12-7-2018

A Hierarchical Spectrum Access Scheme for TV White Space Coexistence in Hetergeneous Networks

Mohammad Zaeri-Amirani
Northern Arizona University

Fatemeh Afghah
Northern Arizona University

Sherali Zeadally
University of Kentucky, szeadally@uky.edu

Repository Citation

Zaeri-Amirani, Mohammad; Afghah, Fatemeh; and Zeadally, Sherali, "A Hierarchical Spectrum Access Scheme for TV White Space Coexistence in Hetergeneous Networks" (2018). *Information Science Faculty Publications*. 52.
https://uknowledge.uky.edu/slis_facpub/52

A Hierarchical Spectrum Access Scheme for TV White Space Coexistence in Hetergeneous Networks

Digital Object Identifier (DOI)
https://doi.org/10.1109/ACCESS.2018.2885732

Notes/Citation Information
Published in *IEEE Access*, v. 6, p. 78992-79004.

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 12, 2018, accepted December 2, 2018, date of publication December 7, 2018,
date of current version December 31, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2885732

A Hierarchical Spectrum Access Scheme for TV White Space Coexistence in Heterogeneous Networks

**MOHAMMAD ZAERI-AMIRANI[1], (Student Member, IEEE),
FATEMEH AFGHAH[1], (Member, IEEE),
AND SHERALI ZEADALLY[2], (Senior Member, IEEE)**
[1]School of Informatics, Computing and Cyber Systems, Northern Arizona University, Flagstaff, AZ 86011, USA
[2]College of Communication and Information, University of Kentucky, Lexington, KY 40506, USA

Corresponding author: Fatemeh Afghah (fatemeh.afghah@nau.edu)

ABSTRACT Among current techniques for dynamic access to television (TV) white space (TVWS), geolocation database-based access provides a promising performance in protecting the TV-band incumbents from interference that cannot be efficiently achieved in other license-exempt models. However, in heterogeneous wireless networks, most portable devices do not have such access and may cause interference to TV incumbents. We propose a hierarchical model for spectrum sharing in TVWS that includes a wide range of fixed and portable devices. In the first tier, the TV broadcaster can lease the spectrum bands to local fixed users based on a soft license agreement. The fixed users are allowed to share access to this spectrum with some mobile users in their proximity in exchange for cooperative relaying. We consider a practical scenario, where only partial channel state information (CSI) is available at the users' transmitters, and we propose a robust algorithm against such uncertainties in CSI values. We also propose a reputation-based relay selection mechanism to identify selfish portable users. The proposed spectrum sharing framework can provide a practical model for TVWS-coexistence that prevents undesired interference to the incumbents while restricting interference among the unlicensed devices. The simulation results show the enhancement of fixed users' rate compared with alternative relay selection methods.

INDEX TERMS Cooperative relaying, reputation, soft-license spectrum sharing, Stackelberg game, imperfect channel state information, TV white space.

I. INTRODUCTION

Due to the ever-growing number of wireless users and the emerging interest in multi-media services, the radio spectrum scarcity has become one of the significant bottlenecks in wireless communication technology. However, recent federal communications commission (FCC's) reports revealed that despite the rapidly developing demand for spectrum access, the assigned licensed spectrum bands including the TV broadcasting bands are not efficiently utilized at certain times and locations [1]–[4]. While a considerable portion of very high frequency (VHF) and ultra high frequency (UHF) radio spectrum is allocated to the broadcast television services, the TV stations (primary network) may not use many channels in different geographic areas due to the chance of causing co-channel interference or interference with adjacent TV stations. This suggests that the unlicensed cognitive devices (secondary users) could operate in such vacant spectrum bands called as TV White Space (TVWS) if they assure causing no interference to the incumbents [5]–[9]. Therefore, the opportunistic access to TVWS can provide affordable spectrum access for several indoor and outdoor communication systems such as rural broadband, home networking and device to device communication through an efficient radio spectrum utilization. Furthermore, this opportunistic access can lead to lower energy consumption and better propagation characteristic with a lower penetration loss for cognitive unlicensed users by allowing them to operate in low-frequency TV bands compared to industrial, scientific, and medical radio (ISM) bands, particularly for indoor applications [10]–[12].

One of the key challenges in the widespread implementation of dynamic spectrum sharing mechanisms in TVWS is managing the severe interference caused by the excellent propagation characteristics over the TV bands. To do so, we need effective mechanisms to protect both legitimate incumbents and the cognitive users from various sources of interference. Most current technical and regulatory radio spectrum sharing approaches focus on protecting the incumbents from the interference caused by the unlicensed users. These approaches can be generally classified into two categories of i) *preventive mechanisms*, and ii) *punitive mechanisms* [13]. The goal of preventive mechanisms is to reduce the probability of harmful interference to the primary users [14], [15]. This can be achieved by determining spatial separation regions around the incumbents (exclusion zones), and enforcing reasonable sensing thresholds on the spectrum sensing approaches [15]–[19]. In punitive approaches, the selfish and malicious unlicensed users are identified and adjudicated based on the level of interference they cause [20]–[24].

To protect the heterogeneous unlicensed devices operating in TVWS, several factors including the diverse characteristics with regard to device types, different communication protocols, and network architectures should be taken into consideration [25]–[29]. In terms of the device categories for access to TVWS, the cognitive users can either act independently and attempt to access the spectrum by sensing the holes in TV bands, or they need to have direct or indirect access to TV databases. Spectrum sensing methods consume a lot of power at the device and often show a poor detection performance in low signal to noise ratio (SNR) regions [30]–[32]. Therefore, the geolocation-based approach or a combination of geo-location-based and spectrum sensing techniques are commonly adopted for spectrum sharing in TVWS [33], [34]. In this method, certain information (such as their frequency, schedule, location, transmitted power, and antenna pattern) about the primary users is made available to the certified cognitive users [35], [36]. This technique is mostly utilized by fixed cognitive users with geolocation capability who can report their locations to a centralized server. The cognitive users utilize this information to estimate the coverage area and availability of the incumbents at their locations. The users that do not have direct access to these TV bands databases can be enabled by authorized master devices.

The majority of existing technical and regulatory recommendations are for coexistence in TVWS and they are based on the model of *license-exempt* wherein the unlicensed users can attempt to access the TVWS while protecting the incumbents' rights [19], [25], [37], [38]. However, several issues related to QoS for unlicensed white space users, interference to other unlicensed users, fairness among these heterogeneous devices, delay, and efficiency of spectrum usage still need further investigation. A regulatory model called *soft-license* is proposed in [39] to provide an access scheme between the two cases of exclusive-license and license-exempt models. This model can provide limited regional-based or temporal-based access for the users that need a higher level of certainty and priority in spectrum access. Suitable candidates for this access category includes the rural broadband services and delay-sensitive services. This regulatory model is based on a hierarchical structure consisting of primary licensed users, protected secondary services (soft-license users) with granted restricted access, and unprotected secondary services (license-exempt users) [39]–[41].

Motivated by this regulatory model, here we propose a hierarchical model for spectrum sharing in TVWS to enable interference-free coexistence among heterogeneous unlicensed networks. In this model, the protected secondary devices which have granted spectrum access through soft license [39], exclusive access by paying the regression fee [42], or an auction-based mechanism [43] can lease their reserved spectrum to unprotected/unregistered secondary services in exchange for cooperative relaying. This model can support the coexistence of a wide range of secondary services that enforces a faithful behavior to the unlicensed users through a reputation-based Stackelberg game theoretic model.

The rest of this paper is organized as follows. In Section II, we present a survey of some recent works on using game theory for spectrum sharing in TVWS followed by the contributions of this paper. The proposed hierarchical spectrum sharing framework is described in Section III. In Section IV, we present a brief overview of the Stackelgberg games. Section V describes our proposed Stackelberg game model for spectrum access. We present a performance evaluation of our proposed method in Section VI followed by our concluding remarks in Section VII.

II. RELATED WORKS

In this section, we present a brief survey on recent applications of game theory in addressing challenges related to coexistence and interference management in TVWS [42], [44], [45].

Based on the fact that many unlicensed devices do not have geo-location capability or access to TV band databases, several hierarchical access mechanisms have been previously proposed to provide spectrum access to a wide range of unlicensed devices. Inspired by the WiFi architecture, an infrastructure-based model for access to white space is proposed in [46], where access of unlicensed devices is enabled via multiple secondary access points (AP)s that have access to the databases. Two distributed game theoretic models were presented to find the optimal solutions for channel selection among the APs, and allocating the secondary devices to the proper APs. The objective of the latter game model is to provide a balanced distribution of the secondary users among the proximity APs while avoiding frequent switching of secondary users by considering the cost of mobility.

In [44], a TVWS ecosystem is defined that includes several parties such as licensees (TV broadcaster), databases, secondary operators, and end-users. An example of the secondary operators can be an infrastructure-based device owned by a secondary operator which provides a wireless service to several end-users or devices. This paper considers the competition among the secondary users from the same pool of end users who are attracted to buy the service from the operators. The operators need to estimate the required dedicated spectrum considering the uncertainty of end users' demand, and determine a competitive price for providing service to the end users noting the potential price offered by other operators. This competition is modeled as a non-cooperative price-quantity competition game. A hybrid pricing framework for spectrum access in geolocation database-based model is proposed in [47], where the owner of the database has the authority to distribute the available TVWS bands to the applicants based on a hybrid registration and service plan pricing scheme. It is assumed that by utilizing a soft-license approach, the white space devices can reserve a part of the TV bandwidth during the registration scheme, while in the service plan scheme, these devices make instant queries to use the spectrum. A non-cooperative game is utilized to model the users' choices of spectrum access based on the bandwidth reservation, registration fee and query plans.

