A Survey of Resource Allocation in TV White Space Networks

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Abstract —Dynamic Spectrum Access (DSA), through the use of cognitive radio, is currently being embraced as a solution to address spectrum scarcity and spectrum underutilization. DSA allows the use of an unutilized spectrum as long the Secondary Users (SUs) do not cause harmful interference to the Primary Users (PUs). TV White Spaces (TVWS) are spectrum bands that have attracted a lot of research and development interest because of the good propagation characteristics attainable within such bands. The aim of resource allocation in cognitive access to TVWS is to efficiently assign the available spectrum and power to SUs such that the interference constraints to PUs and SUs are met. Radio resource allocation is a subset of the DSA that significantly addresses the spectrum scarcity and interference in TVWS networks. However, the existing literature does not adequately provide a comprehensive survey on the resource allocation in TVWS networks. Hence it is difficult to identify the specific focus and direction of the future research, development and application on this subject matter. In this paper, we provide a comparison of TVWS resource allocation proposals and also highlight open research issues on the same. This paper is useful to TVWS and cognitive radio researchers who are designing TVWS resource allocation algorithms and also those who want to know future research directions in this area.

Index Terms—Dymamic spectrum access; cognitive radio; geo-location database; spectrum sesning; TV white spaces; geo-location database congestion, primary user, secondary user, white space device.

I. Introduction

Spectrum occupancy assessments done in USA, Spain, Singapore, New Zealand and Germany [1] and UK [2] indicate that a large portion of spectrum assigned is underutilized. Spectrum is a scarce resource. More and more devices want a pie of the spectrum and yet the useful spectrum is limited. Digital migration has helped solve the problem of spectrum scarcity because it has freed up part of the Very High Frequency (VHF) and Ultra High Frequency (UHF) spectrum through utilization of more efficient modulation techniques [3]. Dynamic Spectrum Access (DSA), through the use of Cognitive Radio (CR) is currently being embraced as a solution to spectrum underutilization and spectrum scarcity. This is because DSA, together with CR, provides an efficient way for spectrum management and spectrum sharing. With DSA, spectrum allocated for exclusive use to a PU but being not used by the PU(incumbent), or any other idle frequency bands (such as guard bands) can be shared by different SUs as long as the interference to the incumbent by the SUs to PUs is kept to an acceptable level [4].

The spectrum band which has attracted a lot interest in the DSA community is the TVWS. TVWS is the spectrum band not being utilized by TV transmitters in the UHF band. The main reason for this increased interest is the good propagation characteristics of the sub-1GHz spectrum [5]. Since DSA allows the use of TVWS as long as the PUs are protected against harmful interference, interference control is a major issue in TVWS networks. Resource (power and spectrum) allocation has to be done appropriately in TVWS networks in order to prevent harmful interference to PUs. Aggregate interference from multiple users, both co-channel and adjacent channel interference (from multiple channels), has to be considered during resource allocation in a TVWS network [6]. Resource allocation addresses the problem interference to PUs and among SUs in TVWS networks so that TVWS can be effectively exploited.

Recent studies have shown that aggregate interference from a high density of users from multiple adjacent channels is as harmful as co-channel interference [6]. Resource allocation, being an optimization problem, it would be important to choose computationally efficient algorithms. In scenarios where the total interference generated by all the users in a network is more than the allowed levels, admission control has to be performed [7].

In this paper, we provide a survey of proposals on resource allocation in TVWS networks that exist in literature. More specifically, we consider power control/allocation, spectrum allocation, joint power and spectrum allocation, and admission control. Existing literature does not adequately provide a comprehensive survey on the resource allocation in TVWS networks.

The first objective of the paper is to present the merits and demerits of different resource allocation approaches in TVWS networks in existing literature. This will allow TVWS researchers choose the right resource allocation solution when designing CR devices and Geo-location

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Database (GLDB). The second objective of the paper is to present open research issues in resource allocation in TVWS networks. This will enable TVWS researchers to know future research directions in resource allocation in TVWS networks. To the best of our knowledge, there is no single survey paper on resource allocation in TVWS networks.

The rest of the paper is organized as follows. In section II, we discuss interference and power allocation in TVWS networks. Section III presents joint power and spectrum allocation in TVWS networks. We conclude the paper in section IV by highlighting the main findings of the paper.

II. Interference and Power Allocation in Tvws Networks

Power allocation in TVWS networks has to be done in such a manner that the PU if fully protected against harmful interference. In this section, we look at techniques of incumbent protection against harmful interference, interference considerations in TVWS networks, TVWS power allocation regulations and as well as existing power control/allocation algorithms.

