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SMART: Coordinated Double-Sided Seal Bid Multiunit First Price Auction Mechanism for Cloud-Based TVWS Secondary Spectrum Market

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ABSTRACT Spectrum trading is an important aspect of television white space (TVWS) and it is driven by the failure of spectrum sensing techniques. In spectrum trading, the primary users lease their unoccupied spectrum to the secondary users for a market fee. Although spectrum trading is considered as a reliable approach, it is confronted with a spectrum transaction completion time problem, which negatively impacts on end-users Quality of Service and Quality of Experience metrics. Spectrum transaction completion time is the duration to successfully conduct TVWS spectrum trading. To address this issue, this paper proposes simple mechanism auction reward truthful (SMART), a fast and iterative machine learning-assisted spectrum trading model to address this issue. Simulated results indicate that SMART out-performs referenced VERUM algorithm in three key performance indicators: bit-error rate, instantaneous throughput, and probability of dropped packets by 10%, 5%, and 15%, respectively.

INDEX TERMS Iterative auction, machine learning, game theory, truthfulness, mechanism design, factorial punishment.

I. INTRODUCTION

Recent telecommunications statistics from Cisco Visual Networking Index forecast indicated that the annual global IP traffic is estimated to be around 3.3 Zettabytes (ZB) (ZB; 1000 Exabytes [EB]) or 278 EB per month by 2021 [1]. Assertively, this is a remarkable 100% increment of the 2016 projection which stood at 1.2 ZB per year or 96 EB (one billion Gigabytes [GB]) per month. The demand for mobile data has increased exponentially while that of voice communications has plateaued out, thus, leading to spectrum crunch problem. Ordinarily, several candidate solutions exist such as: Multiple Input Multiple Out (MIMO)/Massive MIMO technology [2], Heterogeneous Network architecture (HetNet) often known as Small cell/ Femtocell architecture [3], Full Duplex technology [4] and Cognitive Radio (CR) technology [5]. Of all the aforementioned techniques, database market driven CR remains the most feasible as it is based on the Dynamic Spectrum Access (DSA) technique. The DSA scheme enhances spectrum utilization efficiency and must be sustained and encouraged. Moreover, it involves less practical implementation bottlenecks motivated by financial incentives. While the study of spectrum sensing technology is on the decline, that of database market driven TVWS is on the increase [6]. In database market driven TVWS technology, spectrum resources are traded between the Secondary Users (SUs) who make payments to Primary Users (PUs) as an incentive to temporarily lease their spectrum [7]. Therefore, making TVWS technology similar in context to the real market. PU and SU trade resources (bandwidth, time slots or transmission power) under certain market regulations. Consequently, economics and business methods are the natural paths to effectively design, analyze and allocate radio resources in TVWS networks.

The next generation wireless communication in which TVWS technology is a key player must address not only future capacity constraint issues but also, fundamental wireless communication issues notably: network reliability, network coverage and latency. Specifically, auction driven TVWS networks must address latency issue considering the fact that unlike the traditional wireless networks, TVWS networks must bid and win the legal right to use a given radio spectrum before transmission rights are granted. Latency is inimical to the Quality of Service (QoS) and Quality of Experience (QoE) of delay sensitive TVWS applications such as; video streaming, gaming and file sharing. To better understand the scenario; visualize a TVWS setting comprising of say 100 TVWS end-users with information payload to transmit. If it takes for instance 100 nanoseconds for each TVWS end-users to initiate and execute auction protocol. Then, for the spectrum auctioneer, it will take minimum of 10 microseconds to receive and finalize trade dispute. The above scenario is also subject to the type of auction strategy adopted. Furthermore, if PUs are brought into the picture, the spectrum auction completion time will further increase. Consequently, TVWS delay sensitive end-users' QoE and QoS will deteriorate. Based on this, the cardinal objective of this study is to propose a low complexity auction algorithm capable of reducing the computational complexity of auction protocols in TVWS networks. As referenced in [8], the widely used Vicrey-Clarke-Groves (VCG) auction is not strategy proof; it is susceptible to collusion, unfairness and truthfulness issues [7]. Hence, there is a need to design a strategy-proof spectrum market model capable of addressing the aforementioned issues and many more practical questions highlighted below such as:

a. Several of the auction bidding algorithms have failed to address the auction completion time and its adverse effect on end-users QoS [9], [10]. Strategy to reduce auction bidding overhead is essential since control information in general accounts for approximate 20-30% of the total assigned spectrum resources [11].
b. Since spectrum auction is driven by profit maximization, there is need to incorporate punishment design in the utility function of the secondary spectrum players. The primary motive of this punishment design is to serve as deterrence against acts of cheating in spectrum auction mechanism [9], [12].
c. How can Independent Private Valuation (IPV) model [13], [14], facilitate secondary spectrum auction completion time. And, what are the potential proposals to ensure competitiveness among the PUs leading to affordable broadband connectivity.
d. Lastly, strategies to design auction trade resolution protocol which supports auction efficiency considering the fact that it is possible for two SUs to independently evaluate and submit an equal bid for a spectrum resource channel.

Game theory has been extensively used in TVWS secondary spectrum markets because of its reliable and self-enforcing among self-rational entities [15]. Exploring TVWS strategy-proof iterative auction model comprising of game theory and auction models resulting to mechanism design a subfield of microeconomics will be an attractive proposition [16]. The ideal objective of an auction mechanism as a game is to analyze the dominant equilibrium strategy of buyers and sellers with Nash Equilibrium (NE) as a common solution. To reduce TVWS secondary spectrum resource allocation complexity, this work proposes SMART (Simple Mechanism Auction Reward Truthful). SMART is a fast, competitive, iterative and truthful TVWS auction mechanism-driven algorithm. Our contributions are as follows:

a. A graphical and analytical approach towards designing a strategy proof and iterative competitive TVWS auction allocation algorithm.
b. The proposition of a novel approach for SU (bidders) to estimate the asking price of the PU (sellers) through the use of stochastic learning automata. This approach is novel, as it reduces the TVWS spectrum auction-completion time.
c. To enforce truthfulness in a TVWS secondary spectrum market, we propose a punishment scheme to be incorporated into the objective function of each of the players to serve as a deterrent for cheating-inclined players.
d. The use of First come First serve approach for spectrum contention resolution protocol by the spectrum broker to resolve trade issues.

The rest of the article is organized as follows: Section 2 oversees related work. The model and problem description is presented in Section 3 and in Section 4, SMART is formulated. Section 5, focusses on the simulation results. Finally, we draw conclusions in Section 6.

II. RELATED STUDIES

The secondary spectrum auction is a resource optimization problem often referred in the literature as Winners' Determination Problem (WDP) [17]. WDP is an integer/combinatorial NP-hard problem and cannot be solved in polynomial time [18], [19]. Being the norm, spectrum resources are only assigned to the buyers when the submitted bids match or come close to asks. The two notable spectrum auction transaction modes are flexible time [20] and fixed time [21], [22]. Though, both have their pros and cons. From the PUs, the fixed time instance provides ample opportunity to plan spectrum trading. However, the flexible time instance looks favorable to the SUs based on the widely held notion that end-users traffic are stochastic in nature and cannot be accurately predicted. This observation is the reason why spectrum traffic is modelled using Poison model. Notable research work that has considered time flexibilities in spectrum auction could be seen in [9], [23], and [24].

The fixed time spectrum auction approach is a more realistic model because of its reduced overhead complexity property. Another aspect of spectrum quality considered in auction mechanism is the Physical (PHY) layer time varying channel quality/Channel State Information (CSI) attributes [25]. This concept was further extended in [26]. However, it remains unclear how to model and incorporate time-varying CSI considering the difficulties to precisely predict CSI as supported by the presence of feedback channel loop in channel configuration architecture. Deep spectrum learning has been investigated in which the spectrum sellers recalls previously concluded spectrum transaction and uses the experience as a guide to enhance utility [27], [28]. Obviously, this is a form of artificial intelligence in spectrum auction design and was implemented in this study.

