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D-GRACE: Discounted Spectrum Price Game-Based Resource Allocation in a Competitive Environment for TVWS Networks

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ABSTRACT The IEEE 802.22 standard targets rural and sparsely populated regions exploiting television white space (TVWS) technology. In these regions, there are fewer mobile users per density and end-user traffic is light. Hence, there is a need to adopt traffic aware algorithm leveraging on the end-user non-uniform traffic attributes and in essence, promote spectrum efficiency in the TVWS spectrum-management regime. This paper investigates a mechanism to encourage spectrum sharing during low end-user traffic regime motivated by financial inducement. Since incumbent coexistence has been achieved using market models, it is tractable to apply market-assisted spectrum sharing models to address self-coexistence issues in TVWS networks. The purpose of this paper is to use the market model to promote self-coexistence in TVWS networks in the uplink self-frequency reuse. Toward this goal, this paper proposes discounted spectrum price game-based resource allocation in a competitive environment (D-GRACE). Specifically, D-GRACE is a transmit power reduction strategy motivated by financial incentives during light TVWS end-user traffic. When compared with an existing non-market-inspired TVWS self-coexistence resource allocation algorithm under the same scenario, D-GRACE exhibited superior power savings of about 20% and converged after five iterations.

INDEX TERMS IEEE 802.22, self-coexistence, game theory, transmit power algorithm, sub-carrier allocation.

I. INTRODUCTION

The Television white space (TVWS) technology is confronted with three coexistence issues which are: incumbent coexistence, heterogeneous coexistence and self-coexistence [1]. Incumbent coexistence promulgates dynamic spectrum access etiquette between primary users (PUs) and secondary users (SUs) [2]. Heterogeneous coexistence addresses dynamic spectrum sharing etiquette between two or more different TVWS standards such as IEEE 802.11 af and IEEE 802.22 [1]. While self-coexistence offers strategies to attain harmonious dynamic spectrum sharing etiquette between two or more similar TVWS standards operated by different TVWS operators [3]. Progress has been made towards addressing the incumbent and heterogeneous coexistence issues by utilizing geo-locational database scheme enabled by spectrum auction mechanism [2] and the IEEE 802.19.1 Standard respectively [1]. There is no reported work yet from the perspective of using financial inducement to address the issue of self-coexistence in IEEE 802.22 Standard. Studies by [4] and other works including [5], [6] indicate that market forces can push spectrum utilization to the upper bounds. Therefore, market incentive tool has to be further exploited and manipulated to encourage efficient spectrum re-use paradigm.

The participants of economic game theory induced TVWS resource allocation (RA) are: (i) incumbent players - PUs whose spectrum are underutilized and are motivated to temporarily lease their vacant spectrum in exchange for monetary gains, (ii) TVWS networks – the SUs who pays the PU for the temporary transmission rights granted [7] and (iii) spectrum

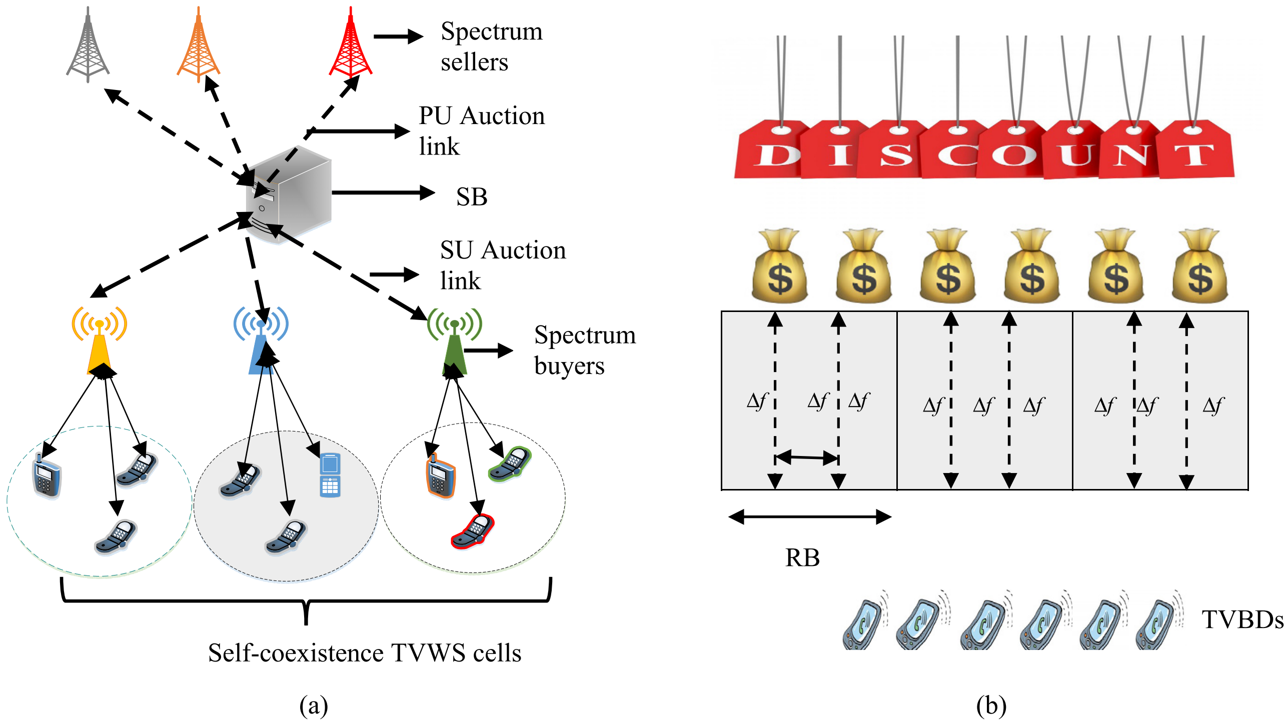

FIGURE 1. **(a) TVWS auction driven resource allocation. (b) Discounted spectrum price resource allocation.**

brokers (SB)/database operator - appointed by the spectrum regulators to oversee real time secondary spectrum market (RTSSM) transaction in TVWS environment [8]. Some literature have referred this type of spectrum configuration between the PU and the TVWS networks as leased spectrum access (LSA) technique [9] and has proposed various TVWS business models [10], [11].

Self-coexistence protocols and strategies are primarily concerned with strategies proposed towards achieving optimal performance of collocated TVWS networks as illustrated in Figure 1 (a) [12]. It is a challenging problem that must be investigated if the desired outcomes of TVWS technology are to be attained. To facilitate self-coexistence, two notable approaches have been adopted: the IEEE 802.22 centralized self-coexistence mechanism [13] and a non-centralized (distributed) approach based on non-cooperative game theory. The efficient use of radio spectrum is an important task that must be considered from the cost of service point of view. As the reduction in the number of purchased spectrum bandwidth will inadvertently lead to a reduction in bits/$. Incumbent coexistence has been successfully addressed with market based non-cooperative game mechanism [14]. There is a need to extend the same concept to the self-coexistence issue. Thus, making the goal of affordable broadband connectivity a reality. The major limitation in intense radio spectrum reuse is interference caused by the environment or other mobiles. Based on Shannon capacity, wireless network capacity is enhanced either by increasing the channel bandwidth or reducing the inter-cell interference (ICI) using interference management/avoidance techniques. This work adopts ICI techniques towards increasing TVWS wireless capacity. The contributions of this work are:

- First, the uplink resource allocation (URA) problem in the multi-cell TVWS was formulated as a discounted spectrum price optimization problem and further decoupled into two sub problems (i): sub-channel allocation (SCA) and (ii); discounted spectrum price transmit power control (TPC).
- Second, the multi-cell TPC is cast as a non-cooperative game and prove that Nash equilibrium exists without inter-cell coordination leading to a unique D-GRACE optimal power solution.
- Third, in the cheating scenario, the game was re-casted as a submodular game and a novel stochastic gradient learning time-based D-GRACE local SCA algorithm was proposed. The algorithm is based on time-based interference trust model, which indicates the level of the truthfulness of another player towards cooperation and thus, relegates the use of virtual referee.

The rest of the article is organized as follows. Overview of related works is presented in Section 2. The problem formulation and system model are presented in Section 3. Section 4 focusses on non-cooperative game theory. Simulated results and discussions in Section 5. Finally, conclusions are drawn in Section 6.