A. Incumbent Protection Methods

There are three main methods for PU protection against harmful interference: use of beacons, spectrum sensing and GLDB [4]. With the beacon method, a dedicated channel is used to give information to White Space Devices (WSDs) as to which channels are available for secondary use [4]. The WSD will only transmit if it receives a beacon from a base station granting it permission to transmit in specific channels [8]. The WSD will continue to use specific channels until it receives a beacon disabling transmission in those channels. The main drawback of the beacon method is that it requires a beacon infrastructure in form of base stations to be rolled out. With spectrum sensing, the WSD uses a sensing algorithm to find out whether there is a signal from a PU in a particular channel [4]. If a PU signal is detected on a particular channel, then the channel will not be used by the WSD. The cognitive radio system (CRS) of the WSD continuously detects current usage of the spectrum so as to know which channel is available for secondary use. The main drawback of this method is that it suffers from hidden node problem whereby an SU fails to detect nearby PUs transmissions. Spectrum sensing also do not utilize spectrum as efficiently as GLDB because of large protection margins required for incumbent protection [9].

GLDB is considered a better technique because it overcomes the shortcomings of the two other methods of incumbent protection [4]. GLDB is used by a WSD to find the set of frequency channels that can be used on a secondary basis at a given area and at any given time. GLDB is populated through the use of a propagation model. The database contains estimated power levels of PUS for any point in a particular region of interest. The WSD, which has a cognitive radio system (CRS), queries a central database. The WSD provides the database with parameters such as its location, device type and antenna height. The GLDB will then use this information along with the parameters of all surrounding TV transmitters such as antenna height, transmit power and frequency of operation in order to come up with the list of available TVWS channels that can be used by the WSD on secondary basis without causing harmful interference to the PU. The GLDB will also give the WSD limits on the transmit power and also the time period in which each channel can be used.

B. Interference Consideration in TVWS Network

In a TVWS network interference could be due to either co-channel interference or adjacent channel interference. Interference in TVWS networks is a major consideration in TVWS networks. TVWS can be used as long as interference to the PUs does not exceed a certain threshold that will cause harmful interference to PUs. Before power allocation is TVWS is discussed, interference considerations in a TVWS network will first be discussed.

Recent studies [10]-[13] have shown that aggregate adjacent channel interference from a high density of mobile users using low power in multiple adjacent channels is as harmful as co-channel interference even if interference caused by each SU in a particular channel stays below the GLDB desired to undesired(D/U) ratio constraint. The desired to undesired ratio is also known as protection ratio. The GLDB D/U ratio constraints for digital TV (DTV) are 23dB and -26 dB for co-channel and adjacent channel interference, respectively [9]. GLDB regulations require that the D/U ratio or protection ratio be measured at the edge of protection region [9]. These ratios are measured at the edge of protection region because TV receivers at this region are the most vulnerable since they are very close to the secondary network and they receive the weakest TV signal. This is illustrated in Fig. 1. Aggregate interference (co-channel and adjacent channel) at the TV receiver, both co-channel and adjacent channels should not make the protection ratio fall below the required D/U ratio threshold.

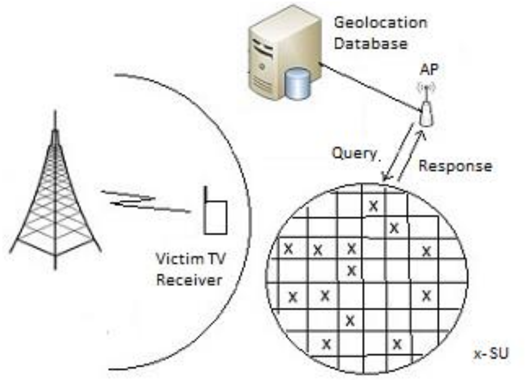

Fig. 1. Interference scenario

The effect of adjacent channel interference in a single and multiple adjacent channels has been studied through measurements by Obregon et al. [11].In the measurement set up, interference from multiple adjacent channels is summed through a combiner and fed into a TV receiver. The picture quality is then analyzed so as to see the effects of aggregate adjacent channel interference. A model for computing the maximum aggregate adjacent channel interference (ACI) that a DTV (digital TV) receiver can tolerate without experiencing degradation of service has also been proposed. In the model,a formula that computes adjacent channel interference as equivalent co-channel interference has been used. It is found that the maximum tolerable power that can be used by SUs decreases as the number channels considered increased. It is concluded that in order to protect TV reception quality, the SUs should either reduce the transmit power or increase distance to the TV receiver. The measurement model confirms the findings of the analytical model.

