Wireless Resource Allocation in Next Generation Healthcare Facilities

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***Abstract*— Healthcare facilities with intelligent wireless devices can reduce the workload of the paramedic staff. These devices include low-power wireless sensors, personal wireless hub (PWH), and receivers. The PWH can act as a relay in the hospital network. To help the wireless sensor devices, we use multiple PWHs to transfer sensor data to the main central controller. The use of multiple PWHs can increase the performance of the wireless network in the hospital. It also adds reliability to the coverage of the wireless network. In this paper, we propose a framework and low-complexity algorithm for interference aware joint power control and multiple PWH assignment (IAJPCPA) in a hospital building with cognitive radio capability. In the proposed framework, any wireless sensor device can send and receive data from multiple PWHs. The proposed IAJPCPA is a nonconvex mixed integer nonlinear optimization problem, which is generally NP-hard. The main objective of IAJPCPA is to maximize the total transmission data rate by assigning PWHs to the wireless sensor devices under the constraint of acceptable interference to the licensed wireless devices. To this end, we present an efficient PWH assignment and power control scheme for IAJPCPA problem by employing an upper bound on the IAJPCPA that converts the nonconvex problem into a convex optimization problem. Finally, we examine the effect of different system parameters on the performance of the proposed algorithm.**

***Index Terms*— Relays, PWHs, wireless sensor devices, automated hospitals, interference aware power control.**

I. Introduction

THE use of wireless sensor devices plays important role in next generation hospitals and healthcare facilities. These devices are useful for remote and infrastructure-based healthcare facilities. One such device is SCP-ECG (standard communications protocol for computer assisted electrocardiography) device used to transmit ECG traces, annotations, and metadata [1], [2]. The ballistocardiograph (BCG) devices transmit the ballistic forces on the heart. Zigbee-based real-time BCG is suggested in [3] and [4]. The authors also implemented a wireless messaging system that uses spread spectrum technology to alert the emergency medical staff if the observed person falls during the wheel chair movement. A Holter monitoring device transmits continuous heart activity [5], [6]. Nowadays, this device is also used for monitoring the brain activity and/or arterial pressure.

The wireless devices in healthcare facilities can be low power wireless sensor devices, PWHs, central controllers etc. A typical modern automated hospital with these wireless devices is shown in Fig. 1. The figure outlines one floor of the healthcare facility equipped with state-of-the-art wireless sensor/monitoring devices. The PWH will act as a relay in the hospital network. The facility has one central monitoring room that keeps track of vital patient information coming from the wireless sensor devices. These wireless devices can be mounted on the patient beds–i.e., pulse monitor, blood pressure monitor, movement monitoring device etc. A number of devices can also be attached to the patient's body–e.g., heart monitoring, pulse monitoring etc. Due to low power wireless devices, the data are transmitted to the central monitoring room with the aid of static PWHs that are installed at different locations in the facility. Human health monitoring devices that use body sensor network for mobile health care are proposed in [7]–[13].

A number of challenges emerge due to the rapid increase in the use of these wireless devices. Limited wireless spectrum availability, reduced power usage, demand of high data rate transmission and reduction in computational complexity of the algorithms are some of the challenges. In this paper, to assist the wireless sensor devices, we use multiple PWHs to transfer wireless sensor device data to the main central controller. The use of multiple PWHs can increase the performance of the wireless network in the hospital. It also adds reliability to the coverage of wireless network.

First, we need to see why cognitive radio (CR) is a critical need of future healthcare system. Due to rapid growth of tiny wireless healthcare/monitoring/alarming devices in every facet of the healthcare facility, the limited frequency spectrum available for wireless applications will be heavily crowded. Therefore, wireless device using cognitive radio techniques are envisioned for future healthcare facilities. The legacy wired communication is not scalable to meet this massive growth and demand of electrical equipments in next generation hospitals.

Manuscript received September 5, 2014; accepted October 7, 2014. Date of publication October 16, 2014; date of current version December 11, 2014. This work was supported by NSERC Discovery Grants. The associate editor coordinating the review of this paper and approving it for publication was Prof. Kiseon Kim.

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Digital Object Identifier 10.1109/JSEN.2014.2363571