A. PROPOSED WORK

In this work, we propose a hierarchical spectrum access solution for heterogeneous networks of unlicensed users to access TV white space. The FCC regulations categorize the TVWS applicants into users with fixed devices (FD) and users with portable devices (PD) [6], [7], [48]. The FDs use outdoor antenna and operate in specific registered locations. These devices have geolocation awareness as well as access to the TVWS database. The portable or personal devices are divided into two types of: 1) Mode I, and 2) Mode II. Mode I devices are not aware of their geolocation and do not have access to the database. Users with Mode I devices are controlled by Mode II devices, which have geolocation capability and have direct or indirect access to the TV band databases. The last category of white space devices is sensing-only devices. These devices do not have any type of access to the TVWS database and can only sense the spectrum to obtain access [48]. Many efforts and updates on several standards such as IEEE 802.11, 802.22, 802.15, 802.19.1, 1900.6, ECMA 392 and DySPAN SC have been developed in response to these regulations [49], [50].

In this work, we consider a set of unlicensed users including an arbitrary number of users with FD who have access to geolocation databases, and users with PD who may be temporarily located in the proximity of a TV broadcaster. The purpose of our proposed model is to provide a distributed spectrum access mechanism for both users with access to geolocation databases as well as mobile users that may not have access to geolocation databases or afford to pay the required monetary amount to the TV network. In this model, the registered FDs act as retailers and can re-assign a portion of their allocated spectrum to the users with PD in exchange for relaying services. Therefore, the TV broadcaster can benefit from only interacting with local certified users whom it can monitor their loyalty to pay the spectrum price or their behavior in terms of imposing any undesired interference, while such a secure interaction with mobile users is not necessarily feasible because of the risk of the presence of malicious and selfish users.

Most current technical and regulatory studies on dynamic spectrum management in TVWS rely on the assumption that the secondary users are trustable to follow the access rules since they are certified by authorities before deployment. However, this assumption can be easily violated by selfish users over the runtime, when they compete over the limited TVWS or even to access the geolocation databases. Examples of such behaviors include imposing harmful interference to the spectrum owner, or refusing to pay the monetary value or the cooperative services the secondary users initially agreed to provide when granted spectrum access. This in turn calls for reliable enforcement mechanisms to monitor the users' behavior [51], [52]. Utilizing reputation-based mechanisms is one way for the spectrum owner or the authority in-charge to monitor the behavior of the unlicensed users in order to differentiate between the users with selfish behaviors and the ones with a higher level of reliability [20], [21], [24]. In this approach, observing the reputation of secondary users can encourage them to maintain a high reputation to have the chance of being trusted by the spectrum owner. The level of harmful interference, reporting false information in cooperative sensing model, the level of cooperation in providing relaying services, or the monetary payment history are examples of reputation metrics for secondary users. The reputation of secondary users can be directly observed by the TVWS owners or via a trusted group of unlicensed TV band users (retailers or registered secondary users). In this paper, we develop a localized reputation-based cooperative spectrum leasing mechanism in which the registered secondary users (i.e., the users with FD) can independently monitor the record of the licensed-exempt secondary users (i.e., the users with PD) during the course of their interactions without relying on reputation inquiries from a central unit in the network. Therefore, this method can be implemented in distributed manner. In this model, the reputation of each user is monitored based on effective cooperative power from each selected user with PD, which is the multiplication of the power by the squared absolute CSI of the corresponding channel. Therefore, the user with FD can monitor the reputations using maximum beam combinations techniques rather than relying on other users' self-reports. It is worth mentioning that compared to the trust mechanisms wherein the users self-report their reputation, the proposed method is robust against false reports disclosed by malicious unlicensed users. Moreover, the self-report reputation methods incur high signaling overheads in large-scale networks in order to enable the unlicensed users to report their reputations. In contrast, in our method the users with FD can locally monitor the reputations of the users with PD. Since a large number of unlicensed users with PD applicants are expected to use the TVWS and given the high mobility of such users, the proposed reputation-based mechanism can provide a practical solution for hierarchical spectrum sharing in TVWS to avoid causing a heavy signaling load on the TV band users and prevent false self-reports.

Another important challenge in coexistence of heterogeneous communication networks is that the perfect channel state information (CSI) of the communication links is not usually available. This could be due to the lack of cooperation between these different networks, or the time delays or frequency offsets between the reciprocal channels as well as inaccuracy of the utilized channel estimation techniques [53]. One way of dealing with imperfect CSI to model the uncertainty in the CSI knowledge as an absolute bounded error and design the system in such a way that is robust against these uncertainties [53]–[55]. In this work, we also considered a practical scenario where the perfect CSI of communication channels is not available and we developed a spectrum sharing mechanism that is robust against these uncertainties.

We should also note that the existing Stackelberg game-theoretic models for time division of spectrum access between the licensed and unlicensed users, the leader's transmission power is assumed to be constant and the algorithms only focus on the time allocation among the users [20], [24], [56]. However, in this paper, we propose a joint optimization problem to optimize the leader's power and the time-allocation for spectrum access and we show that the optimization is equivalent to a convex optimization problem. As a result, we provide a constructive approach of solving the problem that guarantees the uniqueness and convergence of the game solution.

In summary, the key contributions of our proposed model include:

- The proposed hierarchical spectrum sharing model provides an interference-free spectrum sharing framework among the TV broadcasters and a wide set of different types of unlicensed devices defined in FCC regulations.
- To enhance the network performance and protect the network from potential selfish behavior of unlicensed mobile users, we propose a reputation-based game theoretic model to enable the users with FD to observe the behavior of available users with portable PD over the course of time. The best PD candidates for cooperative service are identified by noting their cooperative reputations as well as their channel quality.
- In contrast to the majority of previously proposed solutions which assume a global knowledge of CSI to be available, this model considers uncertainty in estimating the channel state information.

III. SYSTEM MODEL

Let TVB denote a given TV broadcaster which covers a certain geographical region, as depicted in Fig. 1. Several local certified users with FD such as fixed users in rural areas supported by broadband networks also exist in each region, which have geolocation awareness and can obtain the TVWS access on a soft-license agreement or in exchange for monetary benefits. We assume that TVB leases separate frequency bands to these FDs. Hence, we can divide the TVB neighborhood into small sections, each consisting of a single FD. Let FT and FR denote the fixed device's transmitter and receiver located in a given region, respectively. There are several users with PD in this region that may not have access to geolocation databases. The transmitter and receiver associated with the j^{th} user with PD for $j = 1, \ldots, N_P$ are denoted by PT_j and PR_j, respectively.

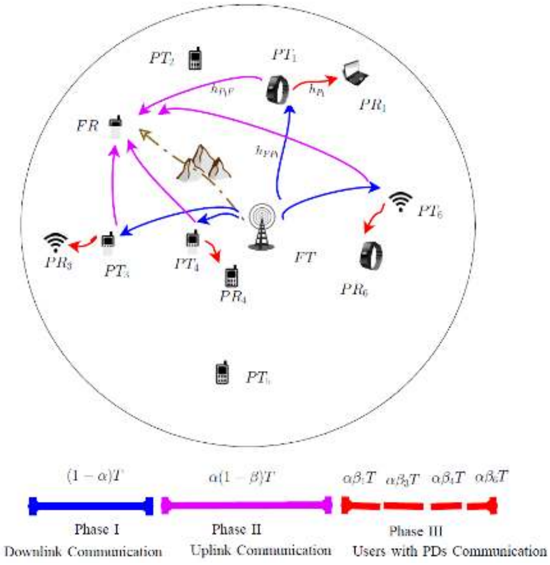

FIGURE 1. An example system model for one section in a TVB region that includes one fixed user and six users with PD. The border of such a section is displayed with a black circle. Four out of these six users with PD devices cooperate with the FD to relay its message. In Phase I, the *FT* broadcasts its message. During Phase II, the selected users with PD forward the FT's message after decoding, and as a reward, in Phase III they transmit their own messages to their corresponding destinations using a time-division access method.

Slow Rayleigh fading channels are assumed, where the channel coefficients remain constant over one time-slot. The complex-valued reciprocal channel coefficients are defined as h_{P_j}, h_{FP_j}, and h_{P_jF} which are the channel coefficients between the transmitter and receiver of the user j with PD, between FT and PT_j, and between PT_j and FR, respectively. It is assumed that a direct link between the FT and FR does not exist due to shadowing. Since the fixed and portable devices belong to different networks, the availability of global CSI is not a reasonable assumption as the standard channel estimation techniques can only estimate an imperfect CSI in such a dynamic and mobile network. Therefore, we assume that there is an uncertainty in CSI estimation where the estimation errors are bounded. Mathematically, this assumption can be expressed as:

$$
\begin{aligned}
h_{P_j} &= \hat{h}_{P_j} + \nabla h_{P_j}, \quad |\nabla h_{P_j}| \leq \epsilon_{P_j} \\
h_{FP_j} &= \hat{h}_{FP_j} + \nabla h_{FP_j}, \quad |\nabla h_{FP_j}| \leq \epsilon_{FP_j} \\
h_{P_jF} &= \hat{h}_{P_jF} + \nabla h_{P_jF}, \quad |\nabla h_{P_jF}| \leq \epsilon_{P_jF}. \qquad (1)
\end{aligned}
$$

where $\hat{h}_{P_j}$, $\hat{h}_{FP_j}$, and $\hat{h}_{P_jF}$ refer to estimated channel coefficients between the transmitter and receiver of the user j with PD, between FT and PT$_j$, and between PT$_j$ and FR, respectively. The notations ϵ_{P_j}, ϵ_{FP_j}, and ϵ_{P_jF} denote the maximum absolute error to estimate channel coefficients between the transmitter and the receiver of the user j with PD, between FT and PT$_j$, and between PT$_j$ and FR, respectively. Also we define the uncertainty regions in CSI estimation by:

$$\Psi = \Big\{\forall\ \nabla h_{P_j}, \nabla h_{FP_j}, \nabla h_{P_jF}\ | \\ |\nabla h_{P_j}| \le \epsilon_{P_j}, |\nabla h_{FP_j}| \le \epsilon_{FP_j}, |\nabla h_{P_jF}| \le \epsilon_{P_jF}\Big\}. \quad (2)$$

The single-sided spectral density of independent Additive White Gaussian Noise (AWGN) at the FD's receiver and the PDs' receivers is shown by N_0. The maximum available power at FT is denoted by P_F and maximum available energy at j^{th} user with PD is shown by $E_j^{\max}$. The notations P_{jc} and P_j denote the power allocated to cooperation and individual transmission of user j with a portable device. To avoid co-channel interference to users in nearby sections and to consider the physical limitation of the devices, the transmission powers P_F, P_j, and P_{jc} are limited by the values P_F^{max}, P_j^{max}, and P_{jc}^{max}, respectively.