Whereas only the effects of adjacent channel interference has been studied in [11], the effect of both co-channel and adjacent channel interference on the number of users that can be admitted into a TVWS network and effect of TV reception has been studied by Shi et al. [6]. The study finds that the cumulative effect of adjacent channel interference has a negative impact on TV reception. Linear programming was used to find the maximum number of users that can be admitted into the secondary system with co-channel interference and adjacent channel interference at the PU as the constraint. The number of SUs admitted to the network drop by almost 50 percent when the effect of both adjacent channel and co-channel interference is considered, compared to when co-channel interference only is considered.

A model for computing aggregate interference from secondary cellular network in the presence of correlated shadow fading has been presented by Ruttik *et al* [14]. In the model, the authors approximate aggregate interference as integration over power spatial density in SUs deployment area. Instead of considering the location for each SU, the power spatial density emitted from the network deployment area is made use of. Each point is considered a source of interference. Aggregate interference then is computed is by integrating over the deployment area. This technique is computationally efficient in large scale networks. Both correlated and uncorrelated shadow fading is incorporated into the model.

C. TVWS Regulations on Power Allocation

There are three main TVWS regulations that have been proposed. They include Federal Communications Commission FCC, Office of Communications (OFCOM) and European Communications Commission (ECC). FCC, OFCOM and ECC are the bodies tasked with regulation of radio communications in US, UK and Europe, respectively. The three different regulations provide guidelines for WSD power limits and allocation.

Under FCC regulations, both spectrum sensing and GLDB are specified as the methods for incumbent protection [4]. FCC permits the use of both fixed and portable devices. Fixed devices are allowed maximum transmit power of 4W while portable devices are allowed a maximum of 100mW. Fixed devices must contact the GLDB to obtain channel list before operation and it has to recheck the GLDB at least once a day. FCC classifies WSDs as either mode I or mode II. Mode II devices acquire spectrum information from the GLDB and then share with mode I devices. Mode II devices have a GPS and internet connection. Mode I devices do not have internet connection and rely on Mode II devices to get information on available TVWS channels. Portable devices operate in either mode I or mode II. If the portable device is operating on adjacent channel, the power should not exceed 40mW. Sensing only devices are allowed to operate but the transmit power is limited to 50mw. Sensing only devices have to detect microphones signals with a power of -107dBm and above. FCC specifies fixed power values for devices while for ECC and OFCOM, the transmission power is not fixed [4]. [15].

The use of fixed power limit to WSDs alone is not enough to protect PUs against aggregate interference from multiple SUs. In order to protect PUs against harmful aggregate interference from multiple users, FCC requires that there be a protection distance around the TV coverage area. This is in addition to the required fixed upper limit on transmission power. FCC required protection distances are summarized in Table I. The protection distance depends on antenna height and whether the channel of use is co-channel is adjacent channel. FCC assumes that the protection zone is enough to protect TV receivers against harmful aggregate interference [10].

Like FCC regulations, OFCOM provide regulations for both GLDB and spectrum sensing [4]. OFCOM saw the benefit of both GLDB and spectrum sensing. Under OFCOM regulations, there are two types of devices: master device and slave device. Unlike FCC which specifies fixed transmit power, OFCOM allows more flexible WSD transmit power. The power is determined by the device and for each TVWS channel based on the specified levels of protection to Digital Terrestrial TV (DTT) and Program Making and Special Events (PMSE).

ECC regulations are similar to those of OFCOM [4]. The regulations are published in a report called Technical and Operational Requirements [15]. ECC regulations do not provide for protection distance for interference protection. ECC regulations instead specify certain location related power constraints and also provides a margin in link budget that will cater for the effects for aggregate interference from multiple SUs [10]. ECC allows the use of adjacent channels inside the protection zone.

D. Power Allocation Algorithms and Methods in TVWS Networks

Limiting the transmit power is an important consideration in a GLDB based TVWS network [16]. This is done using a power allocation or control algorithm. Power control will result in admission of more SUs into the TVWS network without causing harmful interference to PUs and other SUs. In this sub section, we look at other power allocation proposals for a TVWS network that exist in literature.

TABLE I: PROTECTION DISTANCES DEFINED BY FCC

Antenna Height	Required distance from TV coverage contour	
	Co-channel	Adjacent Channel
<3m	6km	100m
3<10m	8km	100m
10-30m	14.4 km	100m

A statistical approach for controlling aggregate interference under adjacent channel interference constraints has been proposed by Shi *et al* [12]. The proposed model allows determination of permissible secondary transmit power so as to avoid detrimental aggregate adjacent channel interference. Cumulant based log-normal approximation has been used to approximate adjacent channel interference.