Truthfulness is a unique feature of spectrum auction and as such has received immense research attention [9], [20], [21], [23], [24]. If there is an effective strategy to motivate truthfulness in mechanism design, then, it must be by *incentive* or *taxation* [29]. To explore strategy-proof auction domain, combinatorial auction for joint spectrum and transmission scheduling in time multiplexed fashion has been proposed [20]. Vidal *et al.* [30] propose the use of token credit to enhance truthful spectrum sharing mechanisms. Similarly, time-frequency domain analysis has as well been exploited [21], on the fly online spectrum auction mechanism was been proposed in [23]. Considering truthful auction mechanism in which collusion-resistance design is inevitable has been investigated in [24]. Location aware context in spectrum auction framework has been explored to facilitate interference free secondary spectrum end-users [9]. Mathematical modeling presents a viable tool to express wireless resources as a physical object making it easy to analyze. Since radio resources are intangible wireless resources, mathematical modeling approaches have been widely applied [31], [32].

Dynamic Knapsack and stochastic problem which targets on maximizing the expected accumulated utility function modelled after Poisson distribution has been investigated [31]. Similarly, dynamic Knapsack problem for resource allocation depicting a sequential arriving requester aimed at deriving optimal policy leading to revenue maximization was studied in [32] and [33] analyzed secondary spectrum auction mechanism from a relaxed Bayesian perspective, where buyer valuations were publicly drawn from a prior distribution. Social efficiency and auction revenue were two important key parameters considered in [34]. Time–varying spectrum demand from the end-users are of considerable importance and has been considered. Take for instance, an end-user's traffic might be delay tolerance, such as FTP, e-mail or delay sensitive applications such as VoIP, video streaming and online gaming. In this case, the end-user preferences to channel quality can play a major role in the spectrum auction design. Exploiting this phenomenon, several research works have considered channel heterogeneity. The case of heterogeneous end-user channel quality demand in time dependent valuation, delay tolerance and starting time instances were considered in [10]. Noticeably, this setting tends to maximize PUs revenue at the detriment of SUs profit. Furthermore, since the main objective of TVWS network specifically in the rural area is to make broadband connectivity affordable. This design setting is considered counter-productive. A single-step allocation for a whole time frame rather than the online allocations has been considered [9], [23], [24].

Notable TVWS market models been proposed are [12], [13], [19], [30]; however, several critical research gaps exist. All the aforementioned mechanism designs suffer one major issue, which is high overhead complexity. Furthermore, spectrum transactions are conducted over many rounds [12]. The secondary spectrum markets in which TVWS operates are characterized by short time leases, which can be for minutes, hours, days, or months, depending on the contractual agreement [35]. Consequently, a mechanism to reduce the TVWS spectrum transaction time will be highly appreciated. *Sinha and Anastasopoulos* [13] propose a methodology to create mechanism which maximize social welfare at the Nash equilibrium with convex constraints and a linear message space.

Tan *et al.* [36] propose an incentive and market-based framework based on a multi-tier shared spectrum-access model. Kamble and Walrand [19] proposed a mechanism-proof strategy to purchase shared resources in a collusion-resistant environment for a group of buyers with private utility expectation. The major limitation of these auction models is collusion which was not solved iteratively. Secondly, the spectrum price is not competitive. Iterative models have multiple advantages: they ensure competitiveness and are considered as transparent process. Recognizing these structural deficiencies, Manickam *et al.* [12] propose an iterative and truthful multi-unit auction that addresses the limitation of VERITAS [37] and SATYA [38]. Luo *et al.* consider the TVWS secondary spectrum market from the perspective of information trading rather than commodity trading [35], which allows database operators to design specific fees for each trading-choice model of the secondary users.

The preceding works did not exploit the use of learning algorithm having identify that the secondary spectrum market occurs regularly and uses punishment as an incentive for truthfulness. There should be a mechanism of reusing already available auction information. Our work is similar to VERUM, as published in [12]. Both are iterative processes, which have been shown to reduce collusion and to enhance truthfulness. However, they are different on many fronts. Our work is driven by principle of IPV model which simply means that any buyer who values the spectrum, tenders bidding price closer to the asking price. This reduces the transaction period and increasing real-time secondary spectrum trading in TVWS.

III. MODEL AND PROBLEM DESCRIPTION

The system model under consideration and the problem formulation were discussed in this section. For convenience, Table 1 lists some important notations used in this paper.

A. SYSTEM MODEL

Consider a TVWS environment consisting of several PUs denoted with $\{M_1, M_2, M_3, \ldots, M_K\}$ and SU[1] denoted as $\{N_1, N_2, \ldots, N_K\}$. Each of the PU owns multiple

[1] SU connotes TVWS networks comprising TVBS and TVBD

TABLE 1. Notable symbols for used.

Symbol	Definition
Γ	auction frame
b	channel bandwidth/slot
P_T	the permissible transmit power
$\gamma_{(j,b)}^{(t)}$	connotes the SINR TVBD j receives by using RB, b, at time t
M	PUs
N	SUs
σ	modulation scheme
J	TVBD
Π	data sample period
Ω	MaxDopplerShift
H	Raleigh channel
Ψ	TVBD instantaneous throughput (Mbps/Hz)
$V_{(l,b)}$	PU utility function of channel, b driven by monetary terms.
τ	the auction completion indicator function
α	learning rate
$x_{(j,b)}$	transmitting signal from TVBD user j on leased PU channel b
$U_{(j,b)}$	concave increasing function of the SU service provider

homogeneous orthogonal channels to serve its subscribed SUs. If at some time there are idle PU channels available, the PUs can allow SUs to access these channels to obtain some extra profits. Each SU is a service provider to TVWS Band Device (TVBD) denoted with $\{J_1, J_2, \ldots, J_K\}$ as illustrated in Figure 1. The PUs and SUs trade spectrum bandwidth by iterative auction game moderated by the social welfare Spectrum Broker (SB) [39]. Social welfare connotes that SB does not take commission for engaging in secondary spectrum market arbitration. The SB can only allocate the spectrum/ Resource Block (RB)[2] to TVBD[3] only when the *bids* submitted by the SU matches the PU *asks*.

TVWS technology has a long delay spread of >60 μ sec without auction scheme [40]. The inclusion of auction schemes that entails several rounds of bidding is capable of degrading the QoS of delay sensitive Guaranteed Bit Rate (GBR) applications such as VoIP, video streaming. Furthermore, let's define auction frame as $\Gamma = [0, T-1]$, which consist of Γ uniform time slots and b as the number of SU leased spectrum channel. As the number of auction frame increases, the TVBD data payload decreases.

B. SCENARIO SETTINGS AND ASSUMPTIONS

For the sake of clarity of expressions, the following assumptions were made:

i. The auctioneer serving as TVWS resource allocator is aware that, there is heavy TVWS end-user traffic. Hence, exclusive channel sharing mode is needed i.e. no channel sharing.

ii. The TVBD leases the PU spectrum by making payment through the TVWS base station (TVBS) using fictitious currency model [7].

iii. The TVBS informs the SB the position of the TVBD which it can acquire using the GPS module. The position vector is necessary for the SB to avoid inter-TVBS cellular interference [18], [41].

iv. The spectrum resources are allocated only on the condition that, the bids matches or close to the ask resulting in market clearing price [10], [39]. Spectral resources discussed in this work explicitly denotes spectrum bandwidth/RBs/Sub-channels. Hence, transmission power level is left out of discussions.

v Spectrum is traded based on RBs unit which may be interleaved or not respecting the OFDM technology configuration and each RB can sustain a certain QoS application.

vi TVBD transmits using permissible transmission power level recommended by the FCC respecting the transmit power spectral mask [6]. In addition, TVWS supports symmetrical and asymmetrical uplink/downlink transmission.