During each time-slot, T, the FD willingly allocates a portion of its own access to the leased spectrum to selected PDs in exchange for relaying service. Section V describes the corresponding relay selection criterion. The Decode-and-Forward (DF) relaying method is employed at the PDs, where the fully decoded message received from FT is forwarded to FR. Each time-slot T is divided into the following three phases:

- *Phase I*: only the fixed user transmits for $(1-\alpha)T$ seconds, $(0 \le \alpha \le 1)$;
- *Phase II*: the selected PDs relay the FD data to its corresponding receiver for $\alpha(1-\beta)T$ seconds, $(0 \le \beta \le 1)$;
- *Phase III*: the selected PDs transmit their data for $\alpha\beta T$ seconds based on a time division multiple access technique.

For the sake of simplicity, we assume $T = 1$.

In Table 1, the notations used throughout the paper are summarized.

IV. OVERVIEW ON STACKELBERG GAMES

Stackelberg game is a category of non-cooperative strategic games, in which the players take their actions sequentially rather than simultaneously. In Stackelberg games, one of the players called *leader* has a higher priority in decision making and can declare his/her strategy first. Then, the lower priority users called *followers* rationally react to the leader's strategy [57], [58].

Let us define $\mathcal{A}_1$, and $\mathcal{A}_2$ as the action set of the leader, and the follower in a single-leader single-follower Stackelberg game, respectively. In this game, the follower selects an action from its action set $\mathcal{A}_2$, after observing the leader's choice. The *Stackelberg equilibrium solution* can be obtained by locating the best strategy of the leader taking into account that the followers are rational and will select their optimal strategy knowing the leader's strategies. The Stackelberg equilibrium solution can be calculated using the following optimization problem,

TABLE 1. Summary of the notations.

Notation	Definition
FD	user with fixed device
PD	user with portable device
$FT(FR)$	transmitter (receiver) user with FD
$PT_j(PR_j)$	j^{th} transmitter (receiver) user with PD
h_{P_j}	reciprocal channel coefficients between PT_j and PR_j
h_{FP_j}	reciprocal channel coefficients between FT and PT_j
h_{P_jF}	reciprocal channel coefficients between PT_j and FR
$\hat{h}$	estimation of the channel coefficient h
ϵ_{P_j}	maximum absolute channel estimation error of $\hat{h}_{P_j}$
ϵ_{FP_j}	maximum absolute channel estimation error of $\hat{h}_{FP_j}$
ϵ_{P_jF}	maximum absolute channel estimation error of $\hat{h}_{P_jF}$
Ψ	uncertainty regions in CSI estimations
P_F	maximum available power at FD
$E_j^{\max}$	maximum available energy at PT_j
P_{jc}	power allocated to cooperation by PT_j
P_j	power allocated to individual transmission by PT_j

$$\max_{(a_1,a_2)\in(\mathcal{A}_1\times\mathcal{A}_2)} \quad U_1(a_1,a_2) \\ \text{Subject To: } a_2 \in \operatorname*{argmax}_{a_2'\in\mathcal{A}_2} U_2(a_1,a_2'), \quad (3)$$

where U_1 and U_2 are the utility functions of leader and follower, respectively. Compared to a game with simultaneous moves (*Cournot games*), in Stackelberg games, the leader always obtains a better payoff, since it knows that the follower plays its best response in order to get at least the simultaneous action's payoff by choosing the Cournot game strategy [59].

V. PROPOSED REPUTATION-BASED STACKELBERG GAME MODEL

The interactions among the users in this spectrum sharing scenario is modeled with a Stackelberg game, in which the FD as the owner of the leased spectrum is the game leader and the users with PD are the followers. The rationale behind selecting this model is that in Stackelberg games, the leader has the right to state its strategy first, then the followers rationally respond to the leader's strategy. Thus, the fixed user (game leader) can enforce its strategy on the followers. In our proposed model, the strategy of the FD includes: i) selecting the best K users with portable devices for the relaying service, ii) selecting its optimal transmission power, P_F, and iii) choosing the best time allocation parameters (α and β) to divide each time-slot of spectrum access among its own transmission, cooperative relaying and individual transmission for PDs. The strategy set of followers includes allocating the optimum transmission powers to their own transmission and cooperation.

Among the users with portable devices, there may exist selfish users who decline to forward the received message from the fixed user, or only assign a small portion of their available power to this cooperation after being granted with the spectrum access. Spectrum leasing to such selfish behavior can significantly degrade the performance of FD's communication due to unavailability of direct transmission link. In our proposed model, the cooperative behavior of users with PDs is observed over the course of time by defining a cumulative reputation factor that enables the fixed user to identify and filter out the selfish portable users. This reputation-based model encourages the portable users to sustain a good reputation in order to increase their chances of being picked out by the FD in future interactions. The commitment of the users with PDs to cooperative services is measured by the amount of power they dedicate to packet forwarding.

The cooperative reputation of the j^{th} PD, denoted by C_j^n, is a cumulative factor that is used to capture the cooperative strategy of this user during the previous time-slots while considering a penalty for generating interference to the neighboring sections. Such cooperative reputation is updated and stored by the FD to be used for relay selection in future time slots. By setting the initial cooperative reputation of PD$_j$ is C_j^0, at each time-slot, the cooperative reputation parameter is updated based on a recursive rule as $C_j^n = C_j^{n-1} + \Delta C_j^n$, $n \geq 0$. The variation in reputation at time-slot n denoted by ΔC_j^n is defined as a function of the power assigned by PD$_j$ to cooperation at time n, P_{jc}^n, the power allocated to its own transmission at time n, P_j^n and also the corresponding channel quality, as defined in (4).

$$\Delta C_j^n = \min_{\psi \in \Psi} C_s \left(\min \left\{ \frac{P_F}{P_{jc}^{max}} |h_{FP_j}|^2, \gamma_1\left(\frac{P_{jc}}{P_{jc}^{max}}\right) |h_{P_jF}|^2 \right\} - \gamma_2\left(\frac{P_j}{P_j^{max}}\right) \right) \qquad (4)$$

for $n \geq 0$, where C_s ($C_s > 0$) is the quantization constant step parameter, and h_{FP_j} and h_{P_jF} are the imperfect CSI of channels between the FD's transmitter and j^{th} PD's transmitter, and j^{th} PD's transmitter and FD's receiver, respectively. The first term in this definition refers to the fact that, from the FD's perspective, the benefit of relaying service depends on the minimum of QoS between the downlink and uplink links. Functions $\gamma_1(x > 0)$ and $\gamma_2(x > 0)$ are defined to prevent the portable users from violating the limits for P_j and P_{jc} regarding the co-channel interference to nearby sections. As an example, these two functions are defined to encourage PDs to set their powers in a range such that the interference to the neighboring sections can be controlled.

$$\gamma_1(x) = \begin{cases} x, & x \leq 1 \\ 2 - x^2, & \text{Otherwise} \end{cases} \qquad (5a)$$

$$\gamma_2(x) = \begin{cases} x, & x \leq 1 \\ x^2, & \text{Otherwise,} \end{cases} \qquad (5b)$$

In the majority of current reputation mechanisms, the non-altruistic users self-report their reputations, therefore these methods are vulnerable to false reputation reported by selfish users and require an audit unit to be in place and verify the reliability of these reported reputations [60]. Moreover, such reputation exchanges among the users can impose a considerable signaling load to the network. In our proposed model, the user with FD directly measures and keeps the record of the reputation of users with PD, as defined in (4). Noting the definition of cooperative reputation in (4) which includes both the transmission power and the channel quality, the behavior of users with PDs can be monitored using simple beam ratio combining techniques [61]–[63]. It is worth mentioning that the user with FD only stores the cumulative reputation of each user with portable device rather than saving the record of all selected strategies over the course of time, hence does not involve a considerable memory. If a user with FD does not have any prior history of interactions with a user with portable device, the user with FD will inquire from other users with FD in its proximity to obtain a second-hand information about reputation of this portable user by averaging the received inputs [64].

Since only an imperfect estimation of CSIs is available to the FD's transmitter, it can consider the worst case scenario to estimate the reputation variation. In this case, using the following lemma leads us to find the closed-form expression of Definition (4) as described in :

Lemma 1: For an arbitrary estimated channel coefficient $\hat{h}$ with uncertainty complex number δh such that $|\delta h| \leq \epsilon$, we have:

$$\min_{\forall |\delta h| \leq \epsilon} |\hat{h} + \delta h| = \begin{cases} |\hat{h}| - \epsilon, & \text{if} \quad \epsilon \leq |\hat{h}| \\ 0, & \text{if} \quad \epsilon > |\hat{h}| \end{cases} = (|\hat{h}| - \epsilon)^+ \qquad (6)$$

Proof: Based on triangle inequality $|\hat{h} + \delta h| \geq ||\hat{h}| - \epsilon|$. Therefore for the case of $\epsilon \leq |\hat{h}|$, we have $|\hat{h} + \delta h| \geq |\hat{h}| - \epsilon$ and $\delta h = -\frac{\epsilon}{|\hat{h}|}\hat{h}$ provides the equality. For the case of $\epsilon > |\hat{h}|$, $\delta h = -\hat{h}$ provides zero norm and it proves our lemma.