Lee *et al* [17], proposed a transmit power control algorithm for a TV white space wireless network. Transmit power control is done in such a manner that the sum interference at the TV service protection contour does not exceed the D/U ratio. Lagrange multiplier is used to determine the optimal power of SUs that maximizes sum uplink throughput at the base station while ensuring that D/U threshold at the primary receiver is met. The work fails to address interference among SUs as the interference constraints at the SUs is not considered in the proposed power control algorithm. Failing to consider interference among SUs will result in poor QoS at SUs.

We have proposed a power control algorithm for a TVWS network based on firefly algorithm in [16]. Firefly algorithm is a relatively new evolutionary algorithm which has been found to perform better that particle swarm optimization and genetic algorithm in term of solution quality and convergence time [18].The proposed algorithm takes into consideration both co-channel and adjacent channel interference and also interference constraints at SUs. We have proposed an algorithm that can be used to optimize power allocation for all the SUs in a network. The algorithm aims to minimize sum power while ensuring that SINR constraints are met at SUs and a PU located at the contour of the protection region.

Power control for a device-to-device network has been studied by Xue *et al.* [19]. In a device-to-device network, devices communicate directly between themselves without going through the base station. This is illustrated in Fig. 2. A heuristic iterative power control algorithm with co-channel and adjacent channel interference considerations has been proposed. Interference constraints at both PUs and SUs are considered. The objective of the proposed algorithm is to maximize total system throughput through power control on each device to device link while considering interference constraints to from SUs to PUs, from PUs to SUs and between SUs.

As discussed in the previous section, Jantti et. al[10] computed how much aggregate interference a secondary network generates if the network is designed by either FCC rules or ECC rules. These rules are discussed in section I(C). The case study is done in Finland. Authors conclude that in order to support large cells, we need high transmission power and in order to provide high data rate density, there is need to have small cells that can use low transmission power.

Selen et al. [20] also studied the effects of aggregate interference. They considered the problem of finding upper power limits which aggregate interference by SUs does not exceed the required limit. The aggregate interference is constrained so that the probability of harmful interference is below a predefined threshold. Log normal shadow fading is factored into the model by the authors. Both co-channel and adjacent channel interference is considered. Felton Wilkinson approximation is used to get the sum of the log normal variables in computing sum interference. An optimization problem is formulated with the objective being maximization of sum capacity.

A detailed method of calculating the maximum permitted emission levels for WSDs has been presented by Karimi *et al* [21]. The proposed method provides a way to calculate location specific maximum power based on location probability. The proposed method makes use of DTT network planning models in order to provide the GLDB with the needed parameters to perform the necessary calculations

Koufous et al. [22] derived an equation describing the aggregate interference in a TVWS network in a fading environment. The authors study the amount of capacity, both for co-channel and adjacent channel, that can be achieved by a secondary system if the interference to the TV system is kept under control. The effect of changing the size of no transmission area (protection zone) on the system behavior is studied. The authors also look at the relationship between the transmission power, the no transmission area around the TV coverage and aggregate interference. The authors conclude that in order to have sufficient power in a large secondary cell, it is necessary to have a large no transmission area.

E. Summary and Concluding Remarks

Table II provides a summary and comparison of power allocation proposals in TVWS network. The following points summarize the section on power and spectrum allocation in a GLDB based TVWS network:

- ECC has no fixed limit SU power while FCC provides an upper limit on SU power.
- ECC allows the use of adjacent channels anywhere while FCC allows the use of co-channels and adjacent channels within a certain distance to the protection region depending on the antenna height.
- The aggregate interference by all the SUs in the secondary network has to be considered in order to ensure full protection of PUs within the protection

region especially when there many users in the network. Limit of power to single individual SUs do not guarantee protection of PUs against harmful interference.

- In a TVWS network, aggregate adjacent channel interference has to be considered during spectrum allocation especially when there is a high density of SUs.
- Due to the effects of aggregate interference from multiple SUs, it is necessary to use power control so as to admit more users into the secondary network without causing harmful interference to PUs and SUs.
- Transmit power control is done in such a manner that the sum interference at the TV service protection contour does not exceed the D/U or protection ratio.
- Fading should be considered during power allocation in a TVWS network