II. RELATED WORKS

Ostensible research works on IEEE 802.22 self co-existence issue have been concluded. Each research work analyzes the self co-existence problem from different microcosm and subsequently propose unique algorithms. In [15], an allocation sharing mechanism targeting inter-cellular interference mitigation was proposed. The algorithm exploited the use of TPC and scheduling mechanism to tackle self-coexistence issue which invariably, leads to superior network throughput. The non-cooperative game has also received its fair share in promoting IEEE 802.22 networks self co-existence regime [16], [17]. While [16] analyze the non-cooperative game from the minority game theoretical perspective focusing on minimization of switching game function, [17] designed the IEEE 802.22 inter-BS resource-allocation mechanism, which culminates to the IEEE 802.22 dynamic resource renting and offering (DRRO) and adaptive on-demand channel contention (AODCC) algorithms. Interestingly, the aforementioned algorithms included a mechanism to evaluate allocation efficiency and proportional fairness. Note, these two parameters are critical for allocation algorithms optimal performance. Similarly, [18] formulated a non-cooperative game targeting switching cost function minimization. The authors adopted a two player matrix format as a tool to analyze the problem. The adoption of two player matrix format is because if a unique solution can be found for two players' game, it can be further extended to the case of N players (or N matrix format). The major limitation of the above is the exclusion of prioritized prerogative scheme as users near the BS and cell edge experiences different received signal-to-interference-plus-noise ratio (SINR). From the downlink soft frequency reuse (DSFR) perspective, several distributed DSFR-based algorithms have been proposed [19], [20]. Reference [19] introduced the concept self-organizing paradigm whereby cell assigns cell-edge users its "best" subchannels permitting high transmit power on those subchannels. Inadvertently, making these subchannels "bad" for other coexisting users. As a result, other coexisting cells try to avoid these bad channels and by extension, eventually turning the bad channels "excellent".

Based on conducted studies, there are few works on uplink soft frequency reuse (USFR). Reference [21] proposed the use of adaptive soft frequency reuse (SFR)-based resource allocation for uplink inter-cell interference coordination (ICIC). The principle highlighted herein is based on assigning different time domain resource blocks (RBs) adaptively to either cell-center users or cell-edge users. In addition, resource borrowing from surplus cells to resource block deficient cells were permitted. Obviously, this requires some level of inter-cell coordination. Reference [22] studied the case of USFR from the view point of semi-autonomous fashion similar to [19]. Unfortunately, the two important elements of USFR which are power consumption and efficiency were neglected. Reference [23] proposed several heuristics based SFR scheduling considering uplink outage probability. A slightly different approach was adopted in [24].

A common observation made so far is that inter-cell coordination is achieved by assigning same radio RB between cell-edge users in one cell and cell-center users in another cell (i.e) in an alternate fashion. Ordinarily to allocate RBs with high interference threshold to cell-edge users in one cell and low interference to the cell-center users in the adjacent cell. The approach adopted in this paper is based on local interference measurement with zero inter-cell coordination. A similar approach has been recently implemented in [3]. Various non-cooperative game motivated multi-cell resource allocation algorithms have been proposed. Some of the notable algorithms are: downlink [25], [26], uplink [27]–[30]. As noticed, for USFR some form of coordination is still needed reference can be found in the case of virtual referee [28], the centralized integer program [29] and the correlated equilibrium [30]. Concluding, none of the above mentioned works have thought of using the discounted price mechanism to promote USFR paradigm. Numerous studies have indicated that coexistence between PUs and TVWS networks have been concluded thanks to market driven geo-location database scheme [14]. The goal of this work is to deploy discounted spectrum price incentive to simulate uplink self-coexistence in TVWS networks. A similar thought has been emphasized in [4] but considering another scenario.

A well-known problem in wireless communication economics is how to attain reduced cost-per-bit for wireless consumers [31]. To solve this, a common goal is: use market incentives to motivate uplink spectrum sharing in a multi-cell OFDMA TVWS networks leading to the proposition of D-GRACE: Discounted spectrum price Game-based Resource Allocation in a Competitive Environment.

III. MODEL AND PROBLEM DESCRIPTION

The system settings, the assumptions, the channel model, uplink soft frequency reuse (USFR) concept description and D-GRACE strategy organization are presented in this section. For convenience, Table I lists some important notations, which will be used in this paper.

A. SYSTEM MODEL

The scenario consists of $n \in N \triangleq \{1, \ldots, N\}$ TVWS network cells operated by different operators all within the transmission range of one another as illustrated in Figure 1(a). Each TVWS Base Station (TVBS) is responsible for assigning RB to $J^{(n)}$ active Television Band Device (TVBD)/sessions. $J^{(n)}$ denotes that active TVBD, j, in cell, n, controlled by home TVBS n. Each $TVBS^{(n)}$ is capable of sustaining multiple sessions j_n for $j_n \in J^{(n)} \triangleq \left\{1, \ldots, J^{(n)}\right\}$ on multiple sub-channels. Thus, making it possible for the common shared channels to sustain multiple active sessions in coexisting cells. The TVBS has agreed to use set of RB /sub-channels based on discounted spectrum price model. The scenario can be summarized as: economically enticing selfish TVWS networks managed by different TVWS network operators to share TV channel band in the absence of a central coordinator as illustrated in Figure 1 (b). This setting can be considered as the extension of sharing incentive through flexible spectrum licensing studied by [10]. In this scenario, global network deployment and frequency planning are not feasible, and

TABLE 1. **Notable symbols for used this study.**

Symbol	Definitions
$\diamond$	Spectrum price discount parameter
$J^{(n)}$	Active Television Band Device (TVBD)
$\gamma^{(t)}_{(j,k)}$	SINR TVBD j receives by using subchannel k., at time t
$P^{(d,opt)}_{j,k}$	Optimal transmission power for TVBD j on subchannel k. in TVWS cell d
$P^{(d,\min)}_{j,k}$	Minimum transmission power for TVBD j on subchannel k., in TVWS cell d
μ	Convex combinator factor
$R^{(th)}_{j,k}$	TVBD, j, minimum expected rate on subchannel k.
$x_{(j,k)}$	Binary indicator on subchannel k.
$\bar{\varpi}^{(d)}_{j}$	Normalized weights
$\mathbf{z}^{(d)}$	Sub-carrier allocation
$\varpi^{(\mathbf{d})}_{j}$	Session weight
$I^{(Aggr)}_{k}$	Aggregate interference on subchannel k.
$I^{(Aggr,th)}_{k}$	Interference tolerance of subchannel k.

co-channel spectrum sharing without inter-cell coordination becomes challenging.

B. PRELIMINARY: UPLINK SOFT FREQUENCY REUSE CONCEPT

The classical approach towards inter-cell interference mitigation relies on fixed frequency reuse scheme. In this approach, each BS statically assign a fixed set of subchannels via frequency planning to a user in need of communication channel. Some literature refers this mode as hard frequency reuse (HFR). It is the earliest and the easiest channel assignment mode [24]. However, it is inefficient and wasteful because random channel usage pattern is not considered [23].

On the other hand, dynamic spectrum assignment targets on-demand assignment model. Channel allocation and assignment is based on channel need and availability. There are various kinds of dynamic spectrum assignment such as: fractional frequency reuse (FFR) and USFR [24]. In FFR scheme, only a fraction of the total channel can be reused while USFR engages in a hierarchical resource management scheme as illustrated in Figure 2. In USFR scheme, active sessions are assigned priority weight driven by their relative position to their home BS. Adopting USFR concept implies that, users are classified as inner users, edge users and far edge users depending on their location referenced to their home BS. The far edge users are scheduled first before the inner and edge users to address the issue of intra-cell fairness.

C. SCENARIO SETTINGS AND ASSUMPTIONS

To aid scenario settings understanding, the following assumptions were made:

i The current TVWS end-users traffic is light and TVWS networks will adopt non-exclusive channel sharing mode.
ii It is assumed that the PU has transmitted to the SB the monetary discount for TVWS networks who want to engage in non-exclusive channel sharing mode.
iii All the TVWS networks responding to the SB auction call at the moment are within the transmission range of one another. Hence, there is self-coexistence awareness.
iv Discounted spectrum price parameter, $\diamond$, connotes both financial and transmit power interpretations. The transmit power connotes a lower transmit power from that proposed by the FCC for a single TV channel.
v The TVWS networks must devise a strategy to coexist among themselves without the supervision of the SB entity.

D. CHANNEL MODEL

The channel model considered here involves all the fading components witnessed in wireless communications such as: the pathloss, slow fading and shadowing. The theoretical SINR at time, t, per RB, k, of each TVBD, j, can be found using (1):

$$\gamma^{(t)}_{(j,k)} = \frac{h_j P_T A d^{-\eta}\Omega}{\sum_{i\neq j} h_{ij} P_T A d^{-\eta}\Omega + N_0} = \frac{h_j P_T A d^{-\eta}\Omega}{I_{S2S} + N_0} = \frac{h_j P_T A d^{-\eta}\Omega}{I_{TOTAL}}, \tag{1}$$

where, h_j is the channel gain, h_{ij} is the interference link, P_T is the transmit power, A is a unit-less constant depending on the antennas characteristics, d is the relative distance of the receiver to the transmitter and η is the path-loss exponent characterizing the propagation environment and is in the range of 3.7 - 6.5 for macro cells, $\Omega = 10^{\xi/10}$ is a log-normal random variable denoting shadowing. ξ is a normal distributed random variable, with zero mean and standard deviation, σ, which is typically between 0 and 8 dB [32].