C. CHANNEL MODEL

The channel model is facilitated by link budget analysis in which TVBS j can estimate the instantaneous signal-to-interference-plus-noise ratio (SINR) at time, t, per RB of each TVBD in its service set as:

$$\gamma_{(j,b)}^{(t)} = \frac{G_j P_T d^{-\eta}}{I_{S2S} + N_0} + 10^{*} \log_{10}(k) + \log_{10}(codeRate), \tag{1}$$

where, $\gamma_{(j,b)}^{(t)}$ connotes the SINR TVBD j receives by using RB, b, P_T, is the permissible transmit power for TVBD stated at 4 Watts or 36 dBm for the 6 MHz TV channel bandwidth using IEEE 802.22 Standard, d, denotes the TVBD distance from the TVBS, η is the pathloss component that can modeled using the ITU-R model [42], N_0 is thermal spectrum noise, G_j denote the channel gain, I_{S2S} denotes the secondary to secondary co-channel interference. In IEEE 802.11 Standard, the convolutional code is the mandatory code rate. Turbo and shortened block turbo code are optional but recommended. The parameter, k, in (1) is responsible for the adopted modulation scheme and is defined as:

$$k = \log_2(\sigma) \tag{2}$$

σ, is the modulation scheme. The IEEE 802.11 Standard supports various modulation scheme of QPSK, 16-QAM and 64-QAM depending on the SNR. This study adopted Raleigh channel, H, which can be modeled as:

$$\mathrm{H} = rayleighchan(\Pi, \Omega) \tag{3}$$

[2] Resource block is the unit for spectrum trading and connotes spectrum channel/ spectrum bandwidth. Hence, all of the terms connotes same except explicitly defined.

[3] TVBD connotes TVWS end-users and both terms will be used interchangeably through this study.

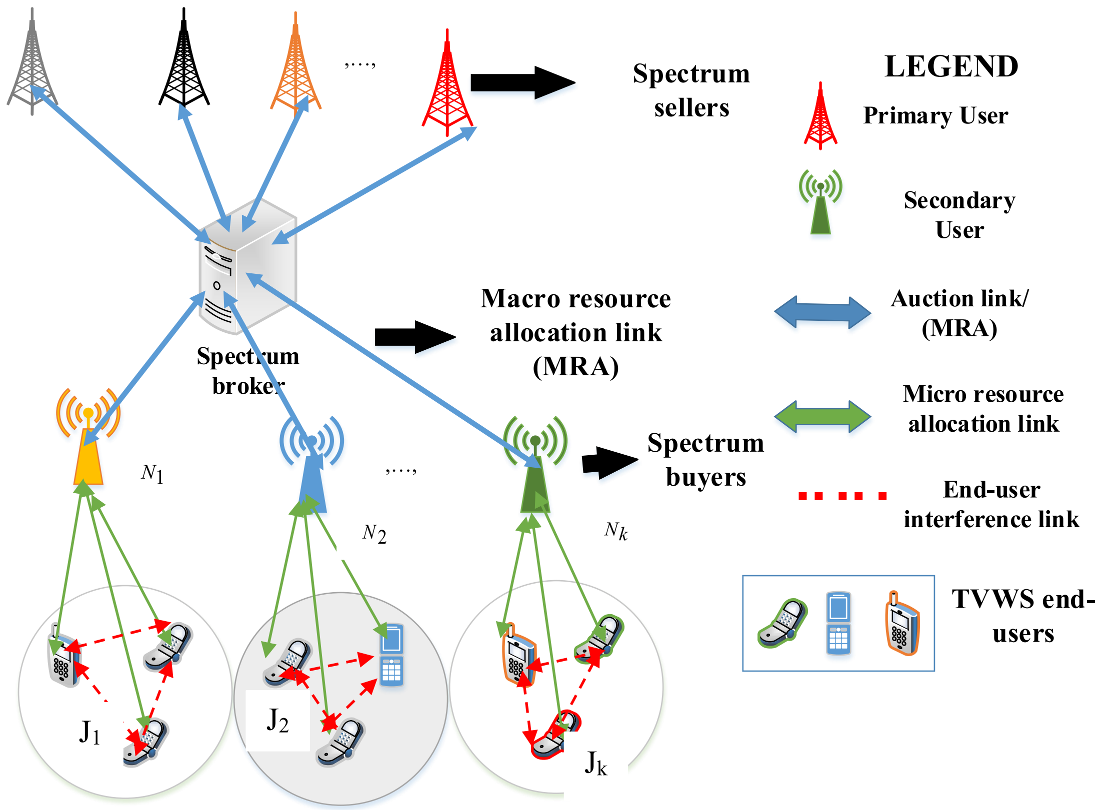

FIGURE 1. Deployment scenario of TVWS spectrum auction settings.

Π is the data sample period and Ω is MaxDopplerShift. IEEE 802.22 PHY is designed to support mobility of up to 114 km/hr. The TVBD instantaneous throughput (Mbps/Hz), Ψ can be estimated as:

$$\Psi = \frac{b \log_2(1 + \gamma_{(Gi,b)})}{\tau} \tag{4}$$

τ is the auction completion indicator function, which highlights the number of bidding rounds to complete a bid. As the bidding rounds iteration increase, the TVBD throughput decreases. The importance of decrease in the number of bidding rounds iterations could be comprehend more in the case of turbo encoders in which as the number of iterations increases, the signal processing iterations consumes more time.

D. UTILITY BASED TVWS BUSINESS MODEL

There must be an interface to connect auction payment and TVWS radio resources. And this is achieved using the *fictitious currency model* (Vidal *et al.* 2013). The model is adopted because the secondary spectrum market is a spot market configuration. Fictitious currency denotes a signal representative of some amount of real currency.

In reality, some of the digital money such as: Bitcoin and electronic money used by laundry services could be used. Compared to real cash, it is easy to circulate in wireless environment because machines understand the money. In addition, the fictitious currency helps SB to punish defaulting bidders by signaling lower PHY layer transmission parameters (Zhang *et al.* 2012). The achievable bit rate referred as revenue-based utility model for TVBD at each epoch of time is stated in (5):

$$U_{(j,b)} = b \log_2 \left(1 + \gamma_{(j,b)} x_{(j,b)}\right) - p^{bid}_{(j,b)}, \tag{5}$$

The term $p^{bid}_{(j,b)}$ denotes the bid price TVBD user j pays through the SU for leasing PU channel b and $x_{(j,b)}$ is the transmitted signal symbol from TVBD user j on leased PU channel b. $U_{(j,b)}$ is an increasing concave function of the SU service provider and $p^{bid}_{(j,b)} \in \Re$.