By using (1) and Lemma 1, the closed-form expression of Definition (4) can be written as:

$$\Delta C_j^n = C_s\left(\min\left\{\frac{P_F}{P_{jc}^{max}}(\tilde{h}^+_{FP_j})^2, \gamma_1\left(\frac{P_{jc}}{P_{jc}^{max}}\right)(\tilde{h}^+_{P_jF})^2\right\} - \gamma_2\left(\frac{P_j}{P_j^{max}}\right)\right), \qquad (7)$$

where $h^+_{FP_j} = (|\hat{h}_{FP_j}| - \epsilon_{FP_j})^+$ and $h^+_{P_jF} = (|\hat{h}_{P_jF}| - \epsilon_{P_jF})^+$.

Using this definition, the user with FD selects the most trusted K PDs among the available candidates for cooperative services. Then, to divide the time portion for PDs' transmission (Phase III) among these selected ones in a fair manner, the allocated time to each user j (i. e. β_j) is computed proportional to $C_j^{n-1} - \min_i\{C_i^{n-1}\}$ such that $\sum_j \beta_j = \beta$.

C_j^{n-1}, where C_j^{n-1} refers to cooperative reputation of user j up to this time slot. Based on these definitions, the total energy consumed by the j^{th} PD can be written as $\alpha\beta_j P_j + \alpha(1-\beta)P_{jc}$. The maximum energy of the j^{th} PD is E_j^{max}, and this constraint can be expressed as:

$$\alpha\beta_j P_j + \alpha(1-\beta)P_{jc} \leq E_j^{max}. \tag{8}$$

During the first stage of the game, the user of FD selects its strategy set including selecting the best portable relays and the optimum time allocation parameters: α and β as well as its own transmission power: P_F. The best K relays are selected among the N active users with PDs based on their reputation scores. The relay selection can be modeled by $\mathcal{S} = \underset{s\in\mathcal{S}_K}{\text{argmax}}(\sum\limits_{j\in s} C_j^n)$, where $\mathcal{S}_K$ is the set of group of users with cardinality K, and C_j^n is the reputation of the j^{th} PD at time n. Hence, the strategy set of the game leader can be summarized as $(\alpha, \beta, P_F, \mathcal{S})$. For simplicity in notations, we omit the superscript n in the rest of paper.

The fixed user determines the time allocation parameters α and β with the goal of optimizing its benefit from cooperative DF relaying. Therefore, the utility of the FD, $U_F(\alpha, \beta, P_F)$, can be defined as its achievable transmission rate through cooperation considering the cost of its transmission. Hence, the best strategy set of the FD can be obtained as follows:

$$\begin{aligned}
&\max_{\alpha,\beta,P_F}\ \min_{\psi\in\Psi}\left\{\min\left\{(1-\alpha)\log_2\Big(1+\frac{\min\limits_{j\in\mathcal{S}} P_F|h_{FP_j}|^2}{N_0}\Big),\right.\right.\\
&\qquad\left.\left.\alpha(1-\beta)\log_2\Big(1+\sum_{j\in\mathcal{S}}\frac{P_{jc}|h_{P_jF}|^2}{N_0}\Big)\right\}\right\}\\
&\qquad -\eta_F(1-\alpha)P_F\\
&\text{Subject to: } 0\leq\alpha,\ \beta\leq 1\\
&\qquad 0\leq P_F\leq P_F^{max},
\end{aligned}\tag{9}$$

where parameter η_F is a pre-defined normalizing coefficient for the energy consumed by FD to make it comparable to the transmission rate. The first and second terms in the min function are the achievable rates form the fixed transmitter to the selected relays during Phase I, R_{FP} and from the relays to the FD's receiver during Phase II, R_{PF}, respectively. Since each relay node independently decodes the message from the fixed user, R_{FP} is dominated by the worst channel between the FD and the selected relays. By considering (1) and Lemma 1, the optimization problem (9) is converted to:

$$\begin{aligned}
&\max_{\alpha,\beta,P_F}\ \min\left\{(1-\alpha)\log_2\left(1+\frac{\min\limits_{j\in\mathcal{S}} P_F(\tilde{h}^+_{FP_j})^2}{N_0}\right),\right.\\
&\qquad\left.\alpha(1-\beta)\log_2\left(1+\sum_{j\in\mathcal{S}}\frac{P_{jc}(\tilde{h}^+_{P_jF})^2}{N_0}\right)\right\}\\
&\qquad -\eta_F(1-\alpha)P_F\\
&\text{Subject to: } 0\leq\alpha,\ \beta\leq 1,\\
&\qquad 0\leq P_F\leq P_F^{max}.
\end{aligned}\tag{10}$$

During the second stage, the selected relays observe the fixed user's strategies and respond by setting the power for cooperative relaying and their own transmission. Each user with PD aims to maximize its transmission rate during its allocated time, $\alpha\beta_j$, while maintaining a good cooperative reputation. On one hand, the user j with PD prefers to select a high value for its own transmission power, P_j, to enhance its transmission rate. On the other hand, this user is required to allocate enough power for cooperation, P_{jc} to maintain a good reputation and increase its chances to be trusted by the FD during the next rounds of the game. Moreover, there exist an upper limit for both P_j and P_{jc} to control the interference level to the nearby sections, and these allocated powers need to satisfy the constraint on the maximum available energy at this user as described in (8). The utility of fixed user j is designed in such a way to meet these requirements as follows:

$$\begin{aligned}
&U_{PD_j}(P_j, P_{jc}, \psi)\\
&\quad=\alpha\beta_j\log_2\Big(1+\frac{P_j|h_{P_j}|^2}{N_0}\Big)\\
&\qquad-\eta_P(\alpha\beta_j P_j+\alpha(1-\beta)P_{jc})+\eta_{PC}\Delta C_j
\end{aligned}\tag{11}$$

where η_P and η_{PC} are pre-defined normalizing coefficient. Finally, by considering the worst-case scenario over all uncertainties $\psi \in \Psi$, and by using (1) and Lemma 1, the utility function of this user can be expressed as the objective function of the following convex optimization problem:

$$\begin{aligned}
&\max_{P_j,P_{jc}}\ U_{PD_j}(P_j, P_{jc})\\
&\text{Subject to: } 0\leq P_j\leq P_j^{max},\qquad 0\leq P_{jc}\leq P_{jc}^{max}\\
&\qquad\qquad \alpha\beta_j P_j+\alpha(1-\beta)P_{jc}\leq E_j^{max},
\end{aligned}\tag{12}$$

where

$$\begin{aligned}
U_{PD_j}(P_j, P_{jc}) &= \alpha\beta_j\log_2\Big(1+\frac{P_j(\tilde{h}^+_{P_j})^2}{N_0}\Big)\\
&\quad-\eta_P(\alpha\beta_j P_j+\alpha(1-\beta)P_{jc})+\eta_{PC}\Delta C_j.
\end{aligned}\tag{13}$$

and $h^+_{P_j} = (|\hat{h}_{P_j}| - \epsilon_{P_j})^+$. The aforementioned reputation-based Stakelberg game is summarized in Algorithm 1. In the next subsection, we present the solution of this game.

A. SOLUTION OF PROPOSED STACKELBERG GAME

In this section, we study the existence, uniqueness, and convergence of the Stackelberg equilibrium for the proposed game.

Theorem 1: During each time slot, the Stackelberg Equilibrium (SE) of the proposed game model exists, and it is unique.

Proof: To prove this theorem, we first need to show that the optimization problem from the followers' (i.e. users with PDs) perspective has a unique solution. The constraints in the optimization problem (12) represent an affine set. By substituting (7) into (13), the objective of the optimization

Algorithm 1 Proposed Reputation-Based Stackelberg Game

```
Step 0: Initialize reputation ▷ All new users with PDs are assigned with an initial cooperative reputation of $C^0$.
while 1 do
    Step 1: The user with FD selects the best $K$ users with PDs with highest reputation factors
    Step 2: The user with FD and the selected users with PD determine their strategies
        ▷ Initialize strategies of the user with FD, i.e. $\alpha$, $\beta$, and $P_F$
    while The convergence criterion is not met do
        Step 2a: Calculate $\beta_j$ proportional to the $j^{th}$ user with PD's reputation factor up to previous time slot, $C_j^{n-1}$
        Step 2b: Maximize the utility of each user j with PD and obtain their strategies, i.e. $P_j$ and $P_{jc}$.
        Step 2c: Maximize the utility of user with FD and obtain $\alpha$, $\beta$, and $P_F$
    end while
    Step 3: Update the reputation factors of the selected users with PDs
end while
```

problem (12) can be rewritten as:

$$\begin{aligned} &U_{PD_j}(P_j, P_{jc}) \\ &\quad = \alpha\beta_j \log_2\big(1 + \frac{P_j(\tilde{h}^+_{P_j})^2}{N_0}\big) \\ &\qquad - \eta_P(\alpha\beta_j P_j + \alpha(1-\beta)P_{jc}) \\ &\qquad + \eta_{PC} C_s\big(\min\left\{\frac{P_F}{P^{max}_{jc}}(\tilde{h}^+_{FP_j})^2, \gamma_1(\frac{P_{jc}}{P^{max}_{jc}})(\tilde{h}^+_{P_jF})^2\right\} \\ &\qquad - \gamma_2(\frac{P_j}{P^{max}_j}\big). \end{aligned} \tag{14}$$

The $\log_2(.)$ function, $\gamma_1(.)$, and $-\gamma_2(.)$ as defined in (5a) are concave functions and the $\min\{.\}$ operation preserves the concavity property. Therefore, the utility function of user j with PD (i.e., 14)) is concave with respect to P_j and P_{jc} which means that the utility maximization problem for the J^{th} user with PD is a convex optimization problem. From the above discussion we conclude that the strategy of the users with PD can be found uniquely and independent from the strategies of other users with PD.

