ENERGY EFFICIENT AUCTION-BASED DYNAMIC SPECTRUM ACCESS NETWORK

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ABSTRACT: A framework aimed at increasing the much-needed revenue of wireless service providers is proposed. The model uses the price paid by the wireless users to control the amount of energy consumed and the admission process based on a dynamic spectrum access network. The scheme is based on a first price auction process with a reserve price, where price is used to allocate the radio spectrum for short term use. The proposed model allows for an opportunistic access to the spectrum white space in a manner that would protect the primary users in the system. The concept of green payment is used to penalize users who require high transmission power and subsidize those who require low transmission power. This work shows that with the proposed green payment in combination with the knowledge of the reserve price, the energy consumed and the delay in an auction based dynamic spectrum access network can be reduced.

ABSTRAK: Satu rangka kerja yang bertujuan untuk meningkatkan hasil yang amat diperlukan daripada pembekal perkhidmatan wayarles dicadangkan. Model ini menggunakan harga yang dibayar oleh pengguna tanpa wayar untuk mengawal jumlah tenaga yang digunakan dan proses kemasukan berdasarkan rangkaian akses spektrum dinamik. Skim ini adalah berdasarkan kepada proses lelongan harga pertama dengan satu harga rizab, di mana harga yang digunakan untuk memperuntukkan spektrum radio untuk kegunaan jangka pendek. model yang dicadangkan membenarkan untuk akses yang oportunis kepada spektrum ruang putih dengan cara yang akan melindungi pengguna utama di dalam sistem. Konsep pembayaran hijau digunakan untuk menghukum pengguna-pengguna yang memerlukan kuasa hantaran yang tinggi dan subsidi mereka yang memerlukan penghantaran kuasa yang rendah. Kerja ini menunjukkan bahawa dengan bayaran hijau yang dicadangkan dalam kombinasi dengan pengetahuan daripada harga rizab dalam, tenaga yang digunakan dan kelewatan dalam rangkaian akses spektrum dinamik lelongan berdasarkan dapat dikurangkan.

KEYWORDS: *first price auction;green payment;cognitive radio;white space; dynamic spectrum access*

1. INTRODUCTION

Increase in the demand for the radio spectrum, and scarcity of the most precious bands for terrestrial mobile communication is one of the main reasons behind the introduction of the concept of Dynamic Spectrum Access (DSA) [1, 2]. This is in addition to the inefficiencies associated with static spectrum allocation [3]. One of the inefficiencies of static spectrum allocation brought about the need for white spaces in the radio spectrum to prevent interference from other users using the same channel in adjacent cells [4]. However, as the demand for the radio spectrum increases, there is a need to allow access to these white spaces. Such white space includes the guard bands that are left unoccupied for technical reasons[5]. White spaces can also be a result of the recent switching off of transmitters that were previously allocated a band; such is the case with TV white space. TV white space is a result of the recent switching over from analogue to digital TV. This resulted in availability of bandwidth that was previously allocated (50 MHz -700 MHz in the UK) to TV around the globe [6].

DSA would enable wireless devices to access the radio spectrum in an opportunistic manner using the concept of cognitive radio. A cognitive radio is defined as a wireless network that can interact with and observe the wireless environment [7]. It also learns based on its interaction with the environment [8]. To allow for opportunistic access to the radio spectrum, there is a need to propose a scheme that would protect the primary users of the radio spectrum [9]. In addition to this, there is also a need to reduce the amount of energy consumed by wireless devices seeking access to the radio spectrum. Reduction in the amount of energy consumed by wireless devices is important mainly due to the following three reasons. Firstly, the spectrum is a shared resource which requires simultaneous access. Accessing the same frequency band simultaneously, using a DSA scheme, could lead to more interference if not properly managed. Secondly, the effects of energy consumption on carbon emissions into the human environment are leading to global warming. Hence, there is an urgent need to reduce the amount of energy consumed in order to slow global warming. Lastly, wireless devices are mostly battery powered. To increase the working time of the batteries, the energy consumed in transmitting and receiving information should be reduced.