E. DISCOUNTED UTILITY BASED TVWS FICTITIOUS CURRENCY MODEL

To avoid inter-cellular interference (ICI), each sub-channel $k \in K \triangleq \{1, \ldots, K\}$ cannot be assigned to more than one session concurrently [21]. The channel rate of a specific TVWS cell d is estimated using Shannon capacity law stated as:

$$R^{(d)}_{(j,k)} = \ell \Delta f \log_2\left(1 + \gamma^{(d)}_{(j,k)}\right), \tag{2}$$

the subscript j, k denotes the sub-channel k is assigned to TVBD user j, $\Delta f = 180$ kHz, while ℓ denotes the degree of spectrum sharing and defined as $\ell \triangleq K/J$. The spectrum utility is stated:

$$U^{(t)}_{(j,k)} = \ell \Delta f \log_2\left(1 + \gamma^{(d)}_{(j,k)} \diamond_{(j,k)}\right) - p^{bid,(t)}_{(j,k)}, \tag{3}$$

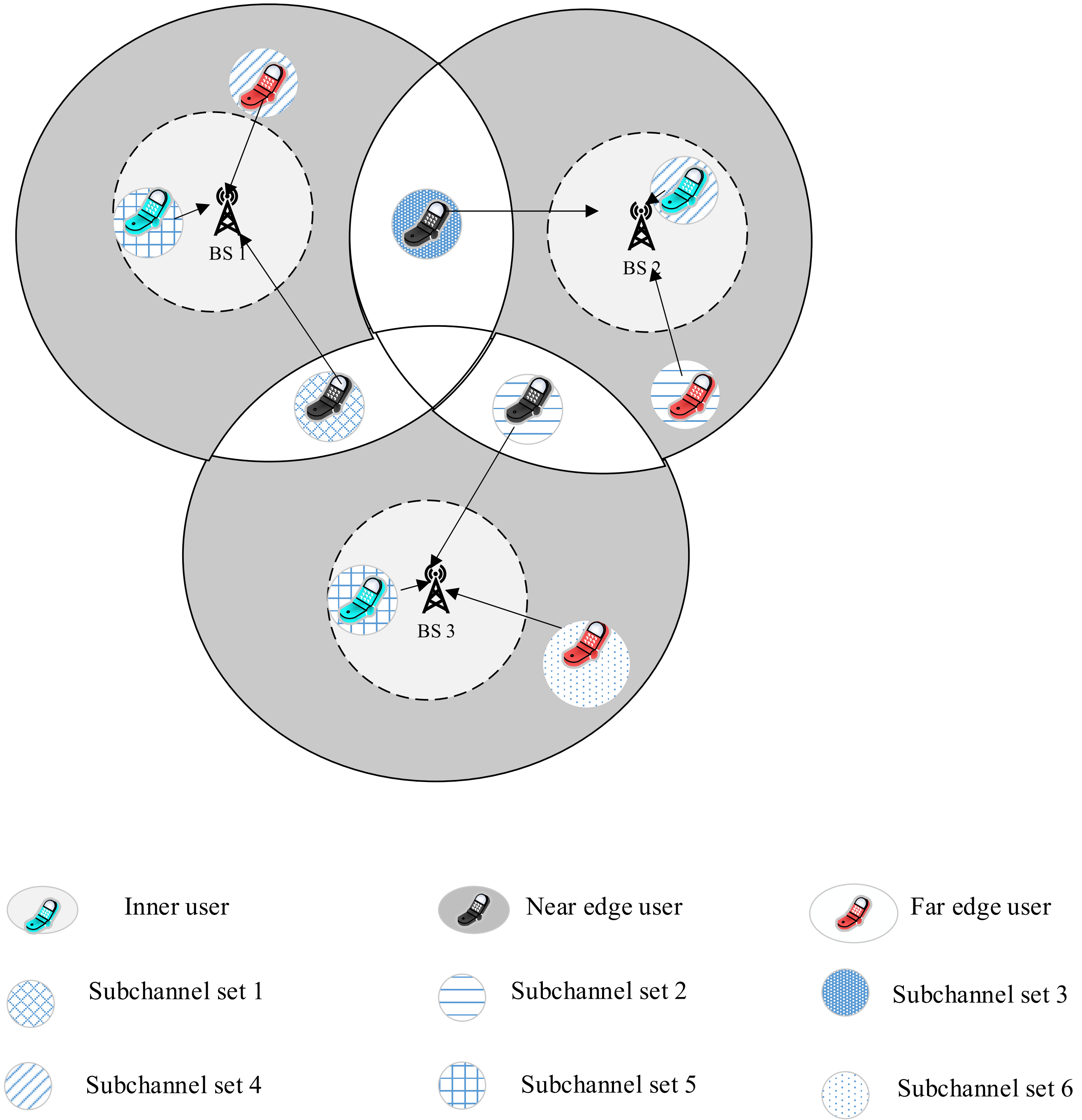

FIGURE 2. **Philosophy behind USFR.**

The term $p^{bid}_{(j,k)}$ denotes the bid price TVBD user j pays through the SU for leasing PU channel k and $\diamondsuit_{(j,k)} \in [0.1, 0.9]$.

F. TVBD SCHEDULING CONSIDERING USFR FAIRNESS

The primary objective of scheduling is to maximize system throughput. If fairness is not considered in a multi-user environment, some of the users will be starved of resources. In this study, fairness is analyzed from TVBD priority perspective. The two widely used session weight approaches are: perfect global channel state information based session weight and estimated global channel state information session weight [3]. The perfect global channel state information defines a situation in which the TVBS possess global knowledge of wireless channel conditions of all the co-located TVWS cells defined as:

$$\varpi_j^{(\mathbf{d})} \triangleq \frac{\sum_{i=1,n\neq d}^{N} h_{J_d}^{(d,n)}}{h_{J_d}^{(d,d)}}, \tag{4}$$

The estimated global channel state information session weight acknowledges the fact that, it is difficult for TVBS d to locally obtain $\sum_{i=1,n\neq d}^{N} h_{J_d}^{(d,n)}$ accurately. The situation becomes complex considering the proposed cell radius of IEEE 802.22 standard which is between 4-100 km [13]. The estimated global channel state information is defined as:

$$\varpi_j^{(d)} \triangleq \mu p_j^{(d)} + (1-\mu)\,\bar{\varpi}_j^{(d)}, \tag{5}$$

where $p_j^{(d)}$ represents session j's predefined normalized priority, $\bar{\varpi}_j^{(d)}$ denotes j's normalized weights based on (5) and μ is a convex combinator factor [3]. The TVBS sort the weights of the TVBD in a decreasing order; $\varpi_{j,1}^{(\mathbf{d})} \geq \varpi_{j,2}^{(\mathbf{d})} \geq \cdots \varpi_{j,K}^{(\mathbf{d})}$. The TVBS d's local objective function in terms of power consumption, $\mathrm{H}^{(d)}$, is illustrated as:

$$\mathrm{H}^{(d)} \triangleq \min \sum_{j=1}^{J} \varpi_j^{(\mathbf{d})} \sum_{k=1}^{K} P_{j,k}^{(\mathbf{d})}, \tag{6}$$

G. PROBLEM FORMULATION

Optimization problem tries to maximize the transmission rate of the TVBD considering the constraints defined below.