TABLE II: A COMPARISON OF POWER ALLOCATION PROPOSALS

Proposal	Advantages	Disadvantages
FCC – Power for single devices [25], [4]. Maximum power for different devices: Fixed device – 4W Personal/portable device – 100 mW Spectrum sensing devices - 50mW. Secondary device must be located a certain protection distance when using co-channel or adjacent channel in order to protect PUs against harmful aggregate interference.	Easy to implement. Considers the effects of aggregate interference from multiple SUs through the use of protection distance.	Co-channel cannot be used in the within 6km to protection zone which will lead loss of white spaces. Model does not consider interference among SUs and this will lead to poor SU QoS. Fixed power allocation that does not take into consideration SU density may limit the number of SUs that can be admitted into the secondary network.
ECC and OFCOM [25], [4]. Transmission power is not fixed. The power is determined by the device and for each TVWS channel based on the specified levels of protection to DTT and Program Making and Special Events (PMSE).	Aggregate interference protection through the use of link margin is easy to implement. PU will be fully protected from interference because the model incorporates the effect of cumulative interference from multiple SUs through the use of link margin.	Use of fixed link margin, which does not take into consideration density of SUs, will lead to loss of white spaces. Model does not consider mutual interference among SUs and this will lead to poor SU QoS.
Controlling Aggregate Interference under Adjacent Channel Interference Constraint in TV White Space [12]. Cumulant based log-normal approximation of ACI. Statistical, probabilistic method based on GLDB for determination of transmit power, based on location probability.	Models a realistic signal propagation since it factors in shadow fading.Compared to ECC and FCC regulations which are deterministic, the statistical method proposed will allow more transmit power while ensuring PUs are fully protected. Location probability modeling allows protection of TV receivers at every possible location even if adjacent channels are used inside the protection region. The model allows use of adjacent channels inside the protection region.	Only adjacent channel interference considered, co-channel interference outside the protection region not considered. Power allocation does not consider mutual interference among SUsand this will lead to poor SU QoS.
Secondary spectrum access in TV-bands with combined co-channel and adjacent channel interference constraints [6]. Linear programming applied to determine maximum number of users to be admitted. Makes use of location probability.	Both co-channel and adjacent channel interference considered. Proposes a single model that allows analysis of the effect of both co-channel and adjacent channel interference. Location probability modeling allows protection of TV receivers at every possible location even if adjacent channels are used inside the protection region.	Linear programming, being an exact algorithm, is not computationally efficient.
Optimizing power limits for white space devices under a probability constraint on aggregated interference[20]. Fenton-Wilkinson approach. Centralized approach to control of interference in GLDB based TVWS network.	Models a real world scenario because log normal shadow fading considered has been factored into the model. Considers aggregate interference from multiple adjacent channels and this will ensure that PUs are fully protected against harmful interference.	Model protects receivers at the protection contour only since it assumes that both co-channel and adjacent channel cannot be used inside the protection region. Since it does not allow the use of adjacent channels inside the protection region, there will be loss of white spaces.
Firefly algorithm based power control in wireless TV white space network[16]	Ensures PUs are fully protected since the model takes into consideration both co-channel and adjacent channel interference. Makes use of a metaheuristic algorithm which has provides a good solution quality with lower time complexity. Model considers mutual interference among SUs.	Assumes both co-channel and adjacent channels cannot be used inside the protection or exclusion region, model designed to protect PUs at the boundary of protection region from one secondary cell. Model will lead to loss of white spaces since it assumes adjacent channels cannot be used inside the protection region.
Transmit Power Control Scheme for TV White Space Wireless System [17]. Power control algorithm based on Lagrange multiplier.	Considers both co-channel and adjacent channel interference, this will ensure adequate protection of PU against harmful interference.	Interference among SUs not addressed and this will lead to poor QoS. Does not factor in the effect of cumulative interference from multiple adjacent channels. Lagrange multiplier that has been applied in the model has high complexity.Ignores the effects of cumulative adjacent channel interference inside the protection contour – TV receivers not fully protected.

Proposal	Advantages	Disadvantages
Geolocation databases for white space devices in the UHF TV bands: Specification of maximum permitted emission levels [21]. Makes use of DTT network planning models in order to provide the GLDB with the needed parameters to perform the necessary calculations. Location probability used.	Considers both co-channel and adjacent channel interference, this will ensure adequate protection of PUs. Location probability modeling allows protection of TV receivers at every possible location even inside the protection region where adjacent channels can be used.	Interference approximation not accurate because the model ignores the effect of aggregate interference from multiple SUs.
Geolocation spectrum database assisted coexistence of multiple device-to-device in TV White Space [23]. Heuristic algorithm for power control.	Co-channel and effects of aggregate adjacent channel interference considered. Model considers mutual interference among SUs.	Lagrange multiplier method used is not computationally efficient. Assumes that both co-channel and adjacent channel cannot be used inside the protection region since the model is designed to protect PU at the boundary of protection region. Model will lead to loss of white spaces since it assumes adjacent channels cannot be used inside the protection region.