In addition to reduction in the energy consumed, there is a need to increase revenue from the use of the radio spectrum. Revenue increase would allow Wireless Service Providers (WSP) to expand their networks [10, 11]. Expansion of the network is necessary as a result of the increase in the number of devices and applications seeking to use the radio spectrum [12]. Therefore, there is a need to use the price paid for the radio spectrum to regulate short-term access to the radio spectrum while implementing DSA. The use of price has proven to be an efficient tool in the allocation of scarce resources like the radio spectrum [13]. In order to use pricing in a fair manner, an auction would be appropriate [14, 15]. An auction allows the highest bidder to be granted access to the use of the radio spectrum [16]. Application of auctions to wireless communication was also studied in [17]. It proposed a low complexity auction framework to allow short-term access to the spectrum in near real-time.

This paper proposes a model for an energy efficient wireless network for a future DSA network based on an uplink scenario in an infrastructure-based cognitive radio network. In the proposed model, the spectrum is allocated dynamically based on a first price sealed bid auction with a reserve price. The auction process is carried out before each transmitting period. A user seeking access to the radio spectrum submits a bid; a number of users equal to the number of available channels emerge as the winners to whom the radio spectrum is allocated. In the proposed model, the accepted bid for the winners must be above a set minimum price known as the reserve price. The concept of Green Payment (GP) is also used to encourage the efficient use of the spectrum white space and to penalize inappropriate behaviors. The GP is in the form of either a tax or subsidy. A user transmitting above the Signal to Noise Ratio (SNR) threshold from the receiver is taxed and a user whose SNR is below the set threshold is subsidized. SNR is used in this work since the users are grouped cell by cell.

In this paper, the users are divided into two groups: the Low Powered Users (LPU) and the High Powered Users (HPU). The LPU require low transmit power while HPUs require higher transmit power relative to the low powered transmitters. We model this type of user based on the proposed heterogonous nature of the future network as proposed in [18]. It is assumed that each user group has a target bit rate and to achieve the set bit rate, the users need a transmitting power level to sustain the Signal to Noise plus Interference ratio (SINR) that is required, as suggested by Shannon [19]. The auction process proposed in this work is an autonomous agent (proxy bidding) to allow for user participation without necessarily having a professional expertise in an auction process. We adopted the first price auction mechanism because of its simplicity and it requires less computation compared to the second price auction.

The rest of this paper is as organized as follows. Section 2 explains the system architecture. The simulation model is described in section 3. Results and discussion are provided in section 4 followed by the conclusions in Section 5.

2. SYSTEM ARCHITECTURE

We consider an infrastructure-based multi-channel wireless communication network in an uplink scenario where users transmit files via an access point (the base station). These users can be mobile phones, computers, laptops, or any other wireless device. The energy model and other components of the proposed model are as described below:

2.1 Energy Model

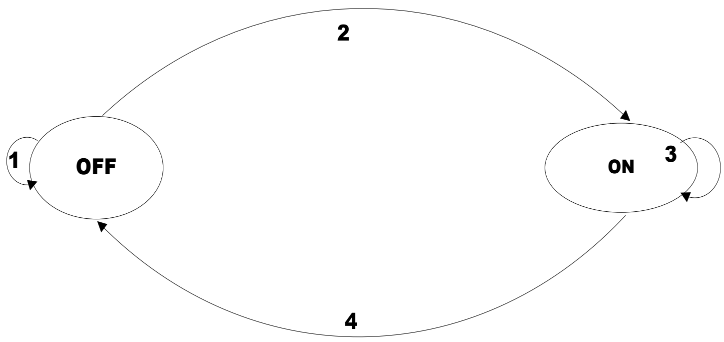

Fig. 1: Energy and System Model as a two-state Markov chain.

