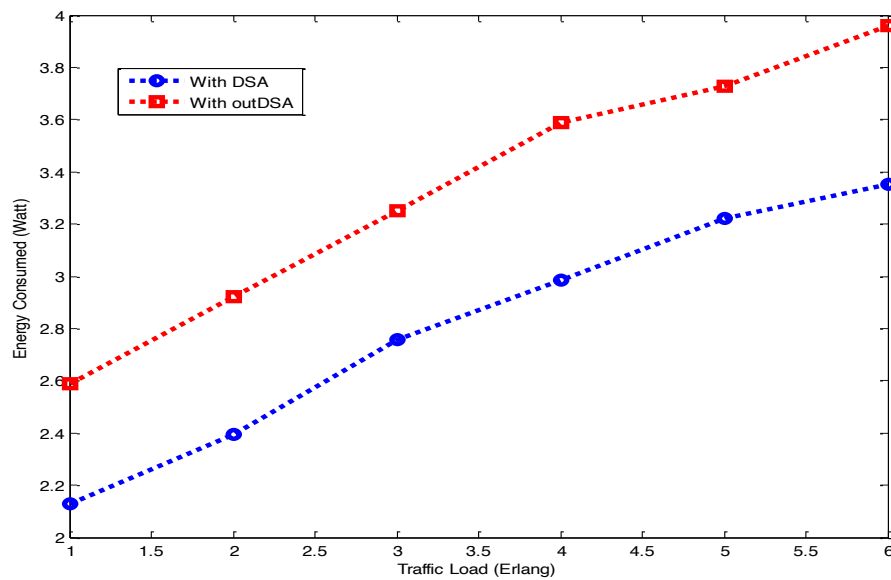


Figure 5. System Energy consumed against traffic load

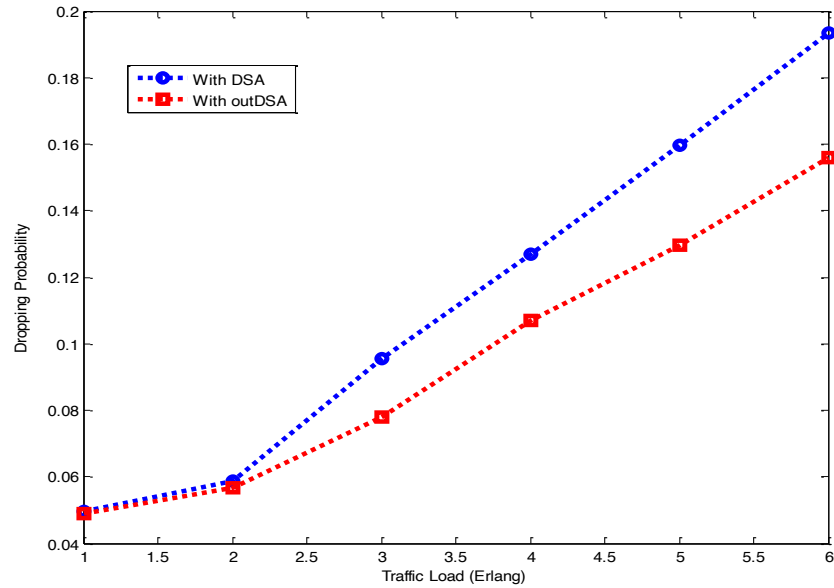


Figure 6. Overall System Throughput energy against traffic load

V. CONCLUSIONS

This paper has developed an economic model using an auction process based on the concept of DSA. First, it develops the utility function to express the satisfaction of the users. A game model is formulated for the WSP's to examine the Nash equilibrium. The paper shows that Nash equilibrium could only be achieved with the cooperation of all the users because no user can be better off without making others worse off. The paper has also examined different auction processes and has proposed model using sealed bid auction model. The results show that the proposed model is not necessarily the most energy efficient since other system performance metrics, such a throughput still has to be taken into consideration. The results obtained also shows that a system with DSA performs better in term of energy saving and blocking probability when compared to a system with static spectrum allocation where an auction process is not used. Future work would examine how machine learning can further aid DSA.

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