F. *Open Research Issues*

The following are the possible open research issues in this section of power allocation in TVWS networks:

i. **Modeling of a network consisting of multiple primary transmitters:** All the models or proposals in this section except [12], [6], [16] and [23] consider a network with one primary transmitter. The proposals can be extended to the more general scenario of multiple PUs and multiple SUs in different cells (under the control of different base stations).

ii. **Experimental verification of models:** The models in [12], [10], [6], [14], [22] and [20] are based on analytical/mathematical model. There is need to perform real world experimentation of the models to validate the accuracy of the models.

iii. **Power allocation with adjacent channel interference considerations:** The in models [22], [29], [31], [32], [33]and[34] ignore the effects of adjacent channel interference. There is need to factor in adjacent channel interference so that aggregate interference is not underestimated.

iv. **Power allocation with fading and shadowing considerations.** Models used in [22], [24], [6] ,[23], [31], [33] and [34] have ignored shadowing and signal fading. Ignoring shadowing and fading overestimates interference to the PUs and this may result in loss of white space opportunities. Performance of the models in [6] and [23] with fading considerations need to be investigated.

v. **Use of hybrid approach to determine maximum permitted power level:** In order to protect PUs, sensors can be deployed where TV receivers are present, especially the area around the boundary of protection region. Phones have been deployed as sensors to detect TV receivers in [24]. ZigBee devices have been used to detect PU transmitters in [25].Sensors can be used to detect harmful interference and report to GLDB so that the power level of devices can be reduced. Zigbee devices can be used for that purpose. Although GLDB usually sets maximum power level that can be used by devices, having a sensor network to detect harmful interference will ensure proper protection of PUs.

vi. **Interference considerations among SUs:** ECC, FCC and OFCOM regulations and the models in [20] and [12] as well as the models in [12] and [17] have ignored interference among SUs in the model proposed.

vii. Interference to SUs cannot be ignored since it affects QoS. The proposed models need to be re-designed to factor in the effects of mutual interference among SUs.

III. Joint Power and Spectrum Allocation in a TVWS Network

In the previous section we discussed the need for power control/allocation in order to control interference in a TVWS network. In this section we provide a survey of TVWS joint power and spectrum allocation proposals that exist in literature.

A. *Cognitive Radio Spectrum Allocation Algorithms – an Overview*

Spectrum allocation in cognitive radio is an optimization problem. There are five different methods for solving the spectrum allocation problem. They include: heuristics, graph theory, game theory, linear programming, fuzzy logic and evolutionary algorithms [26]. In [27]-[30] spectrum allocation has been abstracted as a graph coloring problem. Graph coloring allows easy representation of interference constraints among SUs.

Different channels represent different colors in the graph and vertices represent different users. An effective scheduling algorithm in infrastructure based CR networks has been proposed by Nguyen et al. [31]. The algorithm uses a heuristic greedy algorithm based on graph coloring. The scheduling algorithm has been designed in such a manner that it maximizes the spectrum utilization by the SUs without causing excessive interference to PUs. A heuristic greedy algorithm is chosen instead of mixed integer linear programming method which is NP hard so as reduce computational complexity. Evolutionary algorithms have also been applied in spectrum allocation.

A summary of the use of evolutionary algorithms for spectrum allocation in cognitive radio networks has been presented by Zhao *et al.* [32]. The work discusses the use particle swarm optimization (PSO), genetic algorithm (GA) and quantum genetic algorithm. The work finds that PSO converges much faster and gives a better solution compared to GA and Color Sensitive Graph Coloring (CSGC).

Performance of CSGC is found to be lower than both PSO and GA. Spectrum allocation has been abstracted as a graph coloring problem by Elhachmi *et al* [33]. Genetic algorithm is then been used to find the best spectrum allocation matrix. A spectrum allocation framework based on PSO and simulated annealing has been presented by Jie *et al*. [34]. Simulated annealing is introduced to prevent prematurity of particle swarm optimization. The work finds that PSO with simulated annealing performs better than graph coloring and greedy algorithms. Spectrum allocation using graph coloring and ant colony optimization has been presented by Koroupi *et al.* [35]. Ant colony system is found to perform better than PSO and CSGC. Spectrum allocation using firefly algorithm has been explored by Anumandla *et al.* [36] and Liu et al. [37]. The results of the two papers show that firefly algorithm gives a better solution and converges to a solution faster than genetic algorithm and particle swarm optimization.

B. Joint Power and Spectrum Allocation Methods

This section presents joint power and spectrum allocation methods and standards. Two standards will be discussed: IEEE 802.11af and IEEE 802.22. In addition to the standards, other joint spectrum and power allocation methods will also be discussed.