E. PROBLEM FORMULATION

In this subsection, we formulate the auction problem which aims to maximize the expected auction revenue of the PU, while following the direct revelation principle. In wireless communication settings, bandwidth is extremely valuable, scarce and should be assigned in the most efficient manner (Bykowsky *et al.* 2010; Lu 2007). The SB tries to solve

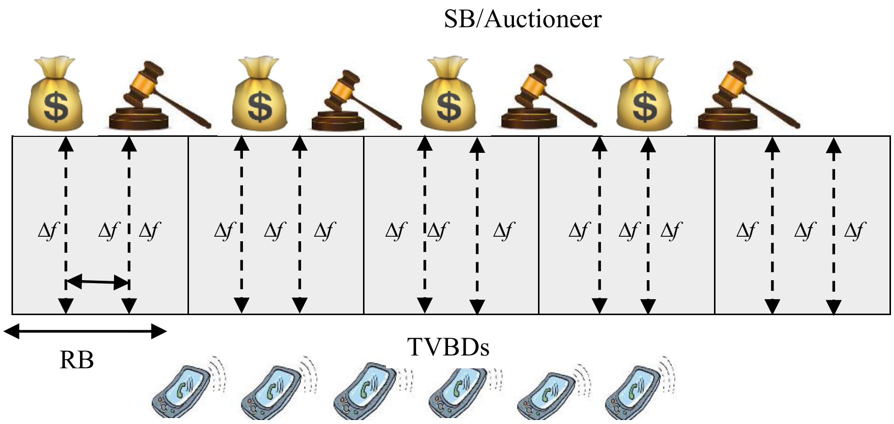

FIGURE 2. Illustration of TVWS auction driven resource allocation.

this WDP by solving (P1) stated as:

$$P1: \max \sum_{j\neq p}^{K}\sum_{j=1}^{K}\sum_{b=1}^{K} U_{(j,b)}^{(n)} x_{(j,b)} V_{(j,b)}^{(m)},$$

$$\text{S.t}\begin{cases} C1: \sum_{j=1}^{K}\sum_{b=1}^{K} x_{(j,b)} \leq c_j, & (P1) \\ C2: x_{(j,b)} \geq 0, & \forall j \in \text{J}, b \in \text{B} \\ C3: x_{(l,b)} \in \{0,1\}, & \forall l, b, \\ C4: \sum_{b=1}^{K} x_{(b)} \leq 1, & \forall b \\ C5: A\left(1+p_{(G_i,b)}^{bid}\right) \geq \pi_i \end{cases}$$

The TVWS environment resource allocation definitions are stated as:

Definition 1: $V_{(l,b)}$ represents the PU utility which is driven by monetary terms.

Definition 2: c_j, denotes the channel link j, $x_{(j,b)}$, is the assignment variables which must$\in \{0,1\}$, C denotes case and the number denotes the case no and s.t is abbreviation of *such that.*

Definition 3: C1, C2 and *C3* denotes that the assignment variables must support a TVBD channel link, must be greater than zero and must be chosen between zero and one.

Definition 4: C4 signifies that the total assignment RBs must not exceed the available spectrum to avoid inter-cellular interference.

Definition 5: C5 is the SU profit function which it considers before submitting a bid adopted from (Duan *et al.* 2010) with slight modification. This parameter drives the independent private valuation (IPV) model and explained in the next section.

The SB moderates spectrum auction game between the SUs and the PUs. The above problem is represented pictorially in Figure 2. This WDP which is a convex NP-Hard problem (Xu *et al.* 2013). The overall objective function of the SB is to maximize the network gain with the constraints guaranteed. In real world scenario, the SB lacks two important information which are (Edalat *et al.* 2011): (i) the knowledge of individual private valuation of the bidders resulting in NP-hard problem and (ii) system global information. The centralized resource allocation problem is decomposed into sub-problems and solved iteratively in a distributed fashion via the non-cooperative game. This approach is known as a sub-game perfect principle (Luo *et al.* 2014). The above strategy leads to the formulation and proposition of ***SMART*** (*S*imple *M*echanism *A*uction *R*eward *T*ruthful), a fast and iterative machine learning-assisted spectrum trading model. The ***SMART*** algorithm is derived using backward induction strategy.

IV. PROPOSED SMART ALGORITHM

In this section, proposed ***SMART*** algorithm is derived based on backward induction strategy. Backward induction is a strategy to analyze a dynamic game with a view of finding the perfect subgame equilibrium (PSE). It is widely used in game theory involving auction theory (Duan *et al.* 2012; Gibbens *et al.* 2000). In subgame strategy, the original game is sub-divided into sub-games, and the NE of the sub-games metamorphosed into the equilibrium of the original game. Focusing on the social interactions of TVWS ecosystems, a four-stage design mechanism is proposed and illustrated in Figure 3.

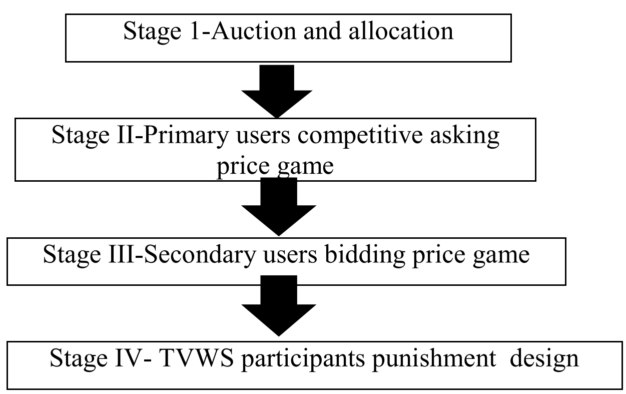

FIGURE 3. Four-stage secondary design mechanism model.

Figure 3 is described as follows: **Stage IV** commences the framework via the punishment design for cheating TVWS networks. At **Stage III**, inter-secondary users' price game was considered. **In Stage II**, PU bandwidth game was studied.**In Stage I**, spectrum auction game and spectrum allocation are executed by the SB. This work is limited on pure strategy PSE, which effectively rules out mixed PSE in the multistage game. This methodology has been widely used in the literature (Duan *et al.* 2012). In a recent study, a similar proposal indicating the hardware modules to drive **SMART** algorithm has been illustrated by (Sarkar *et al.* 2016). The authors limited their work on just the proposal without showing in great details.

A. STAGE IV – PUNISHMENT DESIGN

The market-driven dynamic spectrum auction is widely regarded as an efficient way to improve spectrum utilization in wireless systems (Bykowsky *et al.* 2010). However, it faces the significant challenge of market manipulation. Therefore, a punishment function is highly favourable to establish social harmony with a view of not degrading the QoS of TVWS networks. The first goal of strategy proof punishment function is to incorporate the punishment function into the objective function of the players. Secondly, must be analytical and easy to implement using standard mathematical tools. For this reason, this study adopts the formulated punishment parameter denoted as: $\exp(\theta)$.

PU is considered cheating when, it does not respect the agreed SU channel holding time (Riihijärvi *et al.* 2010). When PU cheats, the SU incurs switching cost, transition cost, and drop in QoS (Kelechi *et al.* 2016; Saleem & Rehmani 2014). Thus, resulting in excessive handoff. Here, the focus is to limit the occurrences of SU channel degradation. On the other hand, SU is considered cheating on the occasion, it causes Co-Channel Interference (CCI) or Adjacent Channel Interference (ACI). ACI may result channel impairments such as cross talk, premature handoffs, dropped calls for voice calls leading to degradation of quality of service (Al-Shalash *et al.* 2010; Katzela & Naghshineh 1996). Although channel filters in the TVWS base station and TVBDs significantly attenuate signal from adjacent channels, severe interferences may occur in which the resulting signals are more than the acceptable threshold of the TVWS system.

B. STAGE III – SU BIDDING PRICE GAME

In this section, the spectrum bidding price is derived according to the following proposition. The purpose of **Game 1** is for the SU to estimate the PU asking price so as to reduce auction bidding rounds. A centralized structure creates a huge trading volume problem in a TVWS cellular system which can be a bottleneck. One solution is to allow the individual players to estimate the spectrum asking price in a competitive manner. This is anchored by the independent private valuation (IPV) model.