The energy model used in this work is represented by a 2 state Markov chain, as shown in Fig. 1, and is similar to the energy model used in [20]. Where the OFF state represents the energy consumed during the bidding process. The amount of energy consumed during the OFF state is considered small compared to the amount of energy consumed in the ON state. Therefore, we assume it to be negligible. The user would continue to be in such a state until the user is among the winning bidders and such a user moves from state 1 to 2. State 2 represents the transition to ON, or transmitting state, and the user is assumed to have transmitted successfully provided the Signal to Noise plus Interference Ratio (SNIR) is above the minimum threshold as indicated in the parameter table presented in section 3.

2.2 The Spectrum Broker

The spectrum broker is the central entity, who is fully aware of all the users present in each cell. The broker is also responsible for issuing a time bound spectrum access to all users. The spectrum is assumed to be owned by the spectrum broker who determines which channel is free via the database. The aim of the broker is to auction off the spectrum to competing users based on their requirement. The spectrum broker can only assign a spectrum that is not in use by the primary users after probing the database. However, primary users are not considered in this work. The broker receives bids submitted by the users based on their valuation. The spectrum broker also calculates the reserve price, which is the minimum acceptable bid.

2.3 The Users Bid

It is assumed that there are N users in each of the cells in the system. N_{USA} represents the users out of the N users who require the use of the spectrum to transmit at time t. Such a user submits a bid, b, to the spectrum broker during a bidding period, t. The bidding period is before the allocation period, T. The bids are formulated based on known principles of bid generation as shown in Eqn. (1)

$$b_i(Price\ Unit) = \frac{(N_{\mathrm{USA}} - N_{\mathrm{AC}})V_i}{N_{\mathrm{AC}}} + V_{\min} \tag{1}$$

For $i = 1,2,3 \ldots \ldots . N_{\mathrm{USA}}$

where subscript i represents one of the N_{USA} users, V_i is the valuation of user i based on the user's budget and the belief of the user regarding the bids of others, a uniform continuous random distribution is assumed for the valuation of each of the users. This valuation is drawn from a known distribution with interval $[V_{min}\ V_{max}]$. N_{USA} is the number of users seeking access and N_{AC} is the number of channels available. Each of the users is assumed to have a fixed budget. We assume the same budget for all the users. In all the scenarios examined, a user cannot offer a bid above the specified budget and the available budget decreases after each payment. We assume that the users are rational, such that a losing bidder in the previous bidding round increases the bid submitted, using a known uniform random distribution $f(x)$ in the next auction round. Users also decrease their bids after winning a bidding round, until a steady state is reached. This is similar to the proposed method in [21]. In some part of this work, we assume that the reserve price is known to all the users. This is known as the Public Knowledge of Reserve Price (PKRP). If a public knowledge of the reserve price is assumed, the users only generate a bid above the reserve price or rather not put in a bid.

2.4 The Reserve Price

The reserve price increases with the traffic load because at high traffic load, the primary user incurs more interference from the secondary users and fewer channels are available. The reserve price, r, which is the minimum acceptable bid by the broker, is calculated as shown in Eqn. (2)

$$r_i = \frac{C_r C_f\, \gamma}{N_{\mathrm{AC}}} \tag{2}$$

where C_f is the congestion factor, C_r is a factor used to specify the value of a particular frequency band and γ is is a constant which is determined by the broker depending on how much profit the broker intends to make. The congestion factor is the ratio of the number of users transmitting at time t compared to the number of channels available.

$$C_f = \frac{N_{\mathrm{USA}}}{N_{\mathrm{AC}}} \tag{3}$$

The C_f is same for all the users who want to transmit within the same period t. For easy analysis and simplicity, γ and C_r are each assumed to be 1 in this work.