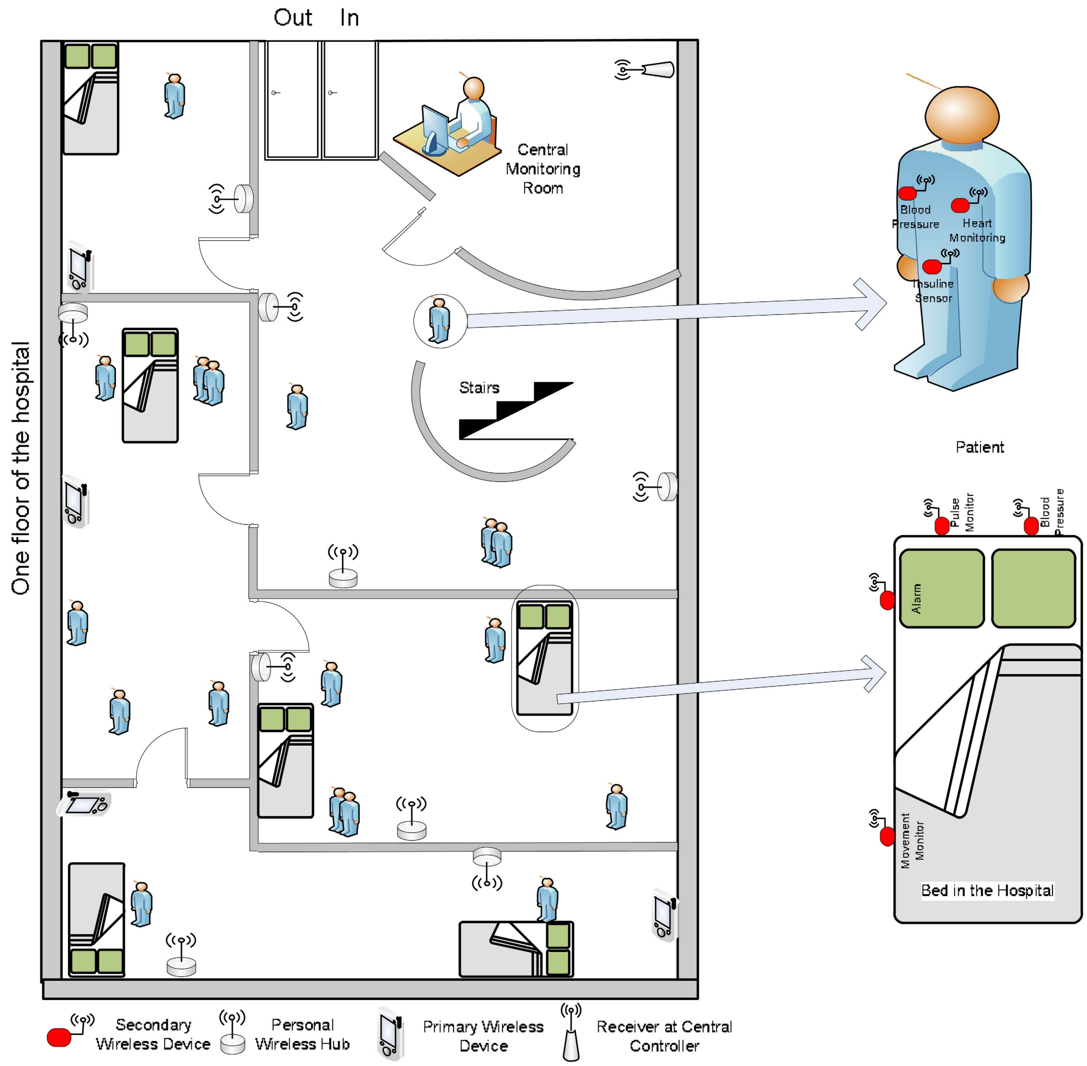


Fig. 1. A new generation healthcare facility.

Also, the telehealth paradigm forces the researchers to focus on wireless technologies that are energy efficient, simple and robust. To cope with the wireless spectrum availability challenge, in this paper, we use cognitive radio technology. Formally, a cognitive radio is defined as [14], "*a radio that changes its transmitter parameters based on the interaction with its environment*". The cognitive radio has been mainly proposed to improve the spectrum utilization by allowing (unlicensed) secondary wireless devices (SWDs) to use under-utilized licensed frequency bands. In this paper, the wireless sensor devices and PWHs act as SWDs and, all other wireless and telecommunication equipment are termed as (licensed) primary wireless devices (PWDs). A well designed multiple PWH assignment and power control scheme can reduce the electromagnetic and in-band interference induced to the other devices in the hospital, where the PWHs act as relays in the hospital network.

Two kinds of channels are considered in the paper. First one is the channel between SWDs and the second is between SWD and PWD. It is well known that for channel between SWD, pilot symbol mechanism gives very good estimate of channel coefficients. The main challenging task is to estimate channel between SWD and PWD. In this paper, we assume that there is some cooperation between primary and secondary network. The base station of secondary user knows in advance the pilot symbol mechanism of the primary users. We also assume that SWD central controller has access to the location database. The combination of pilot signal strength and location give a good knowledge of channels to the central controller. In this paper, we use the recommendation of IEEE 802.22 WRAN standard which has two schemes for PWD protection. These are listen-before-talk (spectrum sensing) and geo-location/database schemes. In the listen-before-talk scheme, the SWD senses the presence of primary network signals in order to select the channels that are not in use. In geo-location/database scheme, the locations of primary and secondary devices are stored in a central database. The central controller of the SWDs has the access to the location database. In this paper, we assume that secondary network's central controller gets the location information of each PWD from the central database. We also assume that BS knows the active PWD's channel gains. The knowledge of PWDs location and channel gains adds overhead on the CR operations. The knowledge of PUs location and channel gains adds overhead on the CRS operations. The overhead refers to any extra sensing time, delay, energy, and operations devoted to cooperative/non-cooperative spectrum sensing. A number of low overhead channel sensing methods are in the literature [15]–[18]. In this paper, we assume that feedback channel is reliable and overhead communication is much less than actual payload data.

A. Literature Review and Contribution

In the this subsection, we will highlight the existing work related to the resource allocation in wireless systems that can be applied to healthcare facilities and hospital. The idea of using cooperating PWHs (relays) has been much discussed in the past decade [19]–[22]. In a wireless communication system, relaying techniques can offer significant benefits in the throughput enhancement as well as in coverage extension [19], [22]. In the cognitive radio system, relays can be particularly useful for reducing the transmission power at the source and thus reducing the interference to the PWDs.