Proposition 6: In the four-stage stage secondary design mechanism model, the bidding price for the SU without considering the IPV model is given by (6).

$$p^{bid,}_{(G_i,b)} = \left[\frac{b\left(1+\gamma_{(G_i,b)}x_{(G_i,b)}\right)}{\exp^{(\theta)}} - \frac{1}{\lambda}\right], \tag{6}$$

Proof: The solution to this SU bidding game can be found by solving **Game 1** using non-cooperative game defined by:

- *Players*: SUs (G_i, G_{-i})
- *Strategy space*: Each G_i chooses bid price from the feasible set $p^{bid,(t)}_{(G_i,b)} = [1, \infty)$
- *Payoff function*: G_i maximizes the revenue, $U_{(j,G_i)}$. The utility function has been given in (5). Implicitly defined as transmitted data rate.

In this analysis, it is assumed that spectrum resources are symmetrical in the context of channel quality, channel impairments and maximum transmission power usage. Hence, no heterogeneity. The spectrum price SUs are willing to pay as a function of their revenue is inferred from:

$$\begin{aligned}(P2):\ &\max U_{(G_i,b)}\left(p^{bid,}_{(G_i,b)}, p^{bid,}_{(G_{-i},b)}\right)\\ &= \left[\begin{array}{l} b\log_2\left(1+\gamma_{(G_i,b)}x_{(G_i,b)}\right)\\ -\phi p^{bid,(t)}_{(G_i,b)}\exp^{(\theta)}\end{array}\right]\\ &\text{s.t}\ \begin{cases} C6: A\left(1+p^{bid,(t)}_{(G_i,b)}\right) \geq \pi_i,\\ C7: \phi p^{bid,(t)}_{(G_i,b)} \geq \hat{p}^{ask,(t)}_{(G_i,b)},\end{cases}\end{aligned}$$

where, ϕ is the IPV single parameter, $\hat{p}^{ask}_{(G_i,b)}$, is estimated PU asking price, $A\left(1+p^{bid}_{(G_i,b)}\right)$ is the SU linear spectrum demand function with A denoting a constant, $\pi(\cdot)$ denotes SU profit function. *C6* ensures that the SU profits by engaging in secondary spectrum trading by providing broadband services to secondary end users. *C7* is the hypothesis that the SU's bidding price is successful and decreases the *losing bid probability,* which is necessary because this is a first-price auction.

1) PROBLEM TRANSFORMATION

In first-auction, the bidder pays the equivalent of the asking price. At present form, (P2), C6 and C7 are complex as there is no way to infer the private valuation of others. Consequently, further decomposition into two sub problems is required, shown below as.

Sub-Problem I (Constrained Optimization Problem):

$$\begin{aligned}(P3):\ &\max U^{(t)}_{(G_i,b)}\left(p^{bid,(t)}_{(G_i,b)}, p^{bid,(t)}_{(G_{-i},b)}\right)\\ &= \left[\begin{array}{l} b\log_2\left(1+\gamma_{(G_i,b)}x_{(G_i,b)}\right)\\ -p^{bid}_{(G_i,b)}\exp^{(\theta)}\end{array}\right]\\ &\text{s.t}\ \left\{C8: A\left(1+p^{bid,(t)}_{(G_i,b)}\right) \geq \pi_i,\right.\end{aligned}$$

Sub-Problem II (Unconstrained Optimization Problem):

$$C9: \phi p^{bid}_{(G_i,b)} \geq \hat{p}^{ask}_{(G_i,b)},$$

(P2), C6 and C7 have been successfully transformed into a convex problem (Xu *et al.* 2010) with lower complexity. Many proposals have suggested capturing users preference via the IPV model, the common-values model, the correlated-values model and the almost-value model (Parsons *et al.* 2011). The IPV model was adopted because it fits rightly into the study. (P3) and C6 can be successfully solved by using normal constrained optimization standard procedures. It is assumed there is enough information to stimulate asking price game. The initial starting guess of the asking price can be inferred from the matured TVWS secondary spectrum market as currently implemented by *Spectrum Bridge Inc*. This type of spectrum pricing scheme falls into the posted price market scheme (Zhang *et al.* 2012). Interested SU players can calculate the current bid price as follows:

$$p^{bid,}_{(j,G_i)} = R_i\left(1 + \Omega_i\right), \tag{7}$$

where, R_i connotes the reservation price that controls the losing bid probability, Ω_i is the SU profit margin and must lie $[0, \infty]$. The profit margin adopted by any of the SU indicates the level of market competitiveness.

2) EXISTENCE & UNIQUENESS OF NEP

The proposed game satisfies the requirements of the non-cooperative game which are: uniqueness and NE point (NEP) phenomenon. Adopting (Fudenberg & Tirole 1991) the solution concept must show that NEP exists if:

1) Ω, the support domain of $U\left(p^{bid,}_{(G_i,b)}\right)$, is a non-empty, convex and compact subset of a certain Euclidean space R^L and
2) $U\left(p^{bid,}_{(G_i,b)}\right)$ is continuous and quasi-convex in $p^{bid,}_{(G_i,b)}$.

Theorem 7 (Existence and Uniqueness): There exists a unique NEP $\overset{*}{p}{}^{bid}_{(l,G_i)}$ for the reduced price competition game and thus a unique NEP $\overset{*}{B}_{(G_i,b)}, \overset{*}{p}{}^{bid}_{(G_i,b)}$ for the original game.

Proof: A sketchy proof for the uniqueness of NE of the original game can be achieved through the principles of the log-transformed game of the original game to a reduced perfect game ζ, denoted by the tuples:

$$\zeta = \left(N, \left\{p^{bid}_{(G_i,b)}\right\}, \left\{\log U\left(p^{bid,}_{(G_i,b)}\right)\right\}\right).$$

It is trivial to show that the log-transformed game, ζ is a subgame perfect and thus has at least one NE. It can be achieved by invoking the property of monotone transformation (Cachon & Netessine 2004). Intuitively, the NE of the log-transformed game is also the NE of the original game. The proof of the uniqueness of NE is conducted by checking the second-order condition to locate where it is negative:

$$-\frac{\partial^2 \mathbf{p}^{\mathrm{bid}}_{(G_i,b)},}{\partial_i^2} = \sum\nolimits_{-i,i} \frac{\partial^2 \mathbf{p}^{\mathrm{bid}}_{(G_i,b)}}{,} \partial p^{bid,}_{(G_i,b)} p^{bid,}_{(G_i,b)}, \quad \forall i \in K \tag{8}$$

Eq. (8) implies that the log-transformed game has a unique NE (Milgrom & Roberts 1990). The NE is the solution to the utility optimization problem for each player given all other players' actions. Therefore, the Lagrange solution to (P.3) and C6 is obtained:

$$L\left(p^{bid,}_{(G_i,b)}, \lambda\right) = \begin{bmatrix} b\log_2\left(1 + \gamma_{(G_i,b)}x_{(G_i,b)} - p^{bid}_{(G_i,b)}\exp^{(\theta)}\right) \\ -\lambda_{G_i}\left(A\left(1 + p^{bid}_{(G_i,b)}\exp^{(\theta)}\right) - \pi_i\right)\end{bmatrix}, \tag{9}$$

where $\lambda \geq 0$, is a non-negative Lagrangian multiplier easily obtained using the sub-gradient technique. After calculus manipulation and respecting the Karush-Kuhn-Tucker (KKT) conditions, the final expression for the bidding price is stated as:

$$p^{bid,}_{(G_i,b)} = \left[\frac{b\left(1 + \gamma_{(G_i,b)}x_{(G_i,b)}\right)}{\exp^{(\theta)}} - \frac{1}{\lambda}\right], \tag{10}$$

Important observation made from (10) is that the spectrum price and cheating are inversely related. Thus, the SU will only bid from the PUs known not to engage in acts of cheating. In the context of SU players, the strategy can be updated on the arrival of new market information. Consequently, there is a need to implement iterative bidding price. Driven by aesthetic, let the spectrum price be denoted simply as:

$$\Theta = \left[\frac{b\left(1 + \gamma_{(G_i,b)}x_{(G_i,b)}\right)}{\exp^{(\theta)}} - \frac{1}{\lambda}\right] \tag{11}$$

Then, adopting the Widrow-Hoff back propagation approach in neural networks (Lee *et al.* 1992), the iterative bidding price is stated as:

$$\Theta_{(\tau+1)} = \alpha\Theta_{(\tau)} + (1-\alpha)\,\beta\left(\Phi - \Theta_{(\tau)}\right), \tag{12}$$

where α, β, Φ, τ denote learning momentum, learning rate coefficient target price and iteration respectively. With careful parameter selection, the iterative bidding price is bound to converge.