Next, in order to prove the existence, uniqueness, and convergence of the SE in an one-leader-multiple-follower Stackelberg game, it is sufficient to show:

- The strategy set of the leader is a non-empty convex subset of some Euclidean space.
- The leader's utility is continues and the leader's utility maximization problem represents a convex optimization problem.

From (10), it is inferred that if $P_F^{max} > 0$ then the leader's strategy set, i.e. $\{P_F, \alpha, \beta\}$, is a non-empty convex subset of some Euclidean space. However, as seen in equation (10), this optimization problem through which the user with *FD* finds its optimum strategy is not a convex one.

Here, we prove that this optimization is equivalent to a convex optimization problem. Let us define $a_1 = 1/\ln(2)$, $a_2 = \frac{\min_{j\in\mathcal{S}}(\tilde{h}^+_{FP_j})^2}{N_0}$, $a_3 = \log_2\big(1 + \sum_{j\in\mathcal{S}} \frac{P_{jc}(\tilde{h}^+_{P_jF})^2}{N_0}\big)$ and $a_4 = \eta_F$. By defining new variables $\rho = \alpha\beta$, $\kappa = (1-\alpha)\ln(1+a_2 P_F)$ and $\xi = 1 - \alpha$, the optimization problem (10) can be converted to the following maximization problem:

$$\begin{aligned} &\max_{\rho,\kappa,\xi} \ \min\{a_1\kappa, a_3(1-\xi-\rho)\} - \frac{a_4}{a_2}\xi e^{\frac{\kappa}{\xi}} + \frac{a_4}{a_2}\xi \\ &\text{Subject To: } 0 \le \rho \le 1 - \xi \le 1 \\ &\qquad\qquad\qquad 0 \le \kappa \le ln(1 + a_2 P_F^{max})\xi. \end{aligned} \tag{15}$$

Furthermore, by defining the auxiliary variable τ, the maximization problem (15) is transformed into the following convex optimization problem:

$$\begin{aligned} &\min_{\rho,\kappa,\xi,\tau} \ -\tau + \frac{a_4}{a_2}\xi e^{\frac{\kappa}{\xi}} - \frac{a_4}{a_2}\xi \\ &\text{Subject To: } \tau \le a_1\kappa \\ &\qquad\qquad\quad \tau \le a_3(1-\xi-\rho) \\ &\qquad\qquad\quad 0 \le \rho \le 1-\xi \le 1 \\ &\qquad\qquad\quad 0 \le \kappa \le ln(1 + a_2 P_F^{max})\xi, \end{aligned} \tag{16}$$

where the objective represents an exponential cone and all constraints represent affine sets. After solving the convex optimization problem (16) by using a quiet fast algorithm such as steepest descent algorithm, the fixed user's strategy (i.e. α, β, and P_F) can be calculated as: $\alpha = 1-\xi$, $\beta = \frac{\rho}{\alpha}$, and $P_F = \frac{1}{a_2}(e^{\frac{\kappa}{\xi}} - 1)$, respectively. This concludes that the FD's utility maximization problem defined in (10) is equivalent to the convex optimization problem (16). Therefore, the optimum strategy set of *FD* is unique and can be obtained from a convex optimization problem. Moreover, the strategies of the users with PD are obtained from a convex optimization problem (12). This concludes the proof of uniqueness and convergence for the SE of the proposed game model.

Theorem 2: The SE solution of the proposed game is a Nash equilibrium (NE).

Proof: For a two-player non-cooperative game, a strategy set $\mathcal{S}^* = (s_1^\star, s_2^\star)$ is NE if and only if

$$\forall i \in \{1, 2\}, \ \forall s_i \in \mathcal{S}, \quad U_i(s_i^\star, s_{-i}^\star) \ge U_i(s_i, s_{-i}^\star), \tag{17}$$

where $\mathcal{S}$ is the strategy set of the game players, and s_{-i} indicates the strategy of the opponent of player *i*.

The SE is obtained through a backward-induction, where in each round, the user with *FD* declares its unique best strategy set by optimizing the convex optimization problem (16), and then the users with PD determine their unique optimum strategy set from (12) as their best response to the leaders' strategy. Therefore, since during both steps of backward-induction, the game players select their strategy as the best response to the other one, the Stackelberg equilibrium follows the definition of NE.

VI. PERFORMANCE EVALUATION

To evaluate the performance of the proposed model, we consider a system that consists of a single user with fixed transmitter-receiver pair, and 20 users with PD as potential secondary relay users. Out of which, two users are assumed to be selfish (unless specified otherwise), meaning that when they are selected by the user with FD for spectrum leasing, they do not assign any power to cooperative relaying and exhaust their available energy for their own transmission. The cooperative reputation of the users is normalized in the range of $[-1, 1]$, assuming an initial credit of 0.1 for all the users and the quantization step parameter of $C_s = 0.01$. All users with PD are randomly located in the proximity with radius of 1 km from the user with FD's transmitter. We also consider six regions in the neighborhood of this use with FD and apply a limit on the maximum allowable power of all users in this region to avoid potential interference to the nearby regions. The maximum available power at the user with FD is assumed to be 10 Watt. The maximum available energy available at the users with PD is assumed to be 1 Joule. All channels' coefficients are generated as a zero mean complex Gaussian random variable with variance of 0 dB. The noise power spectrum is assumed to be 0 dBW. For simplicity, the duration of each time slot is assumed to be one second. During each time slot, the user with FD selects $K = 5$ users with PD for cooperation purposes.

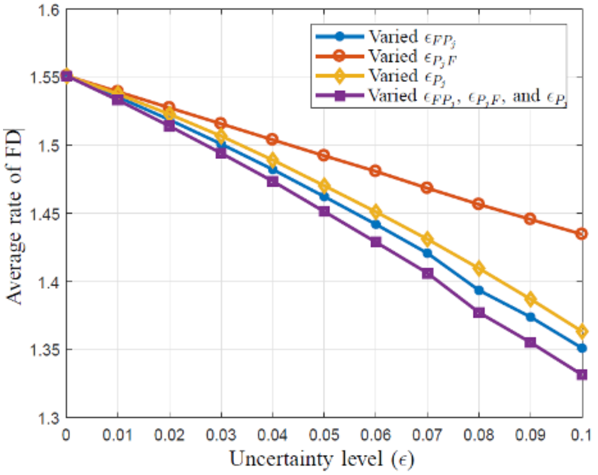

FIGURE 2. **Average rate of *FD* versus uncertainty levels on CSI values.**

First, we show that the proposed game is robust against uncertainties in CSI values. We performed extensive numerical analysis to show the performance of the system with respect to such uncertainties. The CSI values with uncertainty are generated as complex Gaussian random variables and bounded with uncertainty levels as a percentage of the channel's variances. A Monte-Carlo simulation considering the worst case scenario for the knowledge of CSI values is performed for different uncertainty levels. Figure 2 shows the average rate for the *FD* versus the uncertainty levels, i.e. ϵ for four different cases of uncertainty in the CSI's knowledge of: 1) channels between FT and users with PD (downlink channels), 2) channels between users with PD and FR (uplink channels), 3) channels between users with PD and their own receivers, and 4) all channels at the same time. As shown in figure 2, the average transmission rate of *FD* decreases as uncertainty increases for all four cases. The results also indicate the significant effect of quality of downlink channels related to other cases. This is due to the fact that during the first time-slot, the FD's cooperative transmission rate in DF relaying is dominated by the worst downlink channel.

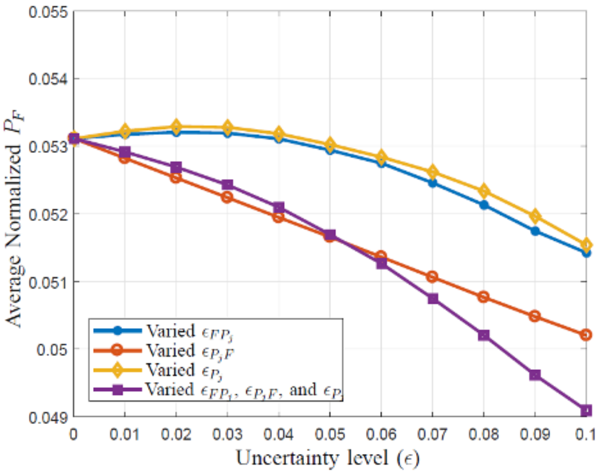

FIGURE 3. **Average optimal power of *FD* versus uncertainty levels on CSIs.**

Figure 3 presents the strategy of *FD* in terms of transmission power (P_F) versus the uncertainty levels in CSI knowledge for the four aforementioned cases. This figure shows that an increase in downlink uncertainty level has more effect on the cost of FD, i.e. P_F compared to uncertainty on the uplink channels. The uncertainty on the channels between users with PD and their destinations forces the *FD* to consume more power to satisfy users with PD's incentive for cooperation.