In [23], [24], [26], and [44], the authors use cognitive radio technology for wireless sensor devices. The relays play an important role in many real life wireless sensor network (WSN) applications [27]–[30]. Experimental results and WSN test-beds for cooperative communication also provide insight of the relay power and lifetime. In [27], the authors experimentally show the performance of amplify and forward (AF) cooperative scheme. The results show that AF scheme is highly beneficial for power–aware wireless sensor devices. In [11], the authors present a relay assisted human monitoring system in body area network that uses IEEE 802.15.3/802.15.4 standards for its monitoring applications. The performance analysis of dual-hop relaying in cognitive radio sensor network (CRSN) is described in [31]. In [33], the authors present spectrum sensing and communication protocols for a dual-hop sensor network operating in VHF-UHF band. An information theoretic data gathering and effect of relaying in CRSN are described in [32]. In [34], a cognitive dual-hop relaying based sensing-transmission protocol is proposed. In [35], the authors present an optimal solution for source sum-power minimization in multi-sensor single-relay networks. Subspace-based cooperative spectrum sensing and correlation-based sensing for CRSN were proposed in [26] and [36] respectively. One open research question in CRSN is the per hop throughput optimization. Increasing the number of hops will increase delay and complexity [37].

Based on the above literature review, a closer look at Table I reveals that wireless resource allocation in next generation healthcare facilities and hospitals is an open area of research. There are some work in the literature that claim resource allocation/management in helathcare facilities. As per the best knowledge of the authors, the literature review reveals that there is no resource allocation scheme in the literature that uses multiple PWH assignment using cognitive radio technology in healthcare facility. The existing research work on resource allocation in wireless network is not always applicable to hospital environment. As depicted in Table I, there are papers that investigate the spectrum reuse in hospital environment [39]–[51]. The closest possible existing work is done in [19]–[21]. In [19]–[21], authors suggested multiple PWH (relay) assignment schemes for wireless network. These schemes are not applicable to hospital environment. Also, we can not apply spectrum reuse (cognitive radio capability) due to lack of interference mitigation capability.

In this paper, we propose a framework and low complexity algorithm for interference-aware joint power control and multiple PWH assignment (IAJPCPA) in a healthcare facility with cognitive radio capability. In the proposed framework, any wireless sensor device can send and receive data from multiple PWHs. The proposed IAJPCPA is a non-convex mixed integer non-linear optimization problem (NC-MINLP) which is generally NP-hard. The main objective of IAJPCPA is to maximize the total transmission data rate by assigning multiple PWHs to the wireless sensor devices under the constraint of acceptable interference to the licensed wireless devices. The computational complexity of the IAJPCPA grows exponentially with the number of PWHs and wireless sensor devices. Therefore, we present an efficient PWH assignment and power control scheme for IAJPCPA.

Throughout this paper, we use $\boldsymbol{A}$, $\boldsymbol{a}$, and a to represent matrix, vector and an element of a vector respectively. The rest of the paper is organized as follows. The system model and problem formulation are presented in section II. In section III, we present our low complexity interference aware (IAGA) algorithm and its computational complexity. Simulation results are presented in section IV. Finally, section V concludes the paper. Table II presents the notations used in this paper.

II. System Model and Problem Formulation

We consider a hospital with wireless sensor devices. Each wireless sensor device can send the data to the central controller with the aid of PWHs as shown in Fig. 1. We use cognitive radio technology to share the spectrum with the licensed wireless devices. The transmitting devices that use cognitive radio technology are known as secondary wireless devices (SWDs) and the licensed wireless devices are known as primary wireless devices (PWDs). The hospital may have a central monitoring room that keeps track of vital patient personal health information (PHI) coming from different SWDs. All the SWDs send the PHI data to central monitoring room with the help of personal wireless hubs (PWHs). The PWH acts as a wireless relay in the hospital. Cooperation of PWH can help in extending the lifetime of low power SWDs and reduce the interference to the PWDs. In this paper, we use the terminology SWDs and wireless sensor devices interchangeably. Also we use the terminology PWH and relay interchangeably.

There are K SWDS, L relay nodes (PWHs) and M PWDs, for which the transmission power of the transmitting nodes must be limited. We consider a half-duplex two-hop cooperative protocol for the SWD and PWH transmission. The channel

TABLE I

COMPARISON OF DIFFERENT APPROACHES FOR WIRELESS RESOURCE ALLOCATION IN HEALTHCARE

Ref	Spectrum Reuse	Interference Mitigation	Applicable to Hospital	PWH (Relay)	Multiple PWH Assignment	Remarks
[9]			✓			A method for ECG Feature Extraction for Mobile Healthcare
[10]			✓	✓		Relaying protocols for human monitoring
[11]				✓		A relay network to increase life time in wireless body area sensor networks
[12]			✓			Network coding for Wireless Body Area Networks
[19]				✓	✓	Bandwidth and Power Allocation for Cooperative Strategies in Gaussian Relay Networks
[20]				✓	✓	Multiple relay/PWH selection schemes and their achievable diversity orders
[21]				✓	✓	Relay/PWH Assignment and Power Allocation in Selection Based Cooperative Cellular Networks
[23]	✓	✓	✓			Design of Cognitive Radio-based WSN
[27]			✓	✓		Testbed of a Cooperative Communication System
[31]	✓	✓		✓		Relaying in Cognitive WSN
[33]	✓	✓	✓	✓		Channel Sensing and communication in cognitive sensor relay networks
[38]	✓		✓			A cognitive radio system for e-health applications in a hospital environment
[37]			✓	✓		Multi-hop transmission: benefits and deficits
[39]	✓	✓	✓			Cognitive Radio-based Wireless Body Area Networks for medical applications
[40]	✓	✓	✓	✓		Cognitive radio based hospital management system
[41]	✓		✓			Cognitive radio for medical wireless BAN
[42]	✓	✓	✓			Interference Mitigating in the hospital area communication's using Cognitive Radio Networks
[43]	✓		✓			Wireless medical telemetry
[44]			✓			Resource management for u-healthcare service in LTE networks
[45]		✓	✓	✓		Electromagnetic Interference-Aware Transmission Scheduling and Power Control in Hospital Environments
[46]		✓	✓			EMI-Aware Prioritized Wireless Access Scheme for e-Health Applications in Hospital Environments
[47]		✓	✓			Bandwidth allocation in view of EMI on medical equipments in healthcare monitoring systems
[48]			✓			Robust license-free Body Area Network access for reliable public m-health services
[49]		✓	✓	✓		Accelerated genetic algorithm for bandwidth allocation in view of EMI for wireless healthcare
[50]	✓		✓			Realization of Public M-Health Service in License-Free Spectrum
[51]			✓			QoS Aware Wireless Communication in Hospitals