2.5 The Green Payments (GP)

The concept of GP, which is in the form of either a tax or subsidy, is used. The GP is based on the inverse of the Shannon truncated bound and previously proposed in [22].

$$\text{Thr}=\begin{cases} 0 & SNIR < SNIR_{threshold} \\ \alpha.S(SNIR) & SNIR_{threshold} < SNIR < SNIR_{max} \alpha.S(SNIR)=log_2(1+SNR) \\ Thr_{max} & SNIR > SNIR_{max} \end{cases} \quad (4)$$

where Thr_{max} is the throughput with a value of 4.5 bps/Hz, $S(SNIR)$ is the Shannon bound and α is the rate reduction factor with value of 0.65, $SNIR_{max}$ is 21 dB and $SNIR_{threshold}$ is 1.8 dB. The Truncated Shannon Bound (TSB) is used to represent the transmission rates that can be achieved in practice given an adaptive modulation scheme in a real world scenario. This is dependent on the SNIR of the user. In order to use the GP to control the interference caused by the users requiring high SNIR in a fair manner, and to penalize or subsidize users based on the interference they contribute into the system, an equation related to the TSB is used to derive the GP equation. The reason for using this equation is due to the fact that the transmission rate is an important parameter in a wireless communication system. This is because the transmission rate is dependent on the SNIR and this is dependent on transmit power and interference. The derived GP equation is shown in Eqn.(5) as formulated from the TSB:

$$\text{R(Price Unit)} = \begin{cases} 2^{1+ß\theta} - 1 & green\ payment\ subsidy \\ 2^{1+ß\theta} + 1 & green\ payment\ tax \end{cases} \quad (5)$$

where ß is the GP factor derived later in this paper. The value of ß is chosen in such a way that the GP does not introduce too much tax/subsidy into the system leading to delay or reduction in the system throughput, hence the reason for it being called the GP factor. θ is the absolute value of the linear difference between the SNR value of a user i (ψ_i) and the value of the SNR of a set threshold (ψ_j).

$$\theta_i = |\psi_i - \psi_j| \text{ for } i=1, 2, 4 \ldots N_{USA} \quad (6)$$

The set threshold is represented as (ψ_j). This is derived by first arranging the received SNR of the N_{USA} users who are seeking access to the radio spectrum at time t in an ascending order

$$\boldsymbol{\psi}_t = [\psi_1, \psi_2, \psi_3 \ldots \psi_{N_{USA}}] \quad (7)$$

Then to determine which of the SNR at time t is the set threshold, Eqn. (8) is used, where P_c is the desired percentile as derived and explained in [22].

$$|j| = \lfloor \frac{P_c N_{USA}}{100} + \frac{1}{2} \rfloor \quad (8)$$

Equation (8) gives an absolute value (integer) known as the percentile rank. This shows that whatever the value of j, the j^{th} SNR in Eqn. (7) is the set threshold (ψ_j). The value of the percentile rank used has an effect on the total revenue needed to subsidize the bids of the users as seen from Eqn. (8). As P_c increases, the percentile ranks also increases. The final bid of the user with the GP is as:

$$b_i^f = \frac{(N_{\mathrm{USA}} - N_{\mathrm{AC}})V_i}{N_{\mathrm{AC}}} + V_{\min} \pm \mathrm{R} \text{ For } i = 1,2,3 \ldots \ldots . N_{\mathrm{USA}}. \tag{9}$$

where R is the value of the GP. For the bids to be accepted by the spectrum broker the bid must be above the reserve price.

$$b_i^f \geq r_i \tag{10}$$

3. SIMULATION MODEL

One spectrum broker and N users are modelled in an uplink scenario where each user is transmitting at a fixed power level depending on the user group as specified in Table 1. Depending on the user's location, each user has an optimal power level. As explained earlier with the GP, the user is either taxed or subsidized depending on whether the user's transmitting power falls below or above the set percentile level. It is assumed that a user cannot transmit in the OFF mode as explained in the energy model. A Poisson distribution process with an arrival rate (λ) and inter-arrival rate described by an exponential distribution is assumed. Each group transmits at a different bit rate depending on the SNIR level according to Shannon bound giving in Eqn. (4).