Figure 4 shows the effect of uncertainty in CSI knowledge on the summation of transmission rates for selected users with portable devices for the aforementioned four cases. While the users with PD can compensate the effect of uncertainty in their CSI knowledge up to a certain point, the increase in this uncertainty level results in decreasing the summation rate of these users. However, the uncertainty in the CSI knowledge of the downlink and uplink channels are beneficial for the users with PD. Since there is no direct transmission link between the *FT* and the *FR*, the user with fixed device has to allocate a bigger portion of the time-slot to the users with PDs (higher values of α, and β) when facing higher uncertainty levels in the CSI of the downlink and uplink channels in order to encourage them for cooperation.

Figure 5 shows the portion of time-slot allocated to the transmission of the users with PD as a reward of cooperative relaying, i.e. $\alpha\beta$, versus the uncertainty levels. It can be

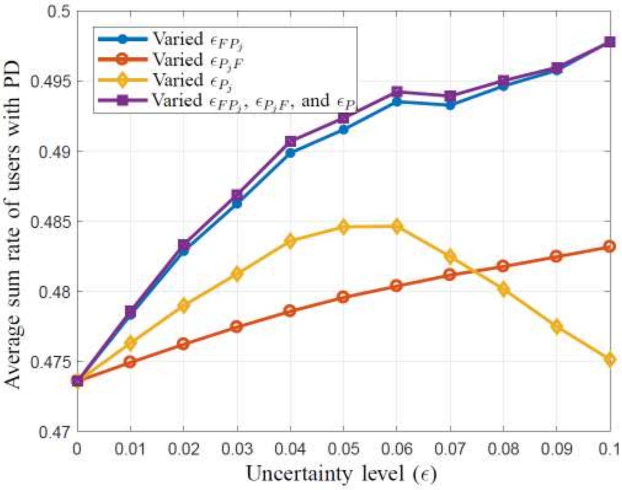

FIGURE 4. Average of summation rates of users with PD versus uncertainty levels on CSI values.

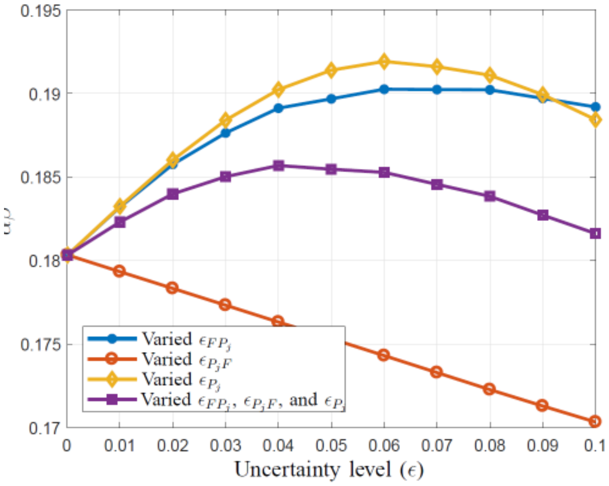

FIGURE 5. Time allocated to the transmission of the users with PD, i.e. $\alpha\beta$, versus uncertainty levels on CSI values.

inferred that in case of uncertainties in knowledge of all CSI values, the award time is less than the cases where there exists an uncertainty in the knowledge of CSI values for only one type of the downlink or uplink channels.

In figure 6, the transmission rate of the user with FD for our proposed reputation-based model, where the *FD* can identify and discard the users with selfish behaviors over the course of time is compared to alternative relay selection mechanisms. In our method, the cooperative reputation of the users with PD is defined as a function of their power assigned to relaying service as well as their CSI values. When such a mechanism is not in place, the selfish PDs simply do not assign any power to packet forwarding after their spectrum access is granted. To show the effectiveness of such reputation-based model, we consider a scenario where two out of 20 users with PD are selfish in the sense that they do not assign any power to cooperation after being selected by the FD, and set the maximum available power for their own transmissions. We performed a Monte-Carlo simulation and show that if such a reputation-mechanism does not exist and $K = 5$ relays are selected either randomly, or based on best minimum downlink and uplink absolute CSI values, then the average FD's rate quickly decreases. In figure 6, the average FD's achievable rate over time is plotted for four different scenarios. First, we simulate the proposed reputation-based algorithm and the results show the increase in the average FD's achievable rate over time. This result confirms the ability of the proposed model in recognizing and discarding the users with selfish behaviors. In the second case, we re-define the incremented reputation based on power only and not CSI. This means that instead of definition (4), we use the following formula:

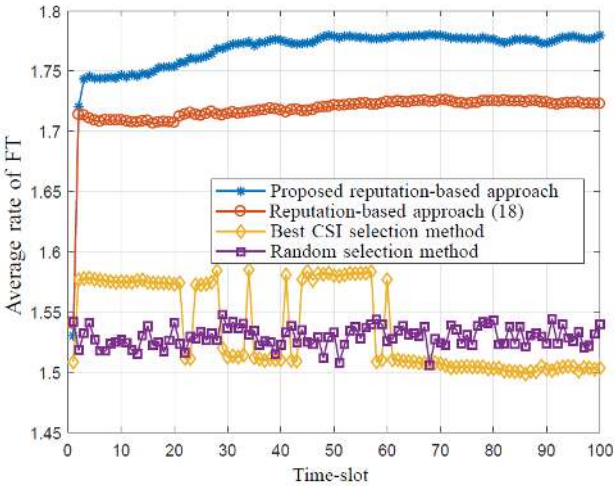

FIGURE 6. Average rate of *FD* over time for four different scenario: 1) proposed reputation-based scenario, 2) reputation-based scenario by only considering power in defining reputation, 3) best CSI selection scenario, and 4) random selection scenario.

$$\Delta C_j^n = C_s\left(\min\{\frac{P_F}{P_{jc}^{max}}\sigma_{FP_j}^2, \gamma_1(\frac{P_{jc}}{P_{jc}^{max}})\sigma_{P_jF}^2\} - \gamma_2(\frac{P_j}{P_j^{max}})\right), \tag{18}$$

where σ_{FP_j} and σ_{P_jF} are the variances of $\hat{h}_{FP_j}$ and $\hat{h}_{P_jF}$, respectively. The results show that for the case with alternative definition of reputation (18), the users with selfish behaviors are still being discarded over time but the average achievable rate is less than first scenario using our proposed reputation formulation in (4). We examine two other cases in which *FD* selects: i) $K = 5$ random users, and ii) $K = 5$ users with the best minimum downlink-uplink absolute CSI values. In these two cases, two users are selfish who utilize all of their available power to their own transmissions, and the rest of users are assumed to be fully trusted in the sense that they consume the same amount of power for cooperation as well as in their own transmissions, i.e. $P_j = P_{jc}$. The results show a lower average FD's achievable rate for those cases compared to the reputation-based scenarios.

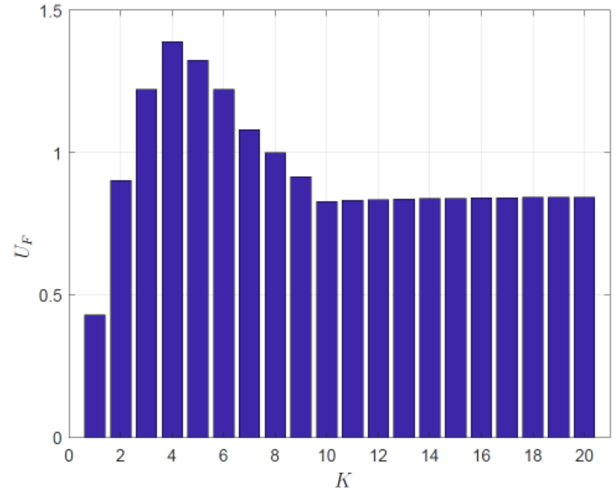

FIGURE 7. Utility of the user with fixed device versus K for different uncertainty levels on CSI values.

Next, we investigate the effect of the number of relays, i.e. K, on the FD's utility. Figure 7 shows that in this figure, there is an optimum value for number of relays. Although selecting more relays can increase the FD's transmission rate due to higher cooperative diversity gain in the second phase of DF relaying, it also increases the chances of having a relay with low quality of downlink channel that would be dominant during the first phase and reduces the overall FD's rate. Selecting a large number of relays can also increase the chance of choosing selfish users that will result in reducing FD's utility.

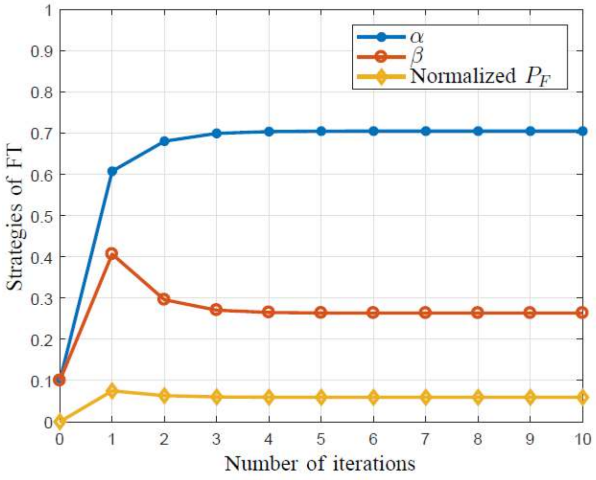

FIGURE 8. Convergence of the strategies of the user with fixed device.

Finally, Figures 8 and 9 show the convergence of the proposed Stackelberg game model for strategies of FT (i.e. α, β, and normalized P_F to P_F^{max}) and strategies of users with PD (power allocation between its own transmission and cooperation). The algorithm converges when the changes in users' strategies over two rounds of game is less than 1%. As these figures show, the stable solution is reached after a few rounds of the game for the given setting. We also performed a Monte-Carlo simulation to investigate the convergence of this method for different network topologies and it was observed that in average the stable solution is achieved in less than 10 iterations.