$$P1: \max \sum_{n\neq n'}^{N} \sum_{j=1}^{J} \sum_{k=1}^{K} U_{(j,k)}^{(t)} x_{(j,k)},$$

$$\text{s.t}\begin{cases} C1: \displaystyle\sum_{j=1}^{J}\sum_{k=1}^{K} P_{j,k}^{(d,opt)} > 0, \\ C2: \displaystyle\sum_{j=1}^{J}\sum_{k=1}^{K} P_{j,k}^{(d,\min)} \leq P_{j,k}^{(d,opt)} \leq P_{j,k}^{(d,\max)}, \\ \qquad\qquad\qquad\qquad \forall j \in \mathbf{J}, \quad k \in \mathbf{K} \end{cases}$$

$$\text{s.t}\begin{cases} C3: I_k^{(Aggr)} \leq I_k^{(Aggr,th)}, \\ C4: \displaystyle\sum_{j=1}^{J}\sum_{k=1}^{K} R_{(j,k)}^{(d)} \geq R_{j,k}^{(th)}, \quad \forall n \in N;\ jn \in J^{(n)} \\ C5: \displaystyle\sum_{J_d=1}^{J^{(d)}}\sum_{k=1}^{\mathrm{K}} \tilde{P}_{j,k}^{(d)} \geq P_{j,k}^{(d,th)}, \\ C6: \displaystyle\sum_{J_d=1}^{J^{(d)}}\sum_{k=1}^{\mathrm{K}} \tilde{P}_{j,k}^{(d)} \geq 0, \\ C7: \displaystyle\sum_{J_d=1}^{J^{(d)}}\sum_{k=1}^{\mathrm{K}} x_{(j,k)} \in \{0,1\}, \end{cases}$$

The uplink resource allocation (URA) consists of subchannel allocation (SCA) denoted in matrix form as $\mathbf{Z}^{(d)} \triangleq \left\{Z_{j,k}^{(d)}\right\} J^{(d)} \times K$ and transmit power control (TPC) in the form as:

$\mathbf{P}^{(d)} \triangleq \left\{P_{j,k}^{(d)}\right\} J^{(d)} \times K$. The subscript j, k denotes matrix rows and column. $x_{(j,k)} \in \{0,1\}$ denotes a binary indicator. It is equal to 1 on the occasion that a subchannel is assigned an active TVBD and 0, otherwise. Similarly, $P_{j,k}^{(d)} \triangleq \left\{\mathbf{P}^{(d)}\right\}$ denotes allocated power. This implies that each RB is assigned to a fixed transmission power level. The constraints are defined below.

H. URA ALLOCATION CONSTRAINTS DEFINITION

Let's denote $P_{j,k}^{(d,\min)}$ as the minimum required power to meet session $j's$ SINR requirement and $P_{j,k}^{(d,\max)}$ the maximum power. The optimal transmission power $P_{j,k}^{(d,opt)}$ must be greater than zero, i.e. $P_{j,k}^{(d,opt)} > 0$ and is bounded by

$$P_{j,k}^{(d,\min)} \leq P_{j,k}^{(d,opt)} \leq P_{j,k}^{(d,\max)}, \tag{7}$$

Using standard notation, $Z_{j,k}^{(-d)} = \tilde{Z}_{j,k}^{(-d)}$ where $\tilde{Z}_{j,k}^{(-d)}$ is a fixed matrix set. The aggregate TVWS cells interference on subchannel k is defined as :

$$I_{j,k}^{(Aggr)} = \sum\nolimits_{n'=1}^{N} \sum\nolimits_{Jn'}^{J(n')} P_{Jn,k'}^{(n')} h_{nn'}^{(n'n)}, \tag{8}$$

It is possible to obtain local instantaneous channel gain by decoding the signal samples of co-located TVBS and determine the channel gain. Furthermore, certain interference condition must be met stated as:

$$I_k^{(Aggr)} \leq I_k^{(Aggr,th)}, \tag{9}$$

$I_k^{(Aggr,th)}$ is the interference tolerance of subchannel k. TVBD users base QoS, $R_{j,k}^{(th)}$, is defined as:

$$\sum_{J_d=1}^{J^{(d)}} \sum_{k=1}^{K} \Delta f \log_2 \left(1 + \frac{P_{j,k}^{(d)} h_j^{(d,n)}}{\sum_{i\neq j} P_i + N_0}\right) \geq R_{j,k}^{(th)}$$
$$\forall n \in N; \quad jn \in J^{(n)}, \tag{10}$$

Eq. (10) emphasizes the need to adhere to the minimum base rate QoS for the TVBD. Replacing the denominator of (10) with $I_k^{(Total)}$ and for the sake of notation simplicity, (11) is stated as:

$$R_{(j,k)}^{(d)} \geq R_{j,k}^{(th)} \quad \forall n \in N;\ jn \in J^{(n)}, \tag{11}$$

The IEEE 802.22 peak data rate per channel: 22.69 Mb/s (coding rate 5/6, 64-QAM). Transmission can only be feasible when the TVBS assign the TVBD uplink minimum transmission power threshold $P_{j,k}^{(d,th)}$ stated as:

$$\sum_{J_d=1}^{J^{(d)}} \sum_{k=1}^{\mathrm{K}} \tilde{P}_{j,k}^{(d)} \geq P_{j,k}^{(d,th)}, \tag{12}$$

Similarly, allocated transmission power must satisfy (13) as stated below

$$\sum_{J_d=1}^{J^{(d)}} \sum_{k=1}^{\mathrm{K}} \tilde{P}_{j,k}^{(d)} \geq 0, \tag{13}$$

Obviously, Problem 1 is a mixed-integer non-linear problem (MINLP) and is NP-hard [33]. Solving the above problem is not feasible and as such, the complexity of the problem is reduced via decoupling. Problem 1, when decoupled results into two sub problems of TCP and SCA. The purpose of the problem decomposition is to reduce the complexity of the main problem and solve the resultant problems iteratively.

IV. DISCOUNTED SPECTRUM PRICE UPLINK MARKET MODEL

Ordinarily, network capacity is maximized via centralized coordinator using a radio network controller (RNC). Unfortunately, it is associated with the following: excessive channel control overhead, synchronization signals, feedback overhead, and worst of all, coordination between entities manage by different operators are difficult to implement. To mitigate against this, a decentralized process involving non-cooperative game theory is proposed in the URA. The URA is a two-step framework consisting of TPC and SCA sub-games.

A. SUB-GAME I: D-GRACE TPC

Let a *finite normal form game*, Γ, be denoted by a tuple $\Gamma = \left(N, (X_i)_{i\in N}, (U_i)_{i\in N}\right)$, where N denotes the finite set of players and $(X_i)_{i\in N}$, $(U_i)_{i\in N}$ denotes player specific possible actions/strategies and utility respectively. The purpose of game is to derive optimal transmission power candidate solution. Before proceeding, some assumptions are needed. First, it is assumed that TVBS has no intention to cheat and are self-rationale entities i.e. a cheat-free environment is the target. Second, pure strategies are always played. To be precise, TVBS must always act truthfully at all times. The form game definition is as follows:

- Players: TVBSs (G_i, G_{-i}).
- Strategy space: Each G_i chooses cell specific transmission power from the feasible set, denoted with $P_{j,k}^{(d,opt)} = \left[P_{j,k}^{(d,\min)}, P_{j,k}^{(d,\max)}\right)$.
- Payoff function: G_i minimizes power so as maximize the revenue, i.e. each TVBS maps its own transmission power action as well as other TVBS transmission power action to some real value denoted with, $\mathrm{E}_{j,k}^{(G_i,d)}\left(P_{j,k}^{(G_i,d)}, P_{j,k}^{(G_{-i},d)}\right)$. The computational complexity of (P1) can be relaxed by removing other constraints (*C1*), (*C5*) and (*C7*) in (P1). Hence, the optimization problem of (P1) can be rewritten as follows:

$$\mathrm{E}_{j,k}^{(G_i,d)}\left(P_{j,k}^{(G_i,d)}, P_{j,k}^{(G_{-i},d)}\right) = P2: \max \sum_{i,d=1}^{N}\sum_{j=1}^{J}\sum_{k=1}^{K} \log_2 U_{(j,k)}^{(t,disc)} x_{(j,k)}$$

$$\text{s.t}\begin{cases} C1: \sum\limits_{k=1}^{K} P_{j,k}^{(d)} \geq 0, \quad \forall n \in N; jn \in J^{(n)} \\ C5: \sum\limits_{k=1}^{\mathrm{K}} \tilde{P}_{j,k}^{(d)} \geq P_{j,k}^{(d,th)}, \quad \forall n \in N; jn \in J^{(n)} \\ C7: \sum\limits_{J_d=1}^{J^{(d)}}\sum\limits_{k=1}^{\mathrm{K}} x_{(j,k)} \in \{0, 1\}, \end{cases}$$

The discounted optimization problem of (P1) $U_{(j,k)}^{(t,disc)}$ can be explicitly defined as:

$$U_{(j,k)}^{(t,disc)} = \ell \Delta f \log_2\left(1 + \gamma_{(j,k)}^{(d)} \diamondsuit_{(j,k)}\right) - p_{(j,k)}^{bid_d isc,(t)}, \tag{14}$$

The new spectrum price, which is the discounted spectrum price for the TVWS networks is defined as:

$$p_{(j,k)}^{bid_d isc,(t)} = p_{(j,k)}^{bid,(t)} - \diamondsuit_{(j,k)}, \tag{15}$$

Unselfish TVBS aims to solve Eq. (16) stated:

$$\mathrm{E}_{J,k}^{(G_i,d)}\left(P_{J,k}^{(G_i,d)}, P_{J,k}^{(G_{-i},d)}\right) = -\min_{P_{J,k}^{(G_i,d)}} \sum_{i,d=1}^{N}\sum_{j=1}^{J}\sum_{k=1}^{K} I_{j,k}^{(d)}, \tag{16}$$

This type of game falls into the category of *anti-coordination game* because the goal of all unselfish players is to aim for network utility maximization. P2 is a convex problem, in which the optimal solution can be easily derived. The solution to the D-GRACE transmit power problem can be described by the following theorem:

Theorem 1: A Nash Equilibrium Point (NEP) describes a point, in which deviation leads to a lower utility. In this game, only deterministic pure strategies are allowed. Mixed strategies driven in principle by some probability distribution are not considered. References [34] and [35] have shown that NEP exists if:

- Ω, the support domain of $P_{j,k}^{(G_i,d)}$, is a non-empty, convex and compact subset of a certain Euclidean space R^L and
- $f\left(P_{j,k}^{(G_i,d)}\right)$ is continuous and quasi-convex in $P_{j,k}^{(G_i,d)}$.