Table 1: The parameters used in the modeling

Parameters	**Value**
Cell radius	5 km
Interference threshold	-40 dB
SNIR threshold	1.9 dB
Users in a cell	100
Noise Floor	-114 db/MHz
Number of cell	19
System bit rate	1 Mbps 5 Mbps
Target SNR	4 dB Low powered Users 15 dB High powered Users
Average File size	1 Mbyte
Height of Base station	15 m

The broker does not know how much each user is willing to pay, hence the need for an auction. The value $F(v)$ that each bidder is willing to pay is known only to the bidder. It is also assumed that the value each bidder bids does not change even when the bidder knows the values other users are putting in as their bid. The rules of the auction require users to submit bids in discrete bids according to their private valuation $(b_i, b_i \ldots b_N)$ for each round of bidding drawn from $F(v)$ which is strictly increasing for a losing bidder. This is because we assume rational bidders, such that a bidder who lost the previous round increases his bid in the next round and similarly a bidder who wins consecutive rounds decreases his bids in the next round until a steady state is reached. An auction round is carried out for each transmitting period.

Following our model, suppose that a user i transmitting at power p, submits a bid b_i to the broker via the control channel. The bid is either taxed or subsidized by the broker. The path loss is dependent on the propagation model adopted, however, the Winner II model, as detailed in [23], was used in this work. This model was used because other theoretical models do not take obstruction and different terrain into account. The user is assumed to have transmitted successfully provided the SNIR is above the SNIR threshold and the final bid price is above the reserve prices. The system flow chart is as shown in Fig. 2.

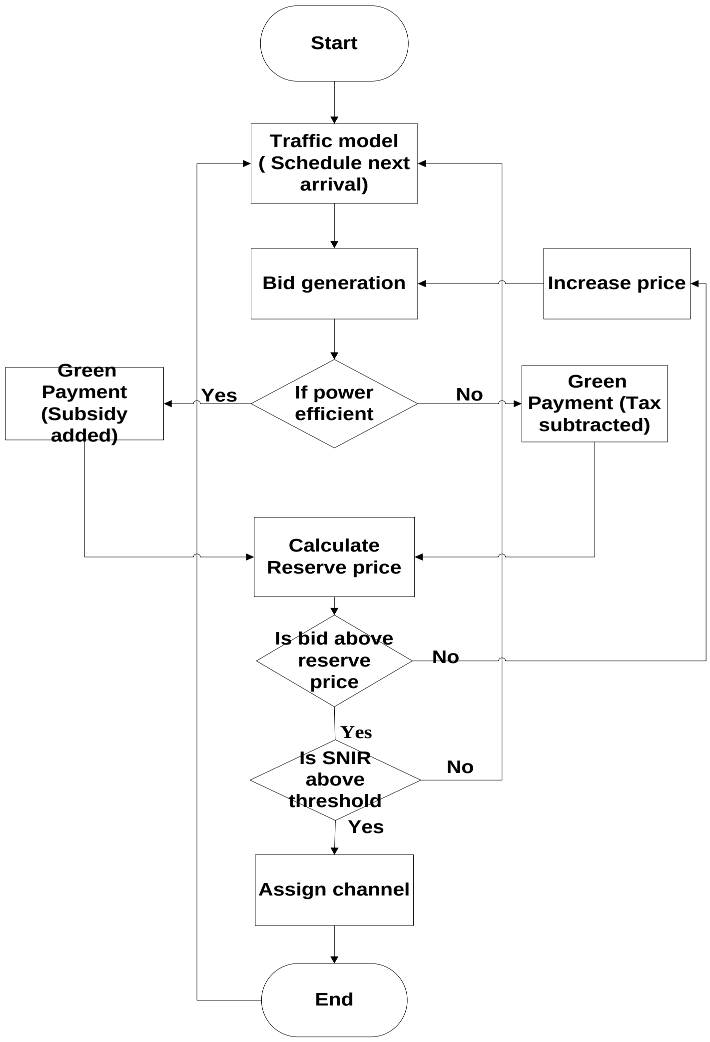

Fig. 2: System flow chart.

3. RESULTS AND DISCUSSIONS

We assume that a user derived the initial bid value from a uniform distribution between a value [3, 5]. The users increase their bids according to the rules of the sealed bid auction as explained earlier. Figure 3 shows the average revenue for each traffic load. The revenue increases with traffic load because as the traffic load increases, the competition between the users to get access to the spectrum increases. As seen from the result, the PKRP lowers the revenue of the WSP compared to the GP when the reserve price is not known to the public. This is expected because when the users are aware of the reserve price, the reserve price will guide the user in fixing their bid as shown in Eqn. (1).