gain between kth SWD and central controller, kth SWD and lth PWH, lth PWH and the central controller, kth SWD and the mth PWD and lth PWH to the mth PWD are denoted by h_k^c, h_k^l, h_l^c, g_m^k and g_m^l respectively. A central controller (CC) jointly assigns PWHs to the SWDs and decides the PWHs and power levels. We denote by p_l, the transmission power of the lth PWH and $\eta(p_l, l, m) = p_l|g_m^l|^2$, the interference power contributed to the mth PWD from the lth PWH with power p_l. We denote by p_k the transmission power of the kth SWD. A system model with channel gains is shown in Fig. 2.

We consider a two-step shared-band half-duplex amplify and forward (AF) scheme for PWHs to retransmit the wireless sensor device data [19]. Table III shows the half-duplex protocol. In the first time slot, SWDs will transmit, and central controller and PWH will receive data. In the second time slot, PWH will retransmit its data to central controller. We assume that each wireless sensor device operates in its designated frequency band that does not overlap with other SWDs' bands. Each PWH will transmit and receive in the same frequency band. Each symbol is transmitted in two time slots. First time slot is for source and the second time slot for PWHs' transmission. In the first time slot, the signal

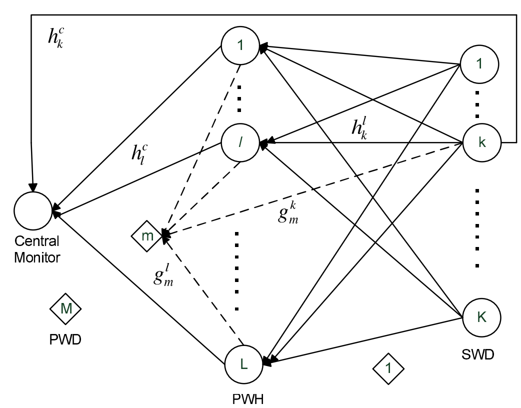


Fig. 2. System Model.

received by the lth PWH (after listening to the kth wireless sensor devices's band) can be written as $\sqrt{(p_k)}h_l^c s + Z_l$, where complex-valued s represents the transmitted symbol and Z_l represents the complex-valued white Gaussian noise at lth PWH. In the second time slot, the PWHs amplify the received signal and re-transmit the amplified signal. We consider a system in which each PWH can be assigned to only one

TABLE II

NOTATIONS

Symbol	Definition
K	number of secondary wireless devices (SWDs)
L	number of personal wireless hubs (PWHs)
M	number of personal wireless devices (PWDs)
h_k^c	channel gain between kth SWD and central controller
h_k^l	channel gain between kth SWD and lth PWH
h_l^c	channel gain between lth PWH and the central controller
g_m^k	channel gain between kth SWD and the mth PWD
g_m^l	channel gain between lth PWH to the mth PWD
$I_{m,k}^{max}$	interference threshold for the mth PWD in the kth frequency band
p_l	transmission power of the lth PWH
$\eta(p_l, l, m)$	interference power contributed to the mth PWD from the lth PWH with power p_l
p_k	transmission power of the kth SWD
P_L	set of PWH power level respectively
P_S	set of wireless sensor device power level
$\mathcal{K}$	set of SWDs
$\mathcal{L}$	set of available PWHs
L_k	subset of PWHs assigned to the kth SWD such that $\bigcup_{k\in\mathcal{K}} L_k = \mathcal{L}$
$\|P_L\|$	cardinality of set P_L
$\|P_S\|$	cardinality of set P_S

TABLE III

HALF-DUPLEX PROTOCOL

	SWD	PWH	CC
Slot 1	Transmit	Listen	Listen
Slot 2	-	Transmit	Listen

SWD while a SWD can receive data from multiple PWHs. The channel capacity of the kth SWD with L PWHs using shared band AF cooperative scheme is [19]

$$C_k = \frac{1}{2}\log\left(1+\gamma_k^1+\gamma_k^2\right) \tag{1}$$

where

$$\gamma_k^1 = \frac{p_k|h_k^c|^2}{N}, \qquad \gamma_k^2 = \frac{p_k\left(\sum\limits_{l\in L_k}|h_l^c h_k^l|\beta_l\sqrt{p_l}\right)^2}{N\left(1+\sum\limits_{l\in L_k}\left(|h_k^l|\beta_l\sqrt{p_l}\right)^2\right)}$$