Proof: There exists a unique NEP $\overset{*}{\underset{j,k}{P}}{}^{(G_i,d)}$ for D-GRACE TPC game. (P.2) is a compact Cartesian product and convex set. Therefore, the first condition has been satisfied. The proof of the NE uniqueness is conducted by checking the second-order condition to locate where it is negative

$$-\frac{\partial^2 U_{(j,k)}^{(t)}}{\partial_i^2 P_{j,k}^{(G_i,d)}} = \sum\nolimits_{-i,i} \frac{\partial^2 U_{(j,k)}^{(t)}}{P_{j,k}^{(G_i,d)} P_{j,k}^{(G_{-i},d)}}, \quad \forall j \in J, \ \forall k \in K$$

The NE is the solution to the utility optimization problem for each player given all other players' actions is stable. Since both conditions are met, then, the NEP of the proposed D-GRACE TPC exists.

B. PROPOSED D-GRACE POWER ALGORITHM

The optimal power algorithm in the USFR D-GRACE power can be derived according to the following proposition.

Proposition 1: In the discounted spectrum price model, the optimal power allocated to the subcarriers by maximizing (P.2) resulting in the optimal power strategy across the subcarriers is formulated as follows:

$$\overset{*}{\underset{j,k}{P}}{}^{(G_i,d)} = \max\left[0, \frac{1}{\sum\limits_{j=1}^{J}\beta^{TVBD} + \sum\limits_{k}^{K}\lambda_k x_{j,k}} - \frac{I_k^{(Total)}}{\left|h_{jd}^{(d,n)}\diamondsuit_{(j,k)}\right|^2}\right]^+, \tag{17}$$

Proof: the Lagrange method was adopted to obtain the closed form optimal constrained D-GRACE transmit power problem of (2). Therefore, the Lagrange function of the optimization problem of (P2) is stated as

$$L\left(P_{j,k}^{(d)},\lambda,\beta\right) = \left[\begin{array}{l}\sum_{i=1}^{N}\log_2\left(\frac{1+P_{j,k}^{(d)}h_{jd}^{(d,n)}\diamondsuit_{(j,k)}}{I_k^{(Total)}}\right)-P_{j,k}^{(d)}\sum_{j=1}^{J}\lambda_j x_{j,k}\\ -\sum_{k=1}^{\mathbf{K}}\beta_k\left(\sum_{k=1}^{\mathbf{K}}P_{j,k}^{(d)}-P_{j,k}^{(d,th)}\right)=0\end{array}\right] \tag{18}$$

where $\lambda, \beta \geq 0$, are non-negative Lagrange multipliers vector that can be obtained using the sub-gradient technique. In this work, optimal values of the Lagrange multipliers are not necessary because the algorithm is derived via sub-optimal techniques. Taking partial derivative with respect to $P_{j,k}^{(d)}$ and considering the Karush-Kuhn-Tucker (KKT) conditions, which are necessary and sufficient for optimality, (14) is transformed to (17) leading to proposed D-GRACE iterative power algorithm in (19):

$$\overset{*}{P}_{j,k}^{(G_i,d)} = \max\left[0, \frac{1}{\sum_{j=1}^{J}\beta^{TVBD}+\sum_{k}^{K}\lambda_k x_{j,k}}-\frac{I_k^{(Total)}}{\left|h_{jd}^{(d,n)}\diamondsuit_{(j,k)}\right|^2}\right]^+, \tag{19}$$

Close observation of the D-GRACE TPC shows that, it is similar in derivation to the conventional iterative water-filling algorithm [36], with the only difference being the price discount parameter. D-GRACE can be updated via:

$$\mathbf{P}_{j,k}^{(n)}(\tau+1) = P_{j,k}^{(n)}(\tau) - \perp P_{j,k}^{(n)}(\tau), \tag{20}$$

where, $\perp$ is the adjusting parameter, which must be carefully chosen for fast convergence.

C. SUB-GAME II: D-GRACE SCA

Once $\overset{*}{P}_{j,k}^{(G_i,d)}$, $\overset{*}{P}_{j,k}^{(G_{-i},d)}$ are determined, they are referred as known constants. The URA problem reduces to that of selecting $Z_{j,k}^{(-d)} \equiv \tilde{Z}_{j,k}^{(-d)}$ and $Z_{j,k}^{(d)} \equiv \tilde{Z}_{j,k}^{(d)}$ stated as:

$$\mathrm{E}_{j,k}^{(G_i,d)}\left(P_{j,k}^{(G_i,d)}, P_{j,k}^{(G_{-i},d)}\right) = P3: \max\sum_{i,d=1}^{N}\sum_{j=1}^{J}\sum_{k=1}^{K}\log_2 U_{(j,k)}^{(t)}x_{(j,k)},$$

$$\text{s.t}\begin{cases} C4: \sum_{j=1}^{J}\sum_{k=1}^{K}R_{(j,k)}^{(d)} \geq R_{j,k}^{(th)}, & \forall n \in N; jn \in J^{(n)}\\ C7: \sum_{J_d=1}^{J^{(d)}}\sum_{k=1}^{\mathrm{K}}x_{(j,k)} \in \{0,1\}, \end{cases}$$

While TPC was solved iteratively, i.e. many times, SCA can only be solved once and relies on probability function and heuristics. As a start, it is assumed that the players act honestly and this leads to the formulation of distributed honest D-GRACE SCA algorithm. In the case the players decide to cheat, further theorem and corollary are required.

Corollary 1: Optimal solution to SCA entails obtaining perfect global knowledge of $\overset{*}{P}_{j,k}^{(G_{-i},d)}$, $\tilde{Z}_{j,k}^{(-d)}$ and $h_{jd}^{(n,n')}$ $\forall n \in N; n \neq d$ in the cell d.

Proof: It is easy to obtain on real-time basis, $\tilde{Z}_{j,k}^{(-d)}$ and $\overset{*}{P}_{j,k}^{(G_{-i},d)}$ by decoding the downlink pilot signals from BS $n^{(')}$, however, it is difficult to obtain $h_{jd}^{(n,n')}$ from the global scale [19], [23]. This prove lays the foundation on why it is necessary to model SCA as a two player submodular game, which will be discussed later.

Corollary 2: In a non-cooperative SCA game, convergence at Nash equilibrium is not certain and guaranteed. Thereore, heurestics remains the only viable option.

Proof: As a result of the discrete strategy searching space of $Z_{j,k}^{(-d)}$, satisfying the neccesary conditions for Nash equlibrium is not guaranteed. As a matter of fact, the proof of NE theorem cannot hold. This proof is consistent with [37].

D. TRUTHFUL D-GRACE SCA LOCAL UPLINK RESOURCE ALLOCATION ALGORITHM

Local SCA are conducted heuristically based on session weights. Session with high weights are regarded as high priority and session with lower weights receive lower priority. For TVBS to make resource allocation, it must solve for $\tilde{Z}_{j,k}^{(-d)}$, $\overset{*}{P}_{j,k}^{(G_{-i},d)}$ and estimate $h_{jd}^{(n,n')}\forall n \in N; n \neq d$, which cannot be estimated accurately. The D-GRACE SCA as described in Algorithm 1, in an attempt to minimize intercelluar interference without coordination.

The implementation chosen herein is a probabilistic version of best-reply dynamics (BRD) [38]. This approach is in contrast to the approach of [3], which relies on measuring aggregate interference $\sum_{k=1}^{K} I_k^{(Aggr)}$ in all the indexed subchanels and thereafter, sort the subchannel interference in decreasing order.