The users' bids are distributed around the reserve price. However, without the public knowledge of the reserve price, the revenue of the WSP increases linearly until the system is approaching its capacity. This is because as the system approaches its capacity, the competition in the system increases therefore the users would only be able to win with a larger value of bid. The revenue with the GP also performs better after 3 Erlangs as a result of the subsidy received by the low powered users.

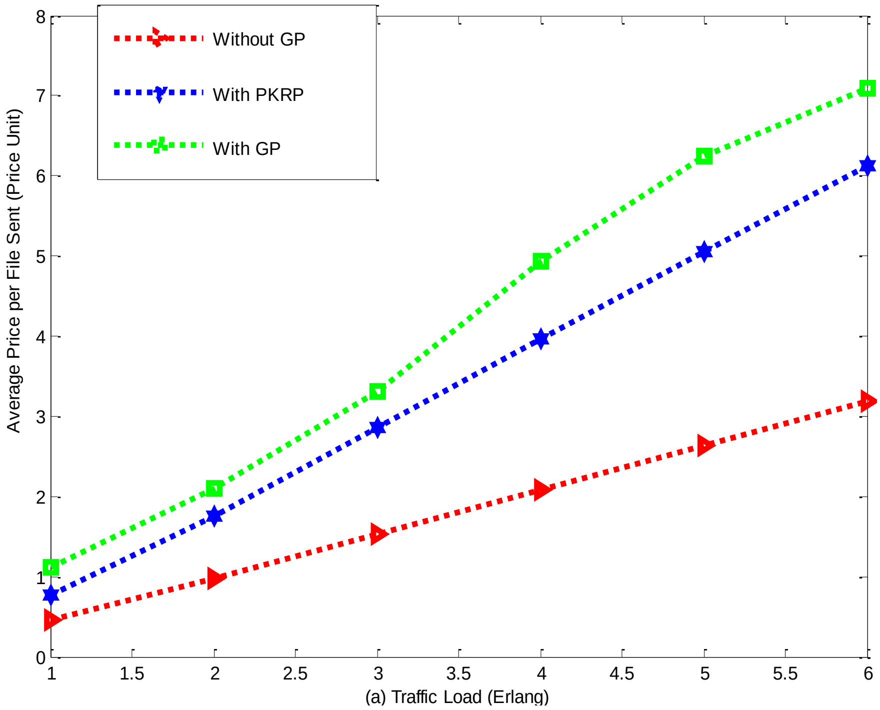

Fig. 3: Average revenue for different pricing scheme.

At lower traffic load, the tax/subsidy would almost balance out but as seen from the figure, the revenue of the LPU also increases significantly at a traffic load above 3 Erlang. This is because the LPU always gets a subsidy at that traffic load and very few high-powered users get through, making the revenue increase significantly. It is worth pointing out that as seen from the proposed model there is no need of subsidizing any user including the low-powered users at lower traffic loads. This is because the system can accommodate all users continently. The result also shows that apart from the reserve price, the GP also has an effect on the revenue. Without the GP, the two user groups have an equal probability of winning and no tax or subsidy is applied, but the reserve price is still applied.

Figure 4(a) shows the average energy consumed for each of the user groups at different traffic loads. Without GP, the average energy consumed by each of the user groups is significantly more than the scenario GP. This is because without the GP, both user groups are competing without any group having an advantage over the other and the HPU would be interfering with the LPU. The HPU are also admitted no matter their level of transmitting power. However, with the GP system, the LPU are given an advantage over the HPU because of the subsidy they receive and the only set of admitted HPU is those in the lower end. This is because the users would be admitted based on the received SNR at the receiver as explained earlier. The public knowledge of the reserve price reduces the average energy consumed at traffic loads above 3 Erlangs. This is because with the public knowledge of the reserve price, a user whose bid is below the reserve price would choose not to transmit and since the reserve price increases with the traffic load more users would have their bids rejected without the knowledge of the reserve price. This is because the valuation of the user without the knowledge of the reserve price does not increase with traffic load until a bidder loses in a bidding round. This shows that our proposed energy model is energy efficient.