and

$$\beta_l = \left(\sqrt{p_k|h_l^c|^2+\frac{N}{2}}\right)^{-1}.$$

Let $\mathcal{K} = \{1, 2, \ldots, K\}$ and $\mathcal{L} = \{1, 2, \ldots, L\}$ be the set of SWDs and available PWHs respectively. We define by $L_k \subseteq \mathcal{L}$, $\forall k \in \mathcal{K}$, the subset of PWHs assigned to the kth SWD such that $\bigcup_{k\in\mathcal{K}} L_k = \mathcal{L}$. Two kinds of PWH assignments are possible in hospitals with relay assisted wireless sensor devices. One is the restricted PWH assignment (RPWHS) and the other is unrestricted PWH assignment (UPWHRS). In the former, each PWH can only help one wireless sensor device in one time slot while in the latter a PWH can help multiple wireless sensor devices. Both schemes have their own advantages and disadvantages. The RPWHS is useful for battery limited PWHs with simple electronics circuitry. In unrestricted PWH assignment, each PWH has a complex electronics circuitry that can be used for different power levels and multiple data transfers. In RPWHS, the subsets $L_k \subseteq \mathcal{L}$ are mutually disjoint-i.e.,

$$\bigcap_{k\in\mathcal{K}} L_k = \varnothing. \tag{2}$$

The interference from the PWHs and wireless sensor devices can be defined as

$$\sum_{l\in L_k} \varepsilon_k^l p_l |g_m^l|^2 \le I_{m,k}^{max}, \quad \forall(m,k), \tag{3}$$

$$p_k|g_m^k|^2 \le I_{m,k}^{max}, \quad \forall(m,k), \tag{4}$$

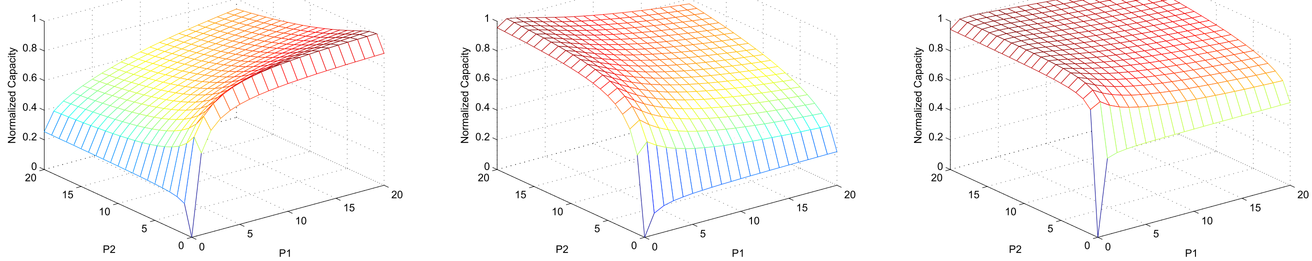
where $I_{m,k}^{max}$ is the interference threshold for the mth PWD in the k frequency band. Since SWDs are operating in the same frequency band as licensed wireless devices, interference threshold is used to protect the licensed wireless devices from the harmful interference to the medical devices. To make wireless sensor devices and PWHs inexpensive and simple, we assume that each wireless sensor device and PWH can not transmit any arbitrary power level; instead, these devices can only transmit at discrete power levels. Discrete power allocation (DPA) also helps in simplifying the end-to-end control channel traffic. The assumption of DPA is also relevant to the networks, which deploy low cost wireless sensor devices and PWHs that do not have sophisticated circuitry to support transmissions on arbitrary power levels. In this work, we consider inexpensive wireless sensor devices and PWHs that can operate only at a finite number of transmission power levels. Let P_L and P_S be the set of PWH and wireless sensor device power levels respectively comprising $\lambda + 1$ uniformly spaced discrete power levels -i.e., $P_L = \left\{0, \frac{p_l^{max}}{\lambda}, \frac{2p_l^{max}}{\lambda}, \frac{3p_l^{max}}{\lambda} \ldots, p_l^{max}\right\}$ and $P_S = \left\{0, \frac{p_s^{max}}{\lambda}, \frac{2p_s^{max}}{\lambda}, \frac{3p_s^{max}}{\lambda}, \ldots, p_s^{max}\right\}$. We denote by $|P_L|$ and $|P_S|$, the cardinality of sets P_L and P_S respectively.

Mathematically, we can write the joint PWH assignment and power allocation problem as:

$$\max_{\boldsymbol{p_k \in P_S, p_l \in P_L}} \sum_{k=1}^{K} C_k$$
$$\text{subject to (2), (3) and (4)} \tag{5}$$

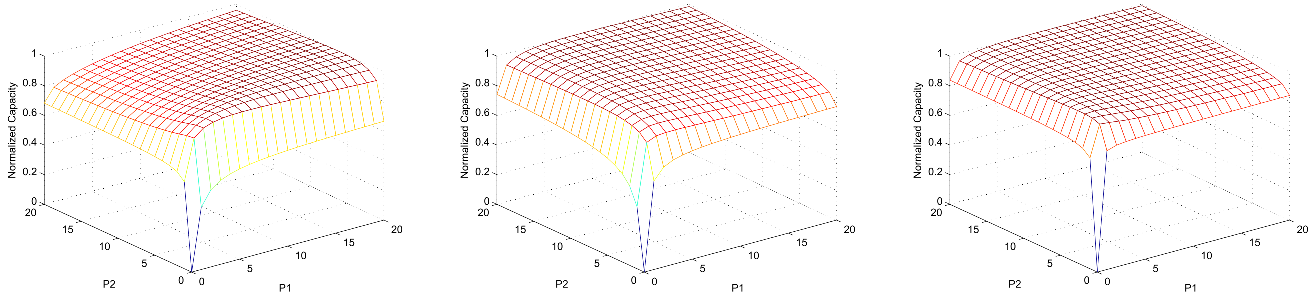
The above problem is NP-hard to solve. It means, we can not get the optimal solution in polynomial time. Also, even for a given realization of integer variables, the optimization problem in (5) is not a concave function of the PWH powers. Thus, even for a given realization of integer variables, convex optimization techniques cannot be applied to the resulting optimization problem. For comparison, we provide an upper bound on the sum-rate capacity. The obtained upper bound is concave for a given realization of integer variables. The concave upper bound can be derived by using the Cauchy-Schwarz inequality on γ_k^2 as:

$$\frac{\left(\sum_l |h_l^c h_k^l|\beta_l\sqrt{p_l}\right)^2}{1+\sum_l\left(|h_l^c|\beta_l\sqrt{p_l}\right)^2} < \frac{\left(\sum_l |h_l^c|^2\right)\left(\sum_l |h_k^l|^2\beta_l^2 p_l\right)}{1+\sum_l\left(|h_k^l|^2\beta_l^2 p_l\right)} \tag{6}$$



(a) (b) (c)

Fig. 3. Non-concave capacity functions for different channel conditions. (a) Non-concave Objective function. (b) Non-concave Objective function. (c) Non-concave Objective function.



(a) (b) (c)

Fig. 4. Concave upper bounds for different channel conditions. (a) Concave upper bound for 3(a). (b) Concave upper bound for 3(b). (c) Concave upper bound for 3(c).

The above upper bound is a concave function of PWH powers. The proof is given in the Appendix. Figs. 3 and 4 show exemplary scenario for non-concave objective function and their respective concave upper bounds for three different sets of channel gains. For this example, number of SWDs, $K = 1$ and number of PWDs, $L = 2$. The channel gains for these three scenarios are set to $h_l^c = \{(0.558, 1.276), (2.45, 0.757), (5.43, 2.54)\}$ and $h_k^l = \{(1.86, 0.96), (0.65, 1.145), (1.38, 2.2)\}$. These gains are chosen randomly. We can easily observe the concavity of the objective upper-bound in these figures.

We first note a special structure of the optimization problem in (5). For any choice of PWH assignment and PWH transmission power, the objective function is an increasing function of variable p_k, the source transmission power. In addition, the only constraints on variable p_k are $p_k \in P_S, \forall k$ and $p_k|g_m^k|^2 \leq I_{m,k}^{max}, \forall (m, k)$, which can be simplified to $p_k \leq \min\left(p_s^{max}, \frac{I_{1,k}^{max}}{|g_1^k|^2}, \ldots, \frac{I_{M,k}^{max}}{|g_M^k|^2}\right)$, and variable p_k does not appear in any other constraints in (5). Therefore, for any choice of PWH assignment $\{\varepsilon_k^l\}$ and PWH transmission power $\{p_1, p_2, \ldots, p_L\}$, maximizing source power p_k is equivalent to the nearest lower member of the set P_S-i.e.,: $\left\lfloor \min\left(p_s^{max}, \frac{I_{1,k}^{max}}{|g_1^k|^2}, \ldots, \frac{I_{M,k}^{max}}{|g_M^k|^2}\right) \right\rfloor \in P_S$, for each k. Although, reducing the decision variable p_k will help in reducing the computational time, this problem is still computationally complex due to integer variables. To reduce the computational complexity, in the next section, we will present a greedy algorithm for multiple PWH assignment with discrete power level control.

III. Algorithm for PWH Assignment With Discrete Power Allocation

One of the basic ideas in designing this algorithm is that we assign a PWH to the SWD k only if the channel between that PWH and the SWD k is the best among all the SWDs and, the PWH satisfies the interference constraint at all M PWDs. In order to make the description of this algorithm clear, we will first use an example to provide an illustration of the algorithm description. Algorithm 1 presents the pseudo code of interference aware greedy assignment (IAGA) and Table IV presents explanatory example of IAGA at the end of different iterations.

A. Illustrative Example

In the example, we consider a system comprising three SWDs (namely K_1, K_2 and K_3), two PWDs (namely M_1, M_2), and seven PWHs (namely L_1, L_2, ...,L_7). The interference thresholds of PWDs M_1 and M_2 are 10mW and 20mW in each SWD's band respectively.

The IAGA is performed in two stages. At stage 1, the algorithm determines the transmission power, p_l, for each PWH l and computes some other quantities for stage 2. Let us denote by $\eta(p_l, l, m) = p_l|g_m^l|^2$ the interference caused by

TABLE IV
EXAMPLE OF IAGA

First Iteration

	p_l^*	Λ			$\eta(p_l^*, l, m)$	
		K_1	K_2	K_3	M_1	M_2
$L_1, -$	p^{max}	8	3	5	6	13
$L_2, -$	p^{max}	15	18	50	8	5
$L_3, -$	$\frac{3p^{max}}{\lvert P_L \rvert}$	49	23	44	2	7
$L_4, -$	p^{max}	8	39	2	10	15
$L_5, -$	p^{max}	20	22	26	1	1
$L_6, -$	$\frac{p^{max}}{\lvert P_L \rvert}$	9	1	40	6	10
$L_7, \times$	0					

(a) Illustration of Stage1 of IAGA, column p_l^* is the selected power level at PWH l, columns K_1, K_2 and K_3, denote individual SNR contribution of each PWH at SWD K_1, K_2 and K_3, respectively. Column (M_1, M_2) denotes the interference contributed by each PWH individually at each PWD.