Sub-Problem II (Independent Private Valuation Modelling) In general, there is a trade-off between auction efficiency and implementation. The main idea of IPV model is that buyer's bid cannot exceed the valuation of the commodity for which the buyer bids, so the buyer has a positive gain after the auction. Similarly, it is assumed that the asking price from the seller must be higher than the valuation for the spectrum to be sold leading to positive profit (Zhang et al. 2012). The final price will be somewhere in between seller's valuation and buyer's valuation for transmission rights to be granted.

The secondary spectrum market consists of short-term spectrum leasing and it is expected to be characterized with high liquidity. Hence, there is a need to reuse the previous asking price, thereby lowering the auction bidding rounds. Invariably, the TVWS secondary spectrum market will be migrating from commodity trading to information trading, as recently studied in (Luo *et al.* 2014). Therefore, this work proposes the asking-price prediction model using a structured stochastic gradient descent algorithm as illustrated in Table 2 of Algorithm 1.

TABLE 2. The stochastic descent algorithm for single parameter IPV model.

Algorithm 1 PU asking price estimation algorithm via IPV model

Input: ϕ ,step size δ , u , $p^{bid}_{(G_i,b)}, \hat{p}^{ask}_{(G_i,b)}$

Output: Spectrum bidding price parameter estimation.

Set number of realizations τ

for $u = 1{:}\ \tau$ ***do***

  for $\phi = 1{:}\ \mathrm{i}$ ***do***

  $$\phi_{i,\tau+1} = \phi_{i,\tau} - \delta \frac{1}{u(i)}\left(p^{bid}_{(G_i,b)}\phi_\tau - \hat{p}^{ask}_{(G_i,b)}\right)$$

  end

end

C. STAGE II- PU COMPETITIVE ASKING PRICE

This study does not consider the difference in the wholesale and retail prices because they are not strategic for the PU. Given $p^{ask}_{(P_i,b)}$, and the cost, c, the PU compute the spectrum profit (i.e., *demand* $\times$ *asking price*) per bandwidth stated below (Luo *et al.* 2014):

$$V\left(p^{ask}_{(P_i,b)}\right) = b^2_{(P_i,b)}\Lambda p^{ask}_{(P_i,b)}\exp(\theta) - c_{(P_i,b)}, \tag{13}$$

where Λ is the PU competitive indicator given as $\Lambda \in [0, 1)$. PU can easily compute the instantaneous spectrum asking price given the probability distribution of other PUs. This is the cumulative distribution function, given as:

$$F\left(\mathbf{p}^{ask}_{(P_i,b)}\right) = \Pr\left(p^{ask}_{(P_i,b)} \le p^{ask}_{(P_i,base)}\right), \tag{14}$$

Pr(.) is the probability density function (pdf). $p^{ask}_{(P_i,base)}$ is the base asking price. Hence, in competitive TVWS secondary market, PU i will win the market when the other *PUN* quote a higher spectrum price, given as

$$\Pr\left(\mathbf{p}^{ask}_{(P_i,b)}\right) = \left(1 - F\left(p^{ask}_{(P_i,b)}\right)\right)^{\mathbf{M}}, \tag{15}$$

The superscript M indicates the cardinality of the PUNs. Eq. (15) is the complementary cumulative distribution function (CCDF), which can only be evaluated when the PUs are able to explicitly define the type of distribution parameter involved. Common form of distribution function that can be used include Rayleigh, Beta, Gamma and Gaussian. In any case, the PUs must generate the first and second moments before extrapolating the pdfs. Based on the above scenario, a non-cooperative spectrum trading game tuple is denoted by

$$\mathrm{T} = \left(N, \left\{\left(b_{(P_i,b)}, p^{ask,}_{(P_i,b)}\right)\right\}_{i\in K}, \{V_i\}_{i\in K}\right),$$

where:

- N is a set of game players (PUs)
- $\left(b_{(P_i,b)}, p^{ask}_{(P_i,b)}\right)$ is the strategy of player i, where $b_{(P_i,b)} \ge 0$ and $p^{ask}_{(J_i,b)} \ge 0$
- V_i is the payoff of player i

It is assumed that the strategy space of each PU is a compact convex bound with minimum and maximum spectrum bandwidths, denoted by $b^{\min}_{(P_i,b)}$ and $b^{\max}_{(P_i,b)}$, respectively, according to

$$b^{\wedge}_{(P_i,b)} = \left\{\mathbf{b}_{(P_i,b)} : \sum_{i=1}^{K} b_{(P_i,b)} \le b^{\max}_{(P_i,b)},\right.$$
$$\left. b^{\min}_{(P_i,b)} \le b_{(P_i,b)} \le b^{\max}_{(P_i,b)} \forall i \in K\right\}, \tag{16}$$

D. STAGE I-SPECTRUM AUCTION DESIGN AND ALLOCATION

In this subsection, SMART and its characteristics are illustrated. The system consists of SUs bidding for channels in their location. Each SU is assumed to have provided an evaluation to generate a marginal preference for the channels. Gradient descent is an information-hungry algorithm, indicating that more information leads to better performance. This is logical because if a bidder evaluates a channel more favorably, it will make more effort to gather information about the PU to win the channel. Before presenting SMART, certain definitions and rules are needed.

Definition 8 (Allocation Binary Variables): Allocated RBs must not intersect $\left(\forall_{i\neq j}, b_i \cap b_j = 0\right)$. Consider a binary variable, $\left(\forall_{i\neq j}, b_i \cap b_j = 0\right)$ which defines allocation as:

$$b_i(k) = \begin{cases} 1, & \text{if } b_i = b_j \\ 0, & \text{Otherwise} \end{cases} \tag{17}$$

The two most widely used bidding languages are the exclusive-OR (XOR), and additive-OR (OR). The XOR allows a bidder to submit multiple bids at once with one of the bids standing the chance of clinching. While in additive-OR (OR), the bidder submits multiple bids with the possibility that any non-intersecting combinations can win. The XOR language was adopted.

Definition 9 (Conflict Graph): Given as $G = (V, E)$, is such that a vertex, V, denoting a TVBS, and an edge, $e = (i, j) \in E$, denoting a TVBD exist whenever SU i, j interfere with each other if both transmit in the same epoch on the same channel. The importance of conflict graph is that, it enables the SB to generate adjacency matrix. Adjacency matrix illustrates the interference map otherwise known as critical neighborhood function.

Definition 10 (Bid Arrival Time): The SB collects the SUs' estimated asking price $\hat{p}^{ask}_{(J_i,b)}$ i.e. the bidding price and matches it with the PUs asking price, $p^{ask}_{(J_i,b)}$. If two SUs have the same bid, the tie is broken by sorting the bid arrival time $\hat{p}^{ask}_{(J_i,b)}$, using *first-come first-serve* (FCFS) principle. In practice, this could be implemented by inspecting the bid arrival timestamp.