Figure 4(b) shows the average energy consumed without the GP, with the GP, and with public knowledge of the reserve price. The public knowledge of the reserve price performs better overall because of the same reason as explained in Fig. 4(a). The knowledge of the reserve price also helps to further reduce the energy consumed because no energy is wasted as a result of the bid been rejected. Predominantly, the most likely reason why a user is not admitted is if the SINR of the user is below the SINR threshold. The price feedback only has significant effect on the energy consumed by the high-powered users because, the probability of rejecting a bid as a result of being below the reserve price is more than that of the low powered users since their bid is subsidized, which increases their probability of winning.

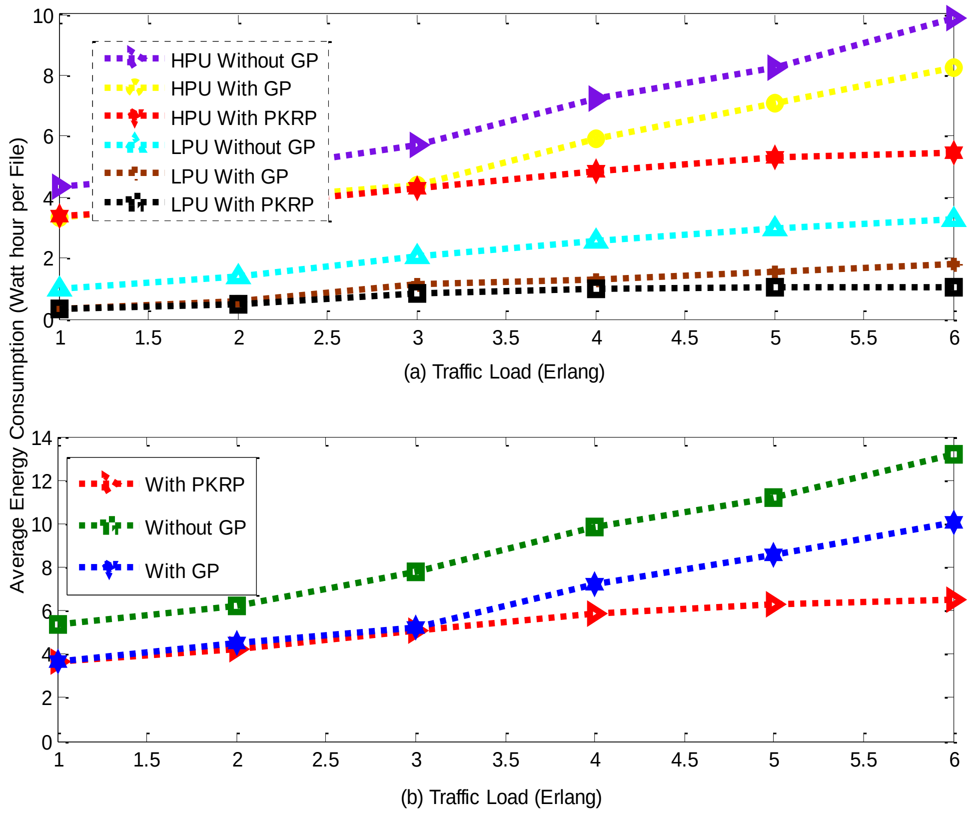

Fig. 4: Energy consumption for each user group and the overall system.

Figure 5(a) shows the delay against throughput for each of the user groups. Delay is one of the major factors and it has tremendous impact on the application a wireless system can be put to use for, some applications are delay sensitive while others can cope with a bit of delay. Without the GP, the HPU and the LPU experience more delay because the interference in the system is significant. The result also shows that users having the knowledge of the reserve price experience less delay because the users tend not to attempt to transmit when they feel their bid is below the reserve price but actually they should have attempted as the GP would have made their bid above the reserve price. This has more effect on the HPU compared to the LPU because they are the user group who get subsidized most of the time.