IEEE 802.11af allows only the use of GLDB for incumbent protection [38]. In an IEEE 802.11af network, a device sends a channel availability query (CAQ) to registered location secure server (RLSS). RLSS operates as a local database. It contains channels available for secondary use and the permitted EIRP for those channels. RLSS serves a number of basic service sets (BSSs). It distributes operating parameters such as the channels and their associated power levels to access points (APs) and WSDs. Once a CAQ is received by the RLSS, it will respond with a white space map (WSM). The WSM contains the list of available channels and their respective effective isotropic radiated power (EIRP). IEEE 802.11af allows for both closed loop power control and open loop power control. With open loop power limitation the WSD has rigid power limitation similar to those provided by FCC regulations. In closed loop power limitation, the WSD has more flexible power limits that depends on location, time of use and the channel.

IEEE 802.22 [39]-[41] allows the use of both GLDB and spectrum sensing for incumbent protection. In the IEEE 802.22 TVWS network architecture, there is an entity called spectrum manager. The spectrum manager makes use of spectrum sensing function and GLDB to find out the channels available for secondary use their respective EIRP limits. The SM has three options whenever secondary use of channels may create interference:

- Reduce CPE operating power.
- If reduction in CPE powers results in unsustainable service, the CPE will be stopped from operating on that channel and will seek another channel from the spectrum manager.
- Reduce base station EIRP in order to eliminate interference.

Joint power control and spectrum allocation algorithms for a GLDB based TVWS network have been proposed in [20], [19] and [7]. GLDB based spectrum allocation with power control, co-channel interference and adjacent channel interference considerations has been proposed Xue *et al*. [19]. A single TV receiver, considered the most vulnerable to interference, is placed near the border of protection region. Co-existence (mutual interference) among SUs is also considered. Channel allocation and power control is then done in such a manner that the TV receiver and SUs SINR constraints are met. A greedy heuristic iterative algorithm is used for power control and spectrum allocation. Each SU is allocated a channel and a power level when it makes a channel request to the GLDB. Simulation results show a decrease in the number of failed links when the joint spectrum and power allocation algorithm is applied. A device-to-device communication network is considered. In device to device communication, two devices communicate directly without going through the base station. Selen *et al* [20], in addition to considering the problem of finding upper power limits which aggregate interference by SUs does not exceed the required limit, also considered the problem of channel allocation under interference constraints.

The aggregate interference is constrained so that the probability of harmful interference is below a predefined threshold. Log normal shadow fading is factored into the model by the authors. Both co-channel and adjacent channel interference is considered. Felton Wilkinson approximation is used in used to sum the log normal variables when computing aggregate interference. The suggested method can be used by GLDB providers to make efficient use of white spaces while ensuring PUs are fully protected.

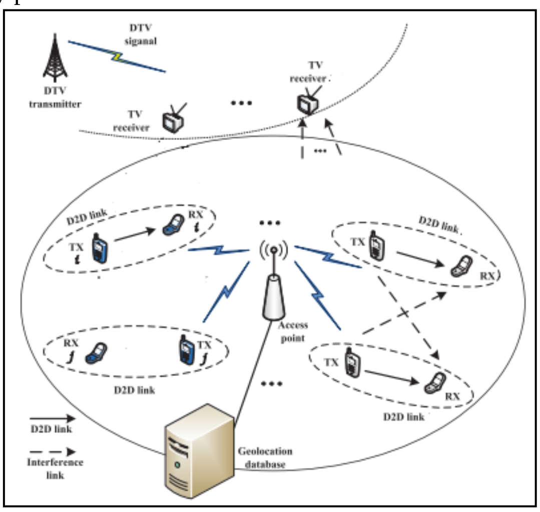

Fig. 2. Interference scenario in a device to device communications in a TVWS network. Adapted from [7].

Admission control will be necessary in a TVWS network if there are many SUs in the secondary network and all the SUs or links cannot be admitted into the network without violating SINR constraints at PUs and SUs even after power control has been applied. Admission control algorithm will choose which the users to be admitted into the network.