Theorem 11 (SMART is Truthful):

Proof: Auction mechanism can be considered as truthful if the winning price is irrelevant, and the allocation strategy optimal. It was shown in (Archer & Tardos 2001) that for

TABLE 3. SMART algorithm.

Algorithm 4.2 Coordinated Double-sided Seal Bid Multiunit First Price Auction Mechanism

Input: $p^{ask}_{(P_i,b)}$, $p^{bid,}_{(G_i,b)}$, m, n

Output: Spectrum allocation decision

1: Adjacent matrix generation
 For i= 1: n, ***do***
  The SB compute the location vector of the SUs, ***then***
   Generate adjacent matrix
   $G(V, E)$

2: SU $p^{bid}_{(G_i,b)}$ ascending order sorting
 For i = 1: n, ***do***
  Sort $p^{bid}_{(G_i,b)_{(n)}}$ in ascending order

3: PU $p^{ask}_{(P_i,b)}$ descending order sorting
 For m = 1: m, ***do***
  Sort $p^{ask}_{(P_i,b)_{(m)}}$ in descending order

4: Matching
 While
  $p^{bid}_{(G_i,b)_{(n)}} == p^{ask}_{(P_i,b)_{(m)}}$ && no edge (E), ***then***
  Match

5: Contention resolution
 Else if
  $p^{bid}_{(G_i,b)_{(n)}} == p^{ask}_{(P_i,b)_{(m)}}$ && edge (E), ***then***
 Resort by *first come, first serve* (Auction frame timestamp)
  Match

6: Allocate spectrum bandwidth

7: ***Repeat*** 2-5
    End for
   End while
  End if

End

single parameter settings, using heuristics auction allocation is necessary and sufficient for strategy proof auction. ***SMART*** is driven by single parametric function. Hence, it is truthful. To prove that ***SMART*** is truthful, it is necessary to show that the pricing function is not the prerogative of the winning player, comprised of the PU and the SU. Evidently, the winning bid is a function of the bid submission time and the demand of the conflict-graph neighbours. Moreover, the punishment function introduced in the objective functions of the players serve as a deterrence for any player intending to cheat.

Price Monotonicity: For the case of monotonicity, if SU wins a channel at bid $p^{bid,(t)}_{(j,G_i)}$, then at any epoch, it will still win the channel provided it showed sufficient interest. ***SMART*** does not depend on the winning bidder. The only way SU will not win the channel can be when the aggregate demand of SU increases by indicated by bid reporting time. It is assumed that the marginal demand is weakly decreasing, leading to monotonically decreasing demand.

TABLE 4. Simulation parameter settings.

Symbol	Quantity
No of RB	25
Code Rate	2/3
Encoder	Convolutional Code
Modulation Scheme	16 QAM
$p^{bid}_{(j,G_i)}$	1
Decoder	Viterbi
σ	specific magnetization
P_T	36 dBm
BitRate	239880
Modulated symbol time	66.7 μs
Channel bandwidth	6 MHz

V. SIMULATION RESULTS

The simulation setting, scenario and results are defined and presented in this section. The focus of this results is to the highlight the superiority of our designed spectrum allocation algorithm and its performance in terms of auction QoS, delay profile and bit-error-rate. Table 4 highlights some of the evaluation parameters.

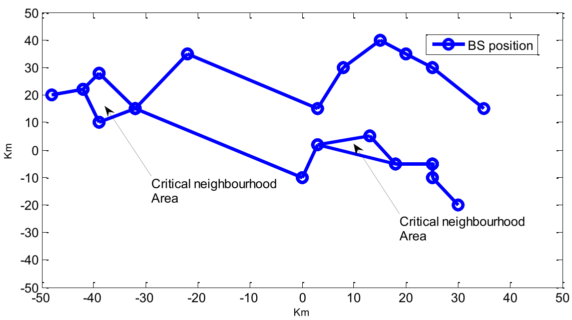

FIGURE 4. TVBS conflict graph.

A. SIMULATION SETTINGS

It is assumed that a single auctioneer handles bidders in a large geographical area consisting of 20 TVBS (bidders) in a square 100 × 100 km^2 randomly place. By using the ITU-R propagation model the conflict graph as illustrated in Figure 4 is generated.

Figure 4 indicates that TVWS networks in close proximity will not be assigned the same TV channel. This is to avoid internetwork interference which will be adversely affects the QoS of TVWS end-users. Adopting IEEE 802.22 standard, each 6 MHz channel bandwidth consists of 2048 subcarriers. 28 subcarriers of which 4 are pilots channels forms a TVWS sub-channel or 1 RB (IEEE 802.22 2010). To demonstrate improvement on the instantaneous throughput defined in (4), ***SMART*** is compared with similar algorithm named ***VERUM*** (Manickam *et al.* 2014). The evaluation starts by evaluating the impact of different step size values on bidding price as derived in (6). It is seen that in Figure 5, it takes five (5) iterations for the algorithm to converge when the alpha value (learning rate) is 0.03.

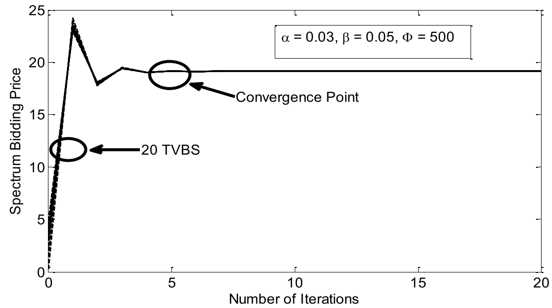

FIGURE 5. Distributed PU bidding price with alpha 0.03.

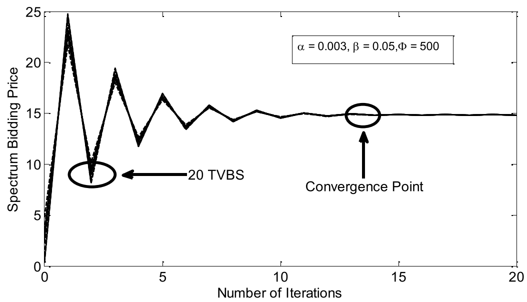

FIGURE 6. Distributed PU bidding price with alpha 0.003.

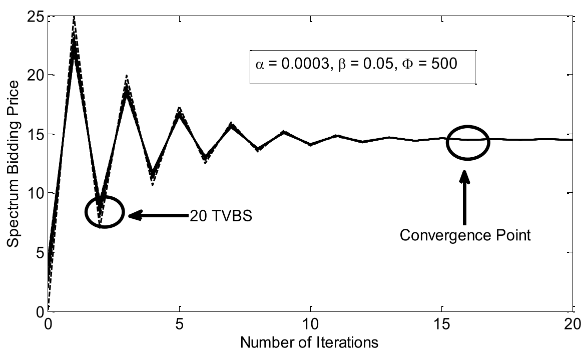

FIGURE 7. Distributed PU bidding price with alpha 0.0003.

As the learning rate decrease by 10 %, the convergence was extended as shown in Figure 6. A similar effect could be seen Figure 7. Convergence indicator is an important parameter for distributed game theory helping to further reduce the bidding rounds.

The convergence indicates that, despite the initial starting point chosen by various players, NEP remains the only feasible point in which no player lacks the motivation to seek an alternative strategy. Clearly, the convergence is fast as it is facilitated by careful choice of learning momentum, learning rate coefficient and target price respectively. The important lesson drawn from this simulation is that learning rate values impact heavily on the convergence of TVWS bidding price game.

Figure 8-11 is generated using Algorithm 2. As discussed earlier, ***SMART*** enhances auction efficiency (i.e. 4). Figures 8 and 9 further examines the performance of different spectrum allocation algorithms of ***SMART*** and ***VERUM***.