Second Iteration

	Λ			$\eta(p_l^*, l, m)$	
	K_1	K_2	K_3	M_1	M_2
$L_1, -$	8			6	13
$L_2, -$			50	8	5
$L_3, -$	49			2	7
$L_4, -$		39		10	15
$L_5, -$			26	1	1
$L_6, -$			40	6	10
$L_7, \times$					

(b) Selection of SWD $\tilde{k} = K_3$ and PWHs to be assigned to SWD $\tilde{k}$, i.e. set $L_k = \{L_2, L_5, L_6\}$.

Third Iteration

	Λ			$\eta(p_l^*, l, m)$	
	K_1	K_2	K_3	M_1	M_2
$L_1, -$	8			6	13
L_2, K_3					
$L_3, -$	49			2	7
$L_4, -$		39		10	15
L_5, K_3					
$L_6, \times$					
$L_7, \times$					

(c)PWHs L_2 and L_5 are assigned to SWD $\tilde{k} = K_3$. PWH L_6 is removed from set R due to violation of interference constraints at M_1.

Fourth Iteration

		Λ			$\eta(p_l^*, l, m)$	
		K_1	K_2	K_3	M_1	M_2
$L_1, -$		8			6	13
L_2, K_3						
$L_3, -$		49			2	7
$L_4, -$			39		10	15
L_5, K_3						
$L_6, \times$						
$L_7, \times$						

(d) Selection of SWD $\tilde{k} = K_1$ and PWHs to be assigned to SWD, i.e. set $L_k = \{L_1, L_3\}$.

Fifth Iteration

	Λ			$\eta(p_l^*, l, m)$	
	K_1	K_2	K_3	M_1	M_2
L_1, K_1					
L_2, K_3					
L_3, K_1					
$L_4, -$		39		10	15
L_5, K_3					
$L_6, \times$					
$L_7, \times$					

(e) PWHs L_1 and L_3 are assigned to K_1. In the next iteration SWD $\tilde{k} = K_2$ is selected and PWH in set L_k is L_4.

Sixth Iteration

	Λ			$\eta(p_l^*, l, m)$	
	K_1	K_2	K_3	M_1	M_2
L_1, K_1					
L_2, K_3					
L_3, K_1					
L_4, K_2					
L_5, K_3					
$L_6, \times$					
$L_7, \times$					

(f) PWH L_4 is assigned to SWD $\tilde{k} = K_2$.

PWH l on PWD m with power p_l. In stage 1, the algorithm sets the transmission power, p_l of each PWH l to

$$p_l^* \leftarrow \max\{p_l \in P_L | \eta(p_l, l, m) \leq I_{m,k}^{max}, \forall(m, k)\}. \quad (7)$$

Note that $p_l |g_m^l|^2$ can be interpreted as the interference the lth PWH would cause on PWD m, if no other PWH were transmitting at that time. In words, the algorithm at stage 1 sets the transmission power of each PWH as high as possible with the constraint that the interference it individually causes on each PWD is within its interference constraint (interference tolerance level). Note that such a transmission power level for some PWH can be zero if every positive power value in set P_L individually causes interference on some PWD above its tolerance level. The PWHs with power level set to zero are removed from further consideration; it means that at the end of this stage, the algorithm selects the PWHs that individually satisfy the interference constraints at all the PWDs. We denote the set of selected PWHs as Ψ. For each of these selected PWHs and power levels, the algorithm evaluates the individual SNR contribution by each PWH at each SWD–i.e., the individual SNR that each SWD would have if it does not receive a signal from the source or other PWHs.

The SNR contributions from the PWHs are stored in matrix Λ. Table IV illustrates the values stored in matrix Λ for up to six iterations. The algorithm then calculates the aggregate or sum-interference, $\Gamma^l = \sum_{m=1}^{M} \eta(p_l^*, l, m)$, from each PWH to the PWDs. Table IV(a) illustrates the transmission power levels of all the PWHs determined as p_l^*, the individual SNRs in Λ, and the individual interferences $\eta(p_l^*, l, m)$ computed in stage 1. Note that PWH L_7 is removed from further consideration for assignment in subsequent steps as its individual interference contribution violates the interference constraints. In stage 2, at each iteration, the algorithm determines the set of PWHs assigned to a SWD in a greedy manner. A step-by-step description of IAGA is described in section III-B later.

For clarity of exposition, we now use our example to illustrate the steps of stage 2. From Table IV(a), for each PWH, we select the SWD where it generates its maximum individual SNR -e.g., PWH L_1 generates maximum SNR at SWD K_1 as we have $\Lambda(1, 1) = 8 > 3 = \Lambda(1, 2)$ and $\Lambda(1, 1) = 8 > 5 = \Lambda(1, 3)$. As mentioned earlier, we assign a PWH to the SWD k only if that PWH has the best channel to the SWD k among all the SWDs. Thus, in Table IV(b) for each PWH, we retain the SNR value of that PWH/SWD pair where the PWH has the best channel gain. The selection of PWH/SWD pair from Table IV(a) in this manner results in Table IV(b), where for PWH L_1 the bins for $\Lambda(1, 2)$ and $\Lambda(1, 3)$ are blanked. Among these selected PWH/SWD pairs, the pair that has the highest SNR value is chosen and the corresponding SWD is denoted as $\tilde{k}$. For illustration, in Table IV(b), $\Lambda(2, 3)$ has the highest individual SNR among all entries of Λ and $\tilde{k} = K_3$. The PWHs whose individual SNR contributions are maximum at SWD $\tilde{k}$ can be potentially assigned to that SWD. From Table IV(b), these PWHs are L_1, L_5 and L_6 and, they constitute the set L_k. Then, the algorithm checks whether

Algorithm 1 : Interference-Aware Greedy Algorithm (IAGA)