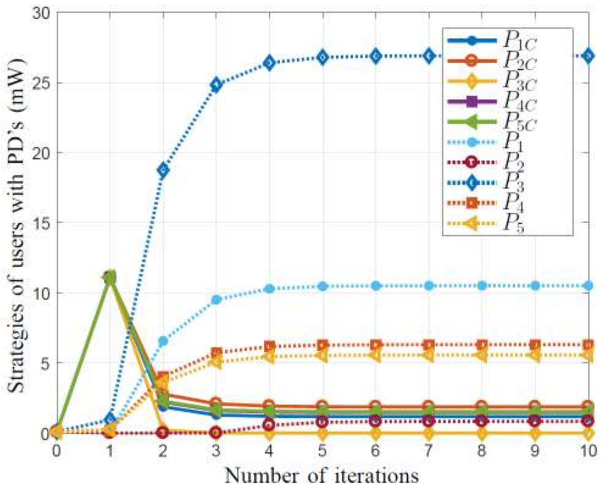

FIGURE 9. Convergence of the strategies of the users with portable device.

VII. CONCLUSION

In this work, we proposed a hierarchical model for spectrum sharing in heterogeneous TVWS. The TV broadcasters can lease a part of their spectrum bands to local users with fixed device, and these local users can decide to sublease a portion of their spectrum access time to the users with PD. In return the users with PDs relay the FT's message to its corresponding destination. This can significantly improve the QoS for users with FD particularly if the quality of the direct transmission link is poor while providing the users with PD with the opportunity of free spectrum access. The proposed algorithm is designed in a way that it is robust against uncertainties in the CSI's knowledge in the network. We proposed a reputation-based mechanism to enable the fixed users to identify the malicious portable users and only choose the trusted users with PDs for relaying purposes. The simulation results show the performance of this system in different network conditions and confirm the improvement of the fixed user's utility as a result of using the reputation-based model compared to the scenario where the behaviors of users with PD are not observed.

ACKNOWLEDGMENTS

The authors would like to thank the anonymous reviewers for their valuable comments which helped them to improve the quality and presentation of this paper.

REFERENCES

[1] *Federal Communications Commission Spectrum Policy Task Force, Report of the Spectrum Efficiency Working Group*, Federal Commun. Commission, Washington, DC, USA, 2002.

[2] R. Jäntti, J. Kerttula, K. Koufos, and K. Ruttik, "Aggregate interference with FCC and ECC white space usage rules: Case study in Finland," in *Proc. IEEE Int. Symp. Dyn. Spectr. Access Netw. (DySPAN)*, May 2011, pp. 599–602.

[3] K. Harrison, S. M. Mishra, and A. Sahai, "How much white-space capacity is there?," in *Proc. IEEE Symp. New Frontiers Dyn. Spectr. (DySPAN)*, Apr. 2010, pp. 1–10.

[4] O. Holland *et al.*, "To white space or not to white space: That is the trial within the OFCOM TV white spaces pilot," in *Proc. IEEE Int. Symp. Dyn. Spectr. Access Netw. (DySPAN)*, Sep./Oct. 2015, pp. 11–22.

[5] M. J. Marcus, "Unlicensed cognitive sharing of TV spectrum: The controversy at the Federal Communications Commission," *IEEE Commun. Mag.*, vol. 43, no. 5, pp. 24–25, May 2005.

[6] *Notice of Proposed Rulemaking and Order, Commissions Rules for Unlicensed White Space Devices*, Federal Communications Commission, Washington, DC, USA, 2016.

[7] *FCC Establishes Rules for Unlicensed Operations in the TV and the 600 MHz Bands*, Federal Communications Commission, Washington, DC, USA, 2015.

[8] *FCC Adopts Rules for Unlicensed Use of Television White Spaces*, Federal Communications Commission, Washington, DC, USA, 2018.

[9] F. Hessar and S. Roy, "Capacity considerations for secondary networks in TV white space," *IEEE Trans. Mobile Comput.*, vol. 14, no. 9, pp. 1780–1793, Sep. 2015.

[10] M. Fitch, M. Nekovee, S. Kawade, K. Briggs, and R. MacKenzie, "Wireless service provision in TV white space with cognitive radio technology: A telecom operator's perspective and experience," *IEEE Commun. Mag.*, vol. 49, no. 3, pp. 64–73, Mar. 2011.

[11] S. Kawade and M. Nekovee, "Can cognitive radio access to TV white spaces support future home networks?" in *Proc. IEEE Symp. New Frontiers Dyn. Spectr. (DySPAN)*, Apr. 2010, pp. 1–8.

[12] W. Zhang, G. Zhang, Y. Zheng, L. Yang, and C. K. Yeo, "Spectrum sharing for heterogeneous networks and application systems in TV white spaces," *IEEE Access*, vol. 6, pp. 19833–19843, 2018.

[13] J.-M. Park, J. H. Reed, A. A. Beex, T. C. Clancy, V. Kumar, and B. Bahrak, "Security and enforcement in spectrum sharing," *Proc. IEEE*, vol. 102, no. 3, pp. 270–281, Mar. 2014.

[14] D. Gurney, G. Buchwald, L. Ecklund, S. L. Kuffner, and J. Grosspietsch, "Geo-location database techniques for incumbent protection in the TV white space," in *Proc. 3rd IEEE Symp. New Frontiers Dyn. Spectr. Access Netw.*, Oct. 2008, pp. 1–9.

[15] S. Bhattarai, A. Ullah, J.-M. J. Park, J. H. Reed, D. Gurney, and B. Gao, "Defining incumbent protection zones on the fly: Dynamic boundaries for spectrum sharing," in *Proc. IEEE Int. Symp. Dyn. Spectr. Access Netw. (DySPAN)*, Sep./Oct. 2015, pp. 251–262.

[16] T. Erpek, M. A. Mchenry, and A. Stirling, "Dynamic spectrum access operational parameters with wireless microphones," *IEEE Commun. Mag.*, vol. 49, no. 3, pp. 38–45, Mar. 2011.

[17] G. P. Villardi *et al.*, "Enabling coexistence of multiple cognitive networks in TV white space," *IEEE Wireless Commun.*, vol. 18, no. 4, pp. 32–40, Aug. 2011.

[18] G. Ding, J. Wang, Q. Wu, Y.-D. Yao, F. Song, and T. A. Tsiftsis, "Cellular-base-station-assisted device-to-device communications in TV white space," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 1, pp. 107–121, Jan. 2016.

[19] H. Maloku, E. Hamiti, Z. L. Fazliu, V. P. Lesta, A. Pitsillides, and M. Rajarajan, "A decentralized approach for self-coexistence among heterogeneous networks in TVWS," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1302–1312, Feb. 2018.

[20] F. Afghah, M. Costa, A. Razi, A. Abedi, and A. Ephremides, "A reputation-based Stackelberg game approach for spectrum sharing with cognitive cooperation," in *Proc. IEEE 52nd Annu. Conf. Decis. Control (CDC)*, Dec. 2013, pp. 3287–3292.

[21] A. R. Korenda, M. Zaeri-Amirani, and F. Afghah, "A hierarchical Stackelberg-coalition formation game theoretic framework for cooperative spectrum leasing," in *Proc. 51th Annu. Conf. Inf. Syst. Sci. (CISS)*, Mar. 2017, pp. 1–6.

[22] L. Zhang, G. Ding, Q. Wu, Y. Zou, Z. Han, and J. Wang, "Byzantine attack and defense in cognitive radio networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1342–1363, 3rd Quart., 2015.

[23] L. Zhang, G. Ding, Q. Wu, and Z. Han, "Spectrum sensing under spectrum misuse behaviors: A multi-hypothesis test perspective," *IEEE Trans. Inf. Forensics Security*, vol. 13, no. 4, pp. 993–1007, Apr. 2018.

[24] F. Afghah, A. Shamsoshoara, L. Njilla, and C. Kamhoua, "A reputation-based Stackelberg game model to enhance secrecy rate in spectrum leasing to selfish IoT devices," in *Proc. IEEE Conf. Comput. Commun. Workshops (INFOCOM WKSHPS)*, Apr. 2018, pp. 312–317.

[25] T. Baykas *et al.*, "Developing a standard for TV white space coexistence: Technical challenges and solution approaches," *IEEE Wireless Commun.*, vol. 19, no. 1, pp. 10–22, Feb. 2012.

[26] G. P. Villardi *et al.*, "Enabling coexistence of multiple cognitive networks in TV white space," *IEEE Wireless Commun.*, vol. 18, no. 4, pp. 32–40, Aug. 2011.

[27] C. Ghosh, S. Roy, and D. Cavalcanti, "Coexistence challenges for heterogeneous cognitive wireless networks in TV white spaces," *IEEE Wireless Commun.*, vol. 18, no. 4, pp. 22–31, Aug. 2011.

[28] S. J. Shellhammer, A. K. Sadek, and W. Zhang, "Technical challenges for cognitive radio in the TV white space spectrum," in *Proc. Inf. Theory Appl. Workshop*, Feb. 2009, pp. 323–333.

[29] B. Gao, J.-M. Park, Y. Yang, and S. Roy, "A taxonomy of coexistence mechanisms for heterogeneous cognitive radio networks operating in TV white spaces," *IEEE Wireless Commun.*, vol. 19, no. 4, pp. 41–48, Aug. 2012.

[30] A. Ali and W. Hamouda, "Advances on spectrum sensing for cognitive radio networks: Theory and applications," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 2, pp. 1277–1304, 2nd Quart., 2016.

[31] G. Ding *et al.*, "Spectrum inference in cognitive radio networks: Algorithms and applications," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 150–182, 1st Quart., 2018.