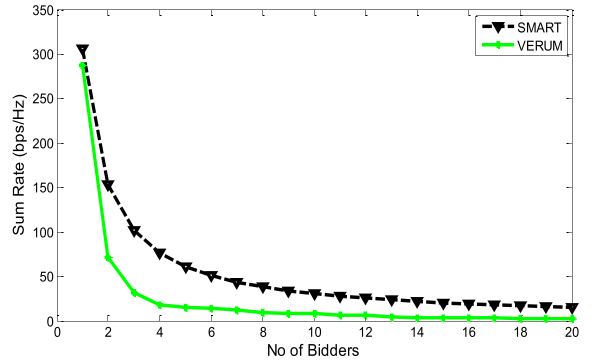

FIGURE 8. Sum rate as a function of no of bidders.

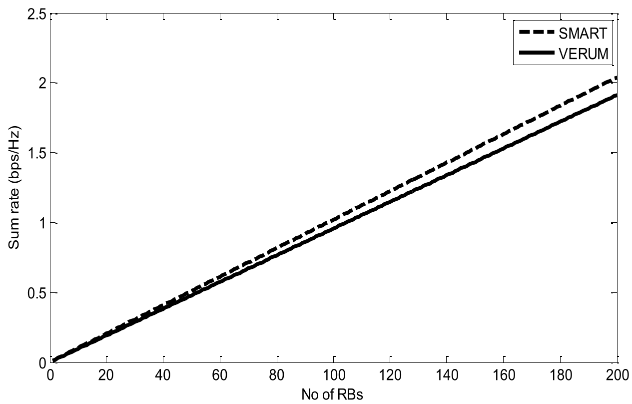

FIGURE 9. Sum Rate as a Function of No of RBs.

First, it can be seen that the proposed algorithm achieves a higher efficiency than iterative ***VERUM*** of about 10%. This is as a result of ***SMART*** being based on the principle of first-price mechanism and the *First-Come, First-Serve* tie breaking strategy. ***VERUM*** needs to address uncertainty regarding valuation faced by bidders, which is an inherent feature of auctions.

Hence, it is not an optimal strategy. It can be seen from Figure 8 that as the number of bidders increases, the sum rate drops by 20 %. The drive for this improved performance is attributed to the fact SB expends many resources in resource allocation algorithm which involves higher computing power and complex algorithms. ***VERUM*** might not suitable for QoS sensitive application as it might support the desired data rate. Conversely, the sum rate increases as the RBs increases. From another perspective, Figure 10 shows the sum rate of TVBS as a function to SINR. At the beginning of the simulation, both ***SMART*** and ***VERUM*** suffers from low SINR values. However, the values of ***SMART*** increases faster than ***VERUM***. At 70 % mark, both algorithms intercept. However, ***VERUM's*** efficiency starts to decline. The reason being the complexity of allocating RBs to many TVBS as their number increases.

Figure 11 compares SMART and VERUM with respect to Bit-Error-Rate (BER). From this figure, it was observed that the BER of SMART is higher that of VERUM. This implies

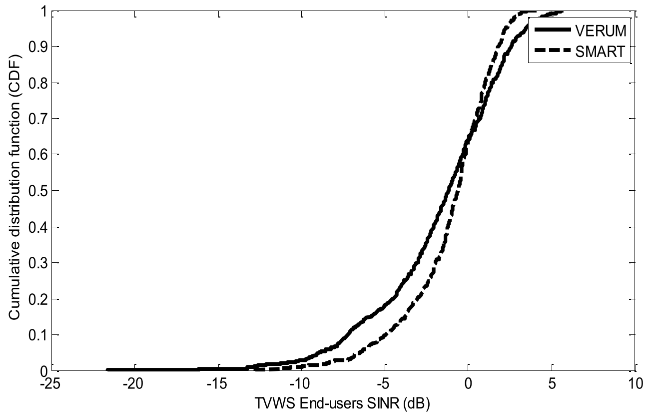

FIGURE 10. CDF Comparison between SMART and VERUM.

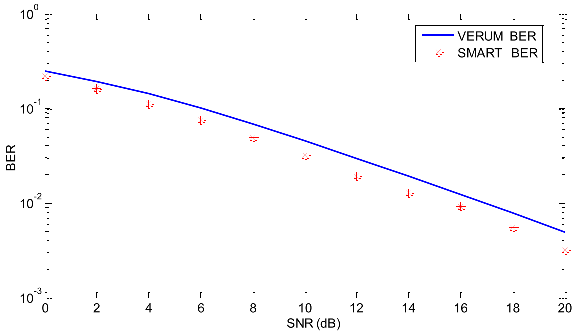

FIGURE 11. BER Comparison between SMART and VERUM.

that SMART is capable of sustaining certain QoS without the need of retransmission and hence improves the TVBS QoE. More importantly, SMART is bandwidth efficient when compared to VERUM. In fact, the performance will increase when as the Doppler Spectrum parameter decreases.

The outcome of any auction depends upon the way in which participants bid. Thus, any analysis will have to model this behavior. Single parametric functions cannot be explicitly modelled in implicit terms, and hence, a generic valuation approach seems the most attainable. Each bidder employs a bid function converting his/her valuation of the object into a buyer function considering its previous bid and private evaluation. At this point, there are several issues to take into account influencing bidding behaviour.

The single-value parametric approach herein maps a bidder's true valuation into reality. As seen from Figure 11 (*Algorithm 1*), as the bidder deploys more information, the error in predicting the estimated PU's asking price decreases. Hence, the accuracy depends on the number of data samples available to secondary users. Note, Figure 12, is generated by implementing Algorithm 1. This is a curve fitting approach widely used in statistics. The error between the actual and estimate decreases with a number of data samples. Based on Figures 8-10 above, it can be seen that all the SUs can attain same bidding price irrespective of their starting point under difference parameter estimation.

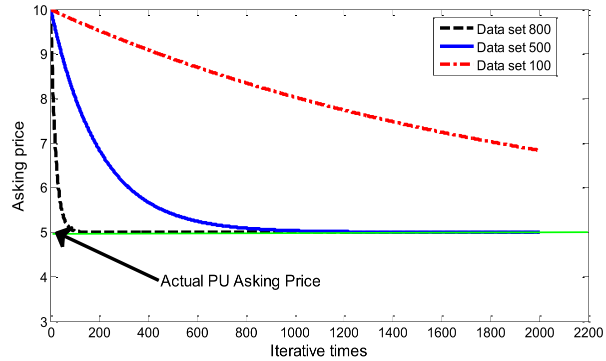

FIGURE 12. Stochastic Primary-user Parameter Estimation.

Furthermore, the discrepancies from the results indicate as the data set increases, the probability of predicting the asking price increases with little error. The data set denotes interest a bidder shows for a particular spectrum channel.

VI. CONCLUSION

In this paper, TVWS spectrum auction based on stochastic learning for homogeneous channel quality was discussed. The secondary spectrum auction is market driven and it is essential to use market models to drive spectrum utilization and subsequently, increase spectrum efficiency. It was clearly seen that the proposed algorithm outperforms the existing algorithm in TVBD QoS metrics. The superior performance of the proposed scheme is attributed to the IPV model which allocates spectrum resources to TVBS based on market forces. In conclusion, this study tends to support the general notion that spectrum efficiency can only be attained by market strategies. Hence, TVWS secondary spectrum auction must be driven by the IPV model.

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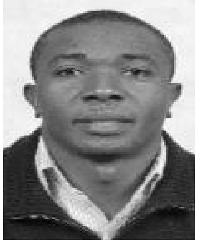

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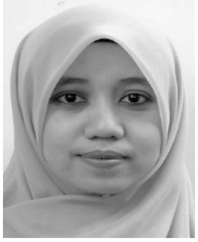

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