1: **Initialization:** $\Lambda(l,k) \leftarrow 0\,\forall l \in \mathcal{L}, k \in \mathcal{K}, \Gamma^l \leftarrow 0, \forall l \in \mathcal{L}$
2: **Define:** $\eta(p_l,l,m) \equiv p_l|g_m^l|^2$
3: $C_k \leftarrow 0, \forall k \in \mathcal{K}, \Psi = \varnothing$
4: **Stage 1:**
5: **for** $l = 1 to |\mathcal{L}|$ **do**
6: $\quad p_l^* \leftarrow \max\{p_l \in P_L | \eta(p_l,l,m) \leq I_{m,k}^{max}, \forall(m,k)\}$
7: $\quad$ **if** $p_l^* \neq 0$ **then**
8: $\quad\quad \Lambda(l,k) \leftarrow \frac{p_l^*|h_k^l|^2}{N}$
9: $\quad\quad \Gamma^l \leftarrow \sum_{m=1}^{M} \eta(p_l^*,l,m)$
10: $\quad\quad \Psi \leftarrow \Psi \bigcup l$
11: $\quad$ **else**
12: $\quad\quad \eta(p_l^*,l,m) \leftarrow 0$
13: $\quad$ **end if**
14: **end for**
15: **Stage 2:**
16: **while** $\Psi \neq \varnothing$ **do**
17: $\quad \Theta(l) \leftarrow \arg\max_{k \in \mathcal{K}} \Lambda(l,k), \forall l \in \Psi$
18: $\quad \bar{\Lambda} \leftarrow \max\{\Lambda(1,\Theta(1)),\ldots,\Lambda(L,\Theta(L))\}$
19: $\quad \tilde{k} \leftarrow \{\Theta(l)|\Lambda(l,\Theta(l)) = \bar{\Lambda}\}$
20: $\quad L_k \leftarrow$ Get the PWHs from Θ that are connected to $\tilde{k}$
21: $\quad$ **while** $L_k \neq \varnothing$ **do**
22: $\quad\quad \Delta_m \leftarrow \sum_{l \in L_k} \eta(p_l^*,l,m), \forall m$
23: $\quad\quad$ **if** $\Delta_{m,k} \leq I_{m,\tilde{k}}^{max}, \forall m$ **then**
24: $\quad\quad\quad C_{\tilde{k}} \leftarrow$ Apply (1) for L_k
25: $\quad\quad\quad \Lambda(l,k) \leftarrow 0\,\forall l, \Psi \leftarrow \Psi \setminus R$
26: $\quad\quad\quad$ Break
27: $\quad\quad$ **else**
28: $\quad\quad\quad \tilde{l} \leftarrow \arg\max_{l \in L_k} \Gamma^l$
29: $\quad\quad\quad \eta(p_{\tilde{l}},\tilde{l},m) \leftarrow 0, \Gamma^{\tilde{l}} \leftarrow 0, L_k \leftarrow L_k \setminus \tilde{l}, \Psi \leftarrow \Psi \setminus \tilde{l}$
30: $\quad\quad$ **end if**
31: $\quad$ **end while**
32: $\quad \Lambda(l,k) \leftarrow 0\,\forall l$
33: **end while**

the cumulative interference level generated by these three PWHs at the PWDs is below the required tolerance level. We observe from Table IV(b) that the cumulative interference from these three PWHs violates the interference threshold of M_1 -i.e., $\Delta_1 = \eta(p_1^*,1,1) + \eta(p_5^*,5,1) + \eta(p_6^*,6,1) = (8 + 1 + 6 > I_1^{max}(10))$. In this algorithm, if the PWHs during the assignment violates the interference constraints at any of the PWDs, then the PWH with the highest sum interference $\Gamma^l = \sum_{m=1}^{M} \eta(p_l^*,l,m)$ is removed from further consideration for PWH assignment. From Table IV(b), it is observed that PWH L_6 has the highest sum interference among the PWHs in set L_k as sum interferences from L_2, L_5 and L_6 are $8 + 5 = 13$, $3 + 1 = 4$ and $6 + 10 = 16$ respectively. Therefore, PWH L_6 is removed from set L_k. Since the remaining PWHs, L_2 and L_5, together satisfy the interference constraints, they are both assigned to SWD K_3 as done in Table IV(c). The PWHs and SWDs that have already been assigned are no longer considered for the rest of the algorithm, as illustrated by the blanks in Table IV(c). These steps are repeated until all the remaining PWHs are assigned or removed from consideration. The subsequent steps are illustrated in Table IV(c) to Table IV(f).

B. Step-by-Step Description of IAGA

We now present a step-by-step description of the pseudo code of stage 2 given in Algorithm 1. In line 17 of stage 2 in Algorithm 1, for each PWH a SWD, that receives the maximum SNR from it, is chosen and stored in the variable Θ as:

$$\Theta(l) \leftarrow \arg\max_{k \in \mathcal{K}} \Lambda(l,k), \quad \forall l \in \Psi. \tag{8}$$

Line 18 determines the PWH–SWD pair that has the maximum SNR which is mathematically expressed as,

$$\bar{\Lambda} \leftarrow \max\{\Lambda(1,\Theta(1)),\ldots,\Lambda(L,\Theta(L))\}. \tag{9}$$

In line 19, the SWD $\tilde{k}$ which has the highest SNR is determined as $\tilde{k} \leftarrow \{\Theta(l)|\Lambda(l,\Theta(l)) = \bar{\Lambda}\}$. The PWHs that generate maximum SNR at SWD $\tilde{k}$ are determined from the set Θ and stored in