TABLE III: A COMPARISON OF JOINT POWER AND SPECTRUM ALLOCATION PROPOSALS

Proposal	Advantages	Disadvantages
IEEE 802.11 af: A standard for TV white space spectrum sharing[38]	GLDB gives each SU a channel upon request - easy to implement.	Interference approximation is not accurate because the model does not consider aggregate interference from multiple users. No admission control algorithm that can be applied in scenarios where not all SUs can be admitted into the network due to interference constraints at PUs. The model does not consider mutual interference among SUs and this may lead to poor QoS at SUs.
IEEE 802.22: the first worldwide wireless standard based on cognitive radios[41]	GLDB gives individual SUs a channel and associated power limit – easy to implement.	Interference approximation is not accurate because the model does not consider aggregate interference from multiple users. PUs will not be fully protected against harmful interference since the model does not consider aggregate interference from multiple users. The model does not consider mutual interference among SUs and this may lead to poor QoS at SUs.
Optimizing power limits for white space devices under a probability constraint on aggregated interference[20]	Models a realistic signal propagation since signal fading is considered.	Adjacent channel interference not considered. The model does not consider mutual interference among SUs and this may lead to poor QoS at SUs.
GLDB based resource sharing among multipledevice-to-device links in TV white space [7]. Spatial adaptive play algorithm for spectrum allocation, SMIRA algorithm for admission control.	Ensures acceptable QoS at SUs since interference among SUs is considered in the model. Ensures PUs are fully protected since both co-channel and cumulative adjacent channel interference considered in the model.	Assumes adjacent channels cannot be used inside the protection region.. Spatial adaptive play is based on game theory, it is difficult to structure the game in a way to guarantee equilibrium is always reached [26].

GLDB based spectrum allocation with power control and admission control for TVWS multiple device-to-device links has been proposed by Xue *et al.* [7]. Only co-channel interference has been considered. Spectrum allocation is done in greedy heuristic manner using an algorithm called spatial adaptive play (SAP). SMIRA algorithm is used for admission control

C. Summary and Concluding Remarks

Table III provides a summary and comparison of joint power and spectrum allocation and admission control proposals in TVWS networks. The following points summarize the section on power and spectrum allocation in a GLDB based TVWS network:

- Joint spectrum and power allocation reduces the number of failed inks.
- Admission control is necessary when there are many links requesting access to the secondary network but not of all them can be admitted into the network because of interference constraints.

D. Open Research Issues

The following are the open research issues in this section:

i. **Optimization of spectrum and power allocation of all existing links:** Power control and spectrum allocation algorithms for have been proposed by Xue *et al* [19] and Xue *et al.* [7]. The proposed algorithms allocate power and spectrum to SUs one by one as they send a channel request to the GLDB in a greedy heuristic manner. Since it is done in a greedy heuristic manner, it will result in a sub-optimal power and spectrum allocation. IEEE 802.11af and IEEE 802.22 standards also propose one by one spectrum and power allocation which will result in suboptimal spectrum and power allocation. It is therefore necessary to have an algorithm that optimizes spectrum and power allocation of all existing links or SUs. This can be done through the use of metaheuristic algorithms such as genetic algorithm, particle swarm optimization or firefly algorithm.

ii. **Joint spectrum and power allocation algorithm under adjacent channel and co-channel interference considerations in multi-cell scenario**: Spectrum and power allocation with adjacent and co-channel interference constraints has been studied Xue *et al.* [19] and Xue *et al.* [7]. In these two papers, effects of combined co-channel and adjacent channel interference on spectrum allocation under power control in single cell (of SUs) scenario and single PU at the boundary of protection region using one channel has been studied. Spectrum allocation and power control with co-channel and adjacent channel interference constraints in multi-cell secondary network and many PUs using different channels in a TVWS has not been studied.

iii. **Shadowing and signal fading considerations:** Models used Shi *et al.* [6]and Xue *et al.* [23] have ignored shadowing and signal fading. Ignoring shadowing and fading overestimates interference to the PUs and this may result in loss of white space opportunities. Performance of the models in [7]. and [19] with fading considerations need to be investigated.

iv. **Application of more efficient admission control algorithms in [7]**: SMIRA has been used by Xue *et al.* [7] for admission control while there exists more efficient algorithms. Whereas SMART is more efficient than SMIRA [42],even more efficient admission control algorithm known as ESPRA has been proposed in [43]. ESPRA (O(Mlog M)) has lower complexity compared to SMIRA O(M3)). Application of ESPRA in [7] instead of SMIRA will improve the performance of the proposed algorithm.

v. **Incorporation of admission control into IEEE 802.11af:** IEEE 802.11af only consider power and spectrum allocation. It lacks an admission control algorithm or technique that can be applied in scenarios where not all SUs can be admitted into the network.

IV. Conclusion

In this paper we have presented a survey of resource allocation in TVWS networks. We have also presented open research issues on the same. It has been found out that it is necessary to consider the aggregate interference from multiple SUs in order to ensure that PUs is fully protected against harmful interference. In a TVWS network, adjacent channel interference cannot be ignored when there is a high density of users in a network. Power control in a TVWS network is necessary so as to protect PUs against harmful interference. Joint power and spectrum will lead to admission of more SUs into a network.

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