Furthermore, the above technique limits the use of fast schedulers and consequently impacts negatively on real time QoS sensitive applications. TVBS being an intelligent entity should be able to find a good solution by introspection which simply denotes, the ability to have a rough idea of other players choice. In other words, TVBS has to learn the set of resources always in use by other TVBS and tend to avoid such.

Each TVBS updates its channel allocation according to a given probability, ε, which can be set to 50%. Relying on local information, $BS^{(d)}$ selects the least measured $\bar{I}_{j,k}^{(Aggr)}$ from the common shared channel. The allocation process can

TABLE 2. **Truthful D-GRACE local SCA algorithm.**

Algorithm 1 Truthful D-GRACE Local SCA Algorithm

```
Input the vectors of : $Z$, $\varpi$, $J$, $I^{(Aggr,th)}$, $R^{(th)}$
Sort the session sequence weight $\varpi_{(j)}$ in descending order of the array $\mathbf{J}(i)$ $1 \rightarrow J$
set $Z=\{\mathbf{0}\}$    # Initial allocation vector set to zero
$v(0,1)$    # Sample a random number between [0,1] with a probability $\varepsilon$
$R=0$    # To initialize the while loop rate
$\tau=0$    # Initial iteration number
$\varepsilon = 50\%$    # probability range
while $v>\varepsilon$ && $R \le R^{(th)}$
    for $m=1 \rightarrow k'$    # Subset of channels with low interference probability
        for $i=1 \rightarrow J$    # No of active TVBD
            measure $I_{k'}^{(Aggr)}$
            if $I_{k'}^{(Aggr)} \le I_{k'}^{(Aggr,th)}$ do
                Sort channels by increasing value of $I_{k'}^{(Aggr)}$
                $R(i,k')=1$    # The first RB allocation
                Compute D-GRACE TPC Eq. (19)    # Optimal transmit power
                Compute D-GRACE SCA
                    $R(i,k') = R(i,k')\ell\Delta f \log_2\left(1+\gamma(i,k')\right)$
                $\tau=\tau+1$    # Update iteration
                $Z(i,k')=\{1\}$    # First D-GRACE RA
end while
end for
end if
END
```

only converge if the interference is symmetrical, i.e., each TVWS network cell affects the other $n-1$ in exactly the same way. The heuristic solution to the SCA problem is illustrated in Algorithm 1.

E. CHEAT INCLINED SCA AS A SUBMODULAR GAME

It is trivial to show that non-cooperative USFR-URA converges to a unique global solution in a cheat-free scenario. However, such observation is unattainable in a cheat inclined URA game [39]. Motivated by this scenario, the USFR-URA is reformulated as a submodular game. Thus, the URA game is re-casted as a mild form of cooperative game entailing truthfulness. The submodular game forms a special class of form games, in which there is a direct and strong coupling whenever there is a unilateral change in strategy from x to x_i' by the other player resulting in a parallel change in utility.

As stated earlier, the major limitation of heuristic approach to non-coordinated USFR-URA is lack of global channel knowledge. Cheating herein is explicitly defined as a scenario in which any of co-located TVBD uses transmission power other than the optimal D-GRACE power derived via the non-cooperative game. To verify it is a submodular game, some layers of abstractions are needed to faciltate understanding. The purpose of this subsection to provide an abridged version that cheat inclined SCA as a submodular game.

Consider $\Re^K$ consisting of x and y k-dimensional vectors in a two-dimensional Cartesian plane. Define $x \wedge y$ as meet operator and $x \vee y$ as join operator [40]:

$$x \wedge y \equiv \{\min(x_1, y_1), \ldots, \min(x_K, y_K)\}, \qquad (21)$$

$$x \vee y \equiv \{\max(x_1, y_1), \ldots, \max(x_K, y_K)\}, \qquad (22)$$

Let Σ denotes the *sublattice* of $\Re^m$ where $x \in \Sigma$ and $y \in \Sigma$ implies that $x \wedge y \in \Sigma$ and $x \vee y \in \Sigma$. $E(x)$ multi-variable function is supermodular on the occasion that:

$$E(x \wedge y) + E(x \vee y) \ge E(x) + E(y), \qquad (23)$$

There exist a *decreasing differences* in utility function in (G_i, G_{-i}) if:

$$E_i(G_i, G_{-i}) - E_i\left(\tilde{G}_i, G_{-i}\right) \le E_i\left(G_{-i}, \tilde{G}_i\right) - E_i\left(\tilde{G}_i, \tilde{G}_i\right), \qquad (24)$$

when $G_i \ge \tilde{G}_i$ and $G_{-i} \ge \tilde{G}_{-i}$ that implies $x \ge y$. Intuitively, for some $x_{(k)} \ge y_{(k)}$ indexed on some real values of k, then, $x_{(k)} > y_{(k)}$ and true, otherwise. Eq. (24) implies that on the occasion that each entity engages in cheating, the system convergence is perturbed and utility decreases. A *submodular* game is a game where the following conditions stand for each player i adopting similar conditions [40]:

- Σ_i is a sublattice of $\Re^{m_i}$.
- E_i has decreasing differences in (G_i, G_{-i}).
- E_i is a supermodular in G_i.

Observing that (22) and (23) fulfill the criterion for the submodular game and hence, the conditions are proved.

F. GAME DYNAMICS

Game dynamics provides learning platform, in which the players try to understudy how the NE plays out after few iteration. In classical game theory, static games are distinguished from the extensive games based on the fact, *static games* are played once, while *extensive games* are repeatedly played. Phenomena like cooperation, trust, revenge and threats are common denominators of extensive games. For this purpose, it is assumed that, for each TVBS to cooperative with another, trust elements are essential. Adopting Klo's trust model [41] with slight modification, an interference trust model is proposed to motivate rational players to cooperate and act truthfully. The normalized interference trust model is defined as the expected total interference $I_k^{(Total,\exp)}$ that

TABLE 3. **Time based D-GRACE stochastic gradient learning algorithm.**

```
Algorithm 2 Time based D-GRACE Stochastic Gradient Learning Algorithm
Initialize: $\Pi$, step size $\delta$, backoff time $\aleph$, iterations $\tau$,
    $\tilde{I}^{(Total,\exp)}$, $\tilde{I}^{(Act)}$
loop
    set the backoff timer as random timer interval
    repeat
        do the countdown of the backoff timer
        until the backoff timer expires
            for $l = 1 : N$        # No of active TVBS
                for $i = 1$ : iterations (s)
                    $\tilde{I}^{(Total,\exp)}_{(n,\tau+1)} = \tilde{I}^{(Total,\exp)}_{(n,\tau)} - \delta\frac{1}{\Pi}\left(\tilde{I}^{(Act)}_{(n,\tau)} - \tilde{I}^{(Exp)}_{(n,\tau)}\right)$
    if $\aleph \leq$ backoff time
        switch Algorithm 1
            update $\Pi = \Pi + \infty$ ($\infty$ is a positive constant)
                end if
            end for
    end loop
END
```

player i will incur without cheating assuming perfect information and stated as:

$$\Pi = TR_{base} + (1 - TR_{base})\left(1 - \frac{1}{xTf + 1 - Tf}\right), \qquad (25)$$

where TR_{base} denotes the base-level of trust, x is the number of consecutive transaction without cheating and the trust development rate is controlled by parameter Tf. The final outcome of (25) is in the range of [0, 1]. The TVBS must acquire the expected interference, $\tilde{I}^{(Exp)}$ for each sub-channel, k, for each TVBD, J, during wireless communication intialization phase. It is assumed that there exist a marginal difference between the actual interference $\tilde{I}^{(Act)}$. The normalized interference trust model helps the TVBS to either cooperate or not.

In the case that TVBS G_i experiences high amount of total interference and the expected rate, $\overset{*}{R}_{(j,k)}$ of TVBD, j, sub-channel K within a time span while cooperating with TVWS G_{-i}, G_i's trust towards G_{-i} will be reduced. In the case that the trust drops below TR_{thres}, G_i will transact with G_{-i} with a lower trust and otherwise. Based on this, *time based D-GRACE* is proposed exploiting on stochastic gradient descent learning in Algorithm 2. Algorithm 2 is the practical implementation of *Better-Reply Dynamics* (BRD) and *Weak Finite Improvement Property* (Weak-FIP), which drives submodular games into convergence. BRD requires a player at each stage of the repeated game to revise its current strategy. Precisely, if player's revised strategy yields better utility, then, that strategy is adopted on the condition that it is a *better reply*. This is implemented via the update mechanism in Algorithm 2. Similarly, *Weak Finite Improvement Property* drives super modular games to converge under a partial strategy Nash equilibrium. Nash equilibrium denotes system stability and stability improves on a gradual basis depending on system component behaviour.