[32] G. A. Ramírez, M. A. Saavedra, and J. L. Araque, "Analysis of an energy detection algorithm for spectrum sensing," in *Proc. IEEE-APS Top. Conf. Antennas Propag. Wireless Commun. (APWC)*, Sep. 2018, pp. 924–927.

[33] H. Zhou, Q. Yu, X. S. Shen, S. Wu, and Q. Zhang, *Dynamic Sharing of Wireless Spectrum*. Cham, Switzerland: Springer, 2017, pp. 17–35.

[34] T. Fujii, K. Inage, and K. Sato, *Spectrum Database and Smart Spectrum*. Singapore: Springer, 2018, pp. 1–24.

[35] J. Xiao, R. Q. Hu, Y. Qian, L. Gong, and B. Wang, "Expanding LTE network spectrum with cognitive radios: From concept to implementation," *IEEE Wireless Commun.*, vol. 20, no. 2, pp. 12–19, Apr. 2013.

[36] *Second Memorandum Opinion and Order in the Matter of Unlicensed Operation in the TV Broadcast Bands and Additional Spectrum for Unlicensed Devices Below 900MHz and in the 3GHz Band*, Federal Communications Commission, Washington, DC, USA, 2010.

[37] A. H. Kelechi and R. Nordin, "Non cooperative cournot economic game model for heterogeneous coexistence in TVWS," in *Proc. IEEE Asia Pacific Conf. Wireless Mobile*, Aug. 2014, pp. 328–334.

[38] M. Song and M. Zheng, "Ecology-based coexistence scheme for heterogeneous cognitive radio networks over TV white space," *IET Commun.*, vol. 12, no. 5, pp. 620–626, Mar. 2018.

[39] S. Kawade, "Long-range communications in licence-exempt TV white spaces: An introduction to soft-licence concept," in *Proc. 7th Int. ICST Conf. Cogn. Radio Oriented Wireless Netw. Commun. (CROWNCOM)*, Jun. 2012, pp. 141–146.

[40] A. Laya, K. Wang, A. A. Widaa, J. Alonso-Zarate, J. Markendahl, and L. Alonso, "Device-to-device communications and small cells: Enabling spectrum reuse for dense networks," *IEEE Wireless Commun.*, vol. 21, no. 4, pp. 98–105, Aug. 2014.

[41] H. Zhou, N. Cheng, Q. Yu, X. S. Shen, D. Shan, and F. Bai, "Toward multi-radio vehicular data piping for dynamic DSRC/TVWS spectrum sharing," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 10, pp. 2575–2588, Oct. 2016.

[42] X. Feng, Q. Zhang, and J. Zhang, "A hybrid pricing framework for TV white space database," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2626–2635, May 2014.

[43] S. Manickam, M. K. Marina, S. Pediaditaki, and M. Nekovee, "Auctioning based coordinated TV white space spectrum sharing for home networks," *CoRR*, vol. abs/1307.0962, Jul. 2013. [Online]. Available: http://arxiv.org/abs/1307.0962

[44] Y. Luo, L. Gao, and J. Huang, "White space ecosystem: A secondary network operator's perspective," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2013, pp. 925–930.

[45] J. Elias, F. Martignon, L. Chen, and M. Krunz, "Distributed spectrum management in TV white space networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 4161–4172, May 2017.

[46] X. Chen and J. Huang, "Game theoretic analysis of distributed spectrum sharing with database," in *Proc. IEEE 32nd Int. Conf. Distrib. Comput. Syst. (ICDCS)*, Jun. 2012, pp. 255–264.

[47] X. Feng, Q. Zhang, and J. Zhang, "Hybrid pricing for TV white space database," in *Proc. INFOCOM*, Apr. 2013, pp. 1995–2003.

[48] C.-S. Sum *et al.*, "Cognitive communication in TV white spaces: An overview of regulations, standards, and technology [accepted from open call]," *IEEE Commun. Mag.*, vol. 51, no. 7, pp. 138–145, Jul. 2013.

[49] A. B. Flores, R. E. Guerra, E. W. Knightly, P. Ecclesine, and S. Pandey, "IEEE 802.11af: A standard for TV white space spectrum sharing," *IEEE Commun. Mag.*, vol. 51, no. 10, pp. 92–100, Oct. 2013.

[50] M. Murroni *et al.*, "IEEE 1900.6: Spectrum sensing interfaces and data structures for dynamic spectrum access and other advanced radio communication systems standard: Technical aspects and future outlook," *IEEE Commun. Mag.*, vol. 49, no. 12, pp. 118–127, Dec. 2011.

[51] K. Woyach and A. Sahai, "The need for a new model of trust in spectrum and the case for spectrum jails," in *Proc. IEEE Int. Symp. Dyn. Spectr. Access Netw. (DYSPAN)*, Apr. 2014, pp. 427–438.

[52] K. A. Woyach, A. Sahai, G. Atia, and V. Saligrama, "Crime and punishment for cognitive radios," in *Proc. 46th Annu. Allerton Conf. Commun., Control, Comput.*, Sep. 2008, pp. 236–243.

[53] J. Wang, G. Scutari, and D. P. Palomar, "Robust MIMO cognitive radio via game theory," *IEEE Trans. Signal Process.*, vol. 59, no. 3, pp. 1183–1201, Mar. 2011.

[54] A. Ben-Tal and A. Nemirovski, "Robust convex optimization," *Math. Oper. Res.*, vol. 23, no. 4, pp. 769–805, 1998.

[55] S. Salari, M. Z. Amirani, I.-M. Kim, D. I. Kim, and J. Yang, "Distributed beamforming in two-way relay networks with interference and imperfect CSI," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 4455–4469, Jun. 2016.

[56] F. Afghah and A. Razi, "Cooperative spectrum leasing in cognitive radio networks," in *Proc. Nat. Wireless Res. Collaboration Symp.*, May 2014, pp. 106–111.

[57] Z. Han, D. Niyato, W. Saad, T. Ba ar, and A. Hjørungnes, *Game Theory in Wireless and Communication Networks: Theory, Models, and Applications*. Cambridge, U.K.: Cambridge Univ. Press, 2011.

[58] P.-Y. Nie and P.-A. Zhang, "A note on Stackelberg games," in *Proc. Chin. Control Decis. Conf. (CCDC)*, Jul. 2008, pp. 1201–1203.

[59] M. J. Osborne and A. Rubinstein, *A Course in Game Theory*. Cambridge, MA, USA: MIT Press, 1994.

[60] Y. Zhang, L. Lazos, and W. Kozma, "AMD: Audit-based misbehavior detection in wireless ad hoc networks," *IEEE Trans. Mobile Comput.*, vol. 15, no. 8, pp. 1893–1907, Apr. 2016.

[61] M. Kokshoorn, H. Chen, Y. Li, and B. Vucetic, "Beam-on-graph: Simultaneous channel estimation for mmWave MIMO systems with multiple users," *IEEE Trans. Commun.*, vol. 66, no. 7, pp. 2931–2946, Jul. 2018.

[62] J. Mansukhani and P. Ray, "Simultaneous detection and channel estimation for censoring-based spectrum sensing in cognitive radio networks," *IEEE Wireless Commun. Lett.*, vol. 7, no. 3, pp. 292–295, Jun. 2018.

[63] S. Haghighatshoar and G. Caire, "Pilot decontamination through compressive wideband channel estimation," in *Proc. 50th Asilomar Conf. Signals, Syst. Comput.*, Nov. 2016, pp. 979–983.

[64] S. Buchegger and J.-Y. Le Boudec, "Self-policing mobile ad hoc networks by reputation systems," *IEEE Commun. Mag.*, vol. 43, no. 7, pp. 101–107, Jul. 2005.

MOHAMMAD ZAERI-AMIRANI was born in Najafabad, Isfahan, Iran. He received the B.Sc. and M.Sc. degrees in electrical engineering from the Sharif University of Technology, Tehran, Iran, and the University of Ontario Institute of Technology (UOIT), Oshawa, ON, Canada, respectively. He is currently pursuing the Ph.D. degree with the School of Informatics, Computing, and Cyber Systems, Northern Arizona University, Flagstaff, AZ, USA. He has worked closely and served several research appointments with the related departments in the Sharif University of Technology, UOIT, Queens University, Kingston, ON, Canada, the University of Waterloo, Waterloo, ON, Canada, Ryerson University, Toronto, ON, Canada, and the University of Calgary, Calgary, AB, Canada, and NAU, from 2002 to 2015. His research interests include cooperative communication, cognitive radio, biomedical signal processing, machine learning, and game theory.

FATEMEH AFGHAH received the B.Sc. and M.Sc. degrees (Hons.) in electrical engineering from the Khajeh Nassir Toosi University of Technology, Tehran, Iran, and the Ph.D. degree in electrical and computer engineering from the University of Maine, Orono, ME, USA, in 2005, 2008, and 2013, respectively. She was a Visiting Student with the Department of Electrical and Computer Engineering, University of Maryland at College Park, College Park, MD, USA, from 2011 to 2012. She is currently an Assistant Professor with the School of Informatics, Computing and Cyber Systems, Northern Arizona University (NAU), Flagstaff, AZ, USA, where she is also the Director of Wireless Networking and Information Processing Laboratory. Prior to joining NAU, she was an Assistant Professor with the Electrical and Computer Engineering Department, North Carolina A&T State University, Greensboro, NC, USA, from 2013 to 2015. Her research interests include wireless communication networks, decision making in multi-agent systems radio spectrum management, game theoretical optimization, and biomedical signal processing.

SHERALI ZEADALLY received the bachelor's degree in computer science from the University of Cambridge, U.K., and the Ph.D. degree from the University of Buckingham, U.K. He is currently an Associate Professor with the University of Kentucky. He is a fellow of the British Computer Society and the Institution of Engineering Technology, U.K.

* * *