It can be seen that our proposed model helps in increasing the revenue of the WSP, reduce the energy consumed and the delay experienced by the users.

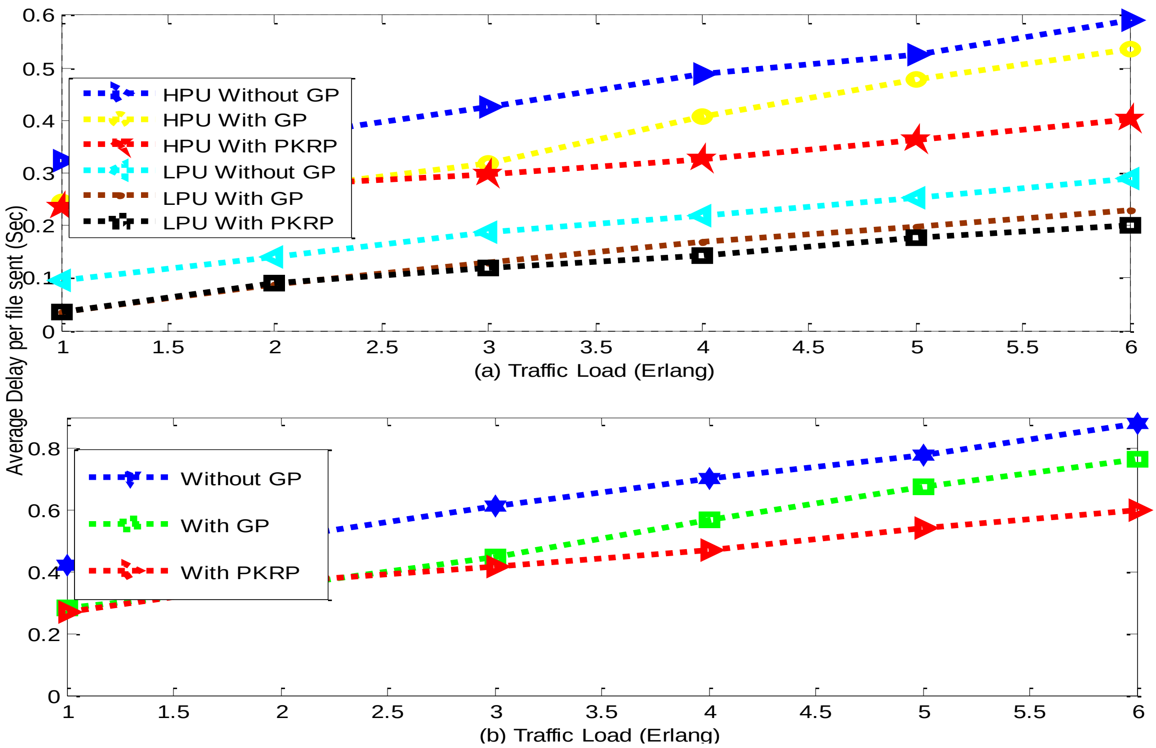

Fig. 5: Delay for each user group and for the overall system.

4. CONCLUSION AND FUTURE WORK

This paper proposes an energy efficiency economic model for dynamic spectrum pricing in a multi-winner scenario using sealed bid auctions with a reserve price. We examined the scenario when the users do not have knowledge of the reserve price and the scenario when they do. It can be seen that our scheme with PKRP might lead to a reduction in the seller's revenue. PKRP also does not provide an incentive for sellers to bid their own true value because they have the knowledge of the reserve price. However, the scheme helps in preventing users who cannot afford to pay above the reserve price of putting in a bid. This helps in saving some energy as a result of putting in a bid and losing out after the auction process. Our scheme shows that the user can use the GP to increase revenue, reduce energy consumed and delay experience. This is in addition to better throughput performance. The future work is expected to examine the impact of the proposed GP model on the primary users.

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