TABLE 4. **Simulation Parameters.**

Symbol	Value
Δf	180 kHz
ε	50%
η	4 dB
m	magnetic moment
Coding rate	5/6
Modulation scheme	64-QAM
Channel Model	Raleigh

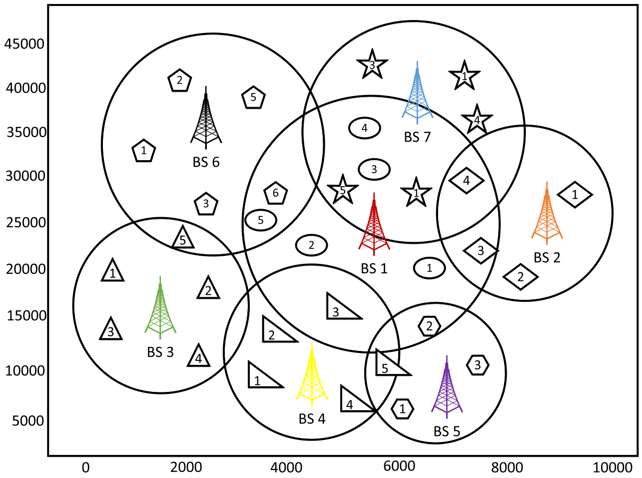

FIGURE 3. **Seven TVWS cell simulation scenario with the TVBS centered at the cell center and other shapes are denoting TVBD. The XY coordinates are all in meters.**

V. SIMULATION RESULTS

In this section, the proposed *D-GRACE* algorithm is analyzed adopting similar topology and parameters of [3] as indicated in Figure 3 and Table 4 respectively with slight modification. The purpose is to compare the performance of both algorithms under similar conditions. Note, [3] is considered as *exclusive spectrum sharing model* which implies there is no channel sharing techniques and TVBD transmit without considering spectrum mask power. The set up consists of seven TVWS network cells driven by discounted spectrum price to solve the issue of self-coexistence. The average cell radius is 11 km. Each of the TVBS controls its cell and direct inter-cell coordination among the different TVBS are feasible. In each TVWS cell n, $J^{(n)}$ several uplink sessions are randomly placed in the TVWS cell. The different session weights definitions were evaluated.

A. SIMULATION SETTINGS

See Figure 3.

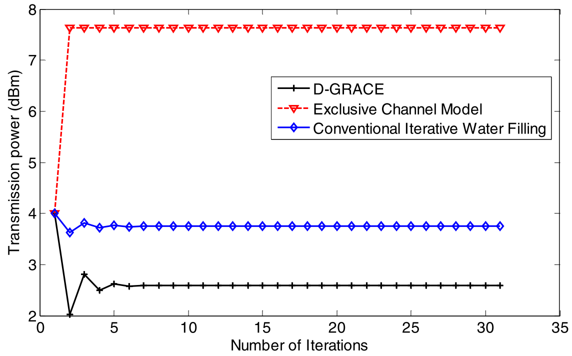

FIGURE 4. Comparison on transmission power iteration convergence.

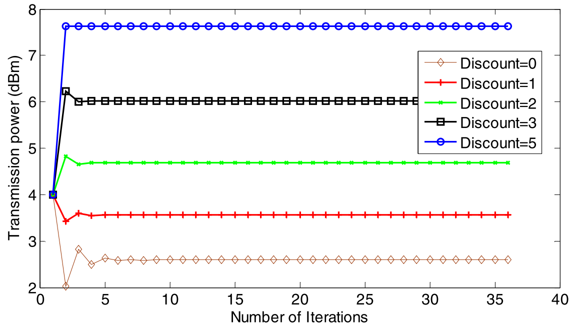

FIGURE 5. The impact of discount on speed of convergence.

B. PERFORMANCE ANALYSIS AND COMPARISON

Figure 4 and 5 are based on (20) and investigate the impact of convergence speed based on a single user model among the seven TVWS cell scenario. The speed of convergence is crucial in iterative systems. The reason being that, the faster it takes for the algorithm to converge, the more stable the system. In the context of resource allocation, the TVBD can only transmit when the TVBS has resolved the power allocation algorithm. D-GRACE is compared with exclusive channel sharing model [3] and conventional iterative water filling algorithm. Evidently, exclusive channel sharing model takes few number of iterations to converge when compared to the D-GRACE. The reason being that, in exclusive there is no need for control overhead and the TVBS considers only the impact of active TVBD under its control.

This is in contrast to D-GRACE which utilizes some resources to understand the dynamics of other rational TVBS before signaling transmitting power parameters to the TVBDs. On the other hand, D-GRACE is transmitting power efficiently, as could be seen from Figure 4. The exclusive algorithm settles with transmit power value of 7.5 dBm, conventional iterative water filling algorithm transmit power is about 3.8 dBm, which is around 20 % lower than an exclusive algorithm and D-GRACE consuming only 50% of the total power utilized by the exclusive algorithm. This implies that D-GRACE is more energy efficient than its counterpart algorithms. In effect, there is a tradeoff between final power and number of iterations.

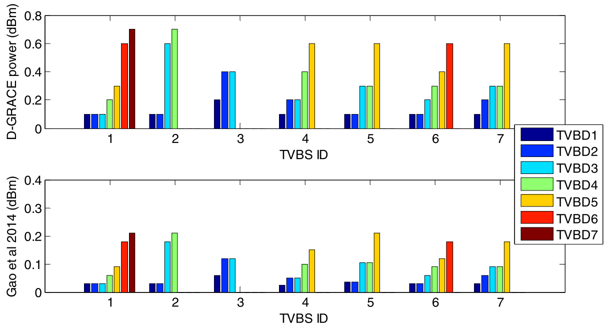

FIGURE 6. TVBS priority scheduling based on weight.

Figure 5 studies the effect of reducing the discount parameter. The discount parameter implies power reduction resulting from channel sharing. It is seen as the discount parameter is reduced, the D-GRACE reduces to exclusive channel sharing convergence model.

As the discount parameter reduces, the transmission power increases from 2 dBm when the discount value is 4 to 8 dBm in the case of no discount. In other words, discount parameter and transmission power are inversely correlated. The maximum transmission power recommended by the FCC for mobile TVBD is 20 dBm.

It is important for TVBS to determine its outage probability before engaging in spectrum sharing. In this case, the outage probability is characterized by the CDF of the SINR defined as:

$$P_{OUT}\left(\gamma_{j,k}^{d,th}, \tau_m\right) = \Pr\left[SINR^{(d)} \le \gamma_{j,k}^{d,th}, \tau_{out} > \tau_m\right], \tag{26}$$

where τ_{out} is the outage duration and τ_m is minimum outage duration. Figure 6 is based on (10). In resource constraint wireless communication environment, scheduling is adopted to maximize system throughput taken into account fairness. The USFR relies on priority based scheduling to allocate transmission power considering the channel gain. The priority based scheduling aims to maximize the raw system data rate of the cell edge users such that, there is no starvation of TVBDs leading to intra system fairness. Though, there are several fairness schemes that can be considered such as: minimum rate, proportional fair factor, utility-based per-user throughput. In this study, distance-based priority scheduling is the most appropriate technique because it considers channel gain and inter-channel interference. The channel gain is attributed to the distance between the TVBD and the TVBS. As could be seen, both D-GRACE and exclusive model adopt same priority based scheduling.

D-GRACE transmission power is considerably lower than that of the exclusive model. Obviously, the reason being the discount parameter. It is expected that all the other TVBS cells will adopt same scheduling strategy for the overall system network capacity improvement. The different color bars indicate the seven TVBS as earlier highlighted.

Figure 7 compares the data rate of the various resource allocation approaches and it is taken from (2). The highest

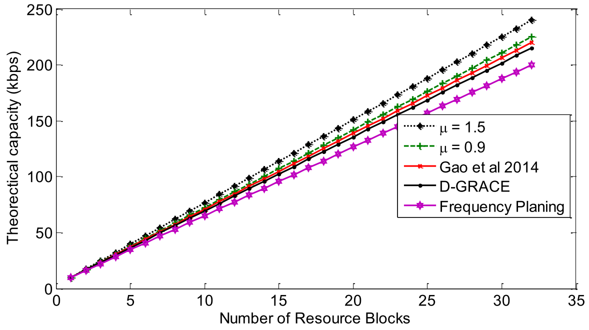

FIGURE 7. **Data rate comparison between different proposals.**

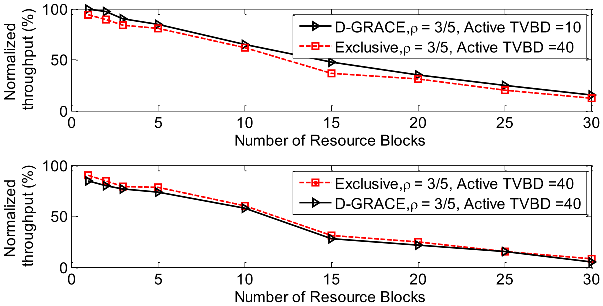

FIGURE 8. **Throughput comparison between D-GRACE and exclusive model.**

data rate was achieved during imperfect channel estimate approach. Invariably, wrong channel state information introduces marginal error and leading to the false data rate. Nonetheless, all the approaches can support the basic IEEE 802.22 proposed spectral efficiency of 0.624 bits/s/Hz - 3.12 bits/s/Hz. The proposal of [3] slightly outperforms D-GRACE because the former does not support spectrum sharing techniques. Hence, the data rate is higher as more transmission power is utilized. Evidently, there is a trade-off to be made either to use higher transmission power to achieve higher data rate or engage in spectrum sharing relying on intrinsic spectrum scheduling technique.

Figure 8 compares the throughput of the proposed D-GRACE and exclusive channel model under some parameters such as: active TVBD, deployment and spectrum sharing based on (3). It is seen that, when the number of active TVBD is less, D-GRACE outperforms exclusive channel model in terms of the throughput in percentage. However, when the number of active TVBD increases, D-GRACE throughput percentage decreases. The analysis tends to support the notion that during low traffic load demand, there is a need for TVWS operators to engage in spectrum sharing more especially in the rural areas where there are fewer mobile users per density. Furthermore, the TVBS can as well engage in application based resource allocation strategy during high spectrum demand as a strategy to reduce the outage probability. For instance, the non QoS sensitive application such as: Non-Real-Time Polling Service (nrtPS), Best Effort (BE) can be scheduled later and real time QoS applications which include: Unsolicited Grant Service (UGS), Real-Time Polling Service (rtPS) are scheduled first. The impact of Raleigh fading and log-normal shadowing is analyzed in Figure 9 and 10 respectively. The graphs are stimulated based on (1).

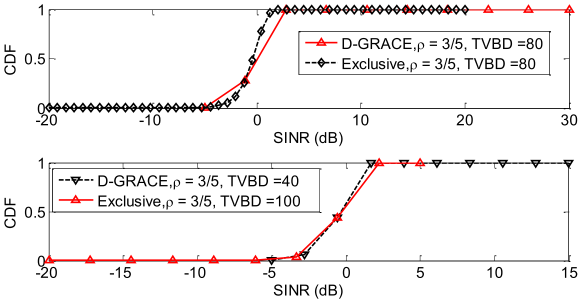

FIGURE 9. **Outage probability between D-GRACE and exclusive in Raleigh fading.**

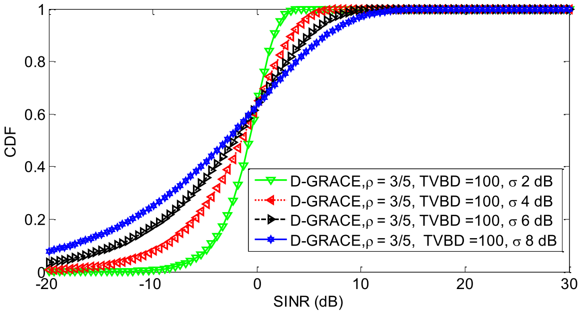

FIGURE 10. **Outage probability comparison based on different shadowing values.**

Raleigh fading is more pronounced in rural area because of the terrain profile characterized by the presence of jungles, big trees, mountains and valleys.

From Figure 9, it is seen that D-GRACE suffers higher outage probability than the exclusive model when both have same number of active TVBD in Raleigh fading environment. This is as a result of lower SINR of the active TVBD. On the contrary, when the number of active TVBD is lower, D-GRACE outperforms the exclusive model.This implies there is signal degradation as more and more active TVBDs are admitted. A useful strategy can be the use of admission control policy which ensures the minimum base data rate is constantly maintained. As could be seen in Figure 10, the log-normal cdf is a very good approximation to the empirical cdf of the outage probability. Evidently, as the shadowing increases from 2 dB to 8 dB, the outage increases from the mean. In overall, channel sharing must take into account the impact of shadowing and terrain profile to reduce the outage probability of the TVBD.

Figure 11 is based on (15) and it illustrates the financial benefits in theory that TVBS operators stand to gain by engaging in spectrum sharing. The discounted spectrum price paradigm has both economic and technical connotation. From the economic perspective, $p^{bid}_{(j,k)}$ connotes the bid price that TVBD pays through the TVWS operator for temporary leasing that spectrum at a time instant. For instance, let 20 USD be the cost that PU charges the TVWS network operators for leasing 1 RB. To motivate intense spectrum reuse, the PU may offer discount, $\diamondsuit_{(j,k)}$.

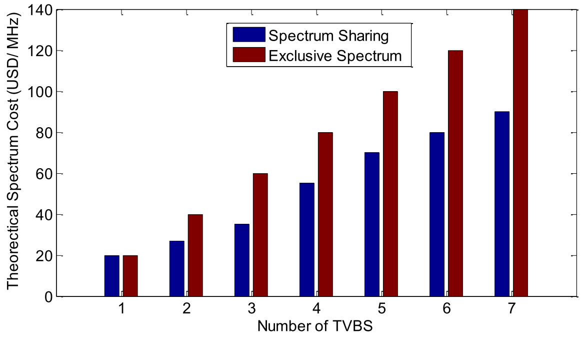

FIGURE 11. Theoretical spectrum costing between exclusive and spectrum sharing.

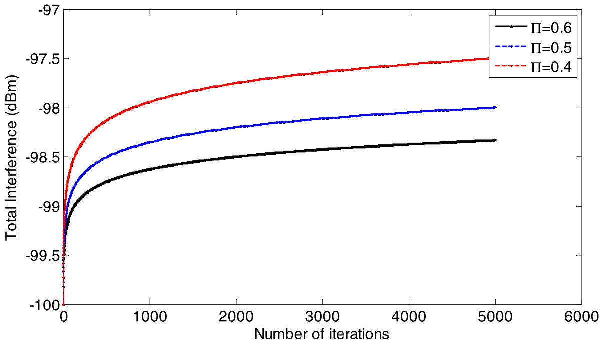

FIGURE 12. Time Based D-GRACE stochastic gradient descent learning.

Following the same line of argument, if two or more TVBS want to use the same subchannel, instead of them to paying full amount which is theoretically stated as 20 USD, they will receive 5 USD discount. In this graph, the pricing template of [10] which is a good approximation technique on how to implement the reduced cost per user problem in wireless communication [31]. As could be seen, there is 10 % reduction in spectrum price as the number of TVBS sharing the same spectrum increases. Based on the fact that IEEE 802.22 was specifically designed for the rural areas with low financial capability, this analysis will help to simulate spectrum sharing among the different TVBS operators.

It is expected that market driven spectrum sharing will usher in the new era of last mile broadband connectivity to the rural areas and hard to reach terrains. Recall that D-GRACE power solution was formulated based on the premise that players would act truthfully. It is equally possible that entities might engage in acts of cheating by deviating from the commonly agreed D-GRACE power solution. Hence, strategies must evolve to prevent this. In this case, each player may decide to dedicate some section of the superframe to monitor the behaviour of other players. Thus, leading to time based D-GRACE stochastic gradient descent learning algorithm. If within the time window, the interference lies within the expected level, the player knows that the other player is acting truthfully and otherwise. As could be seen from Figure 5.13, it is evidently clear that as the trust value increases, the measured instantaneous total interference drops. It is seen that as the trust value increases, the player experienced interference decreases and vice versa.

VI. CONCLUSIONS

In this work, D-GRACE, a dynamic transmission power solution was analyzed. The solution was analyzed from two perspectives which is: cheat-free (the ideal case) and involves cheating tendencies (the worst case). In a cheat-free scenario, each of the player transmits using the derived optimal D-GRACE transmit power solution and there is no need to implement the time-based D-GRACE. While in the cheating scenario, each player adopts a time-based D-GRACE transmit power strategy. In time-based D-GRACE transmit power solution, the player dedicates some of the slot time to underscore the total instantaneous interference. In conclusion, D-GRACE highlights the dual benefits engaging in dynamic spectrum sharing in a TVWS environment characterized by low active TVBD which are power savings and financial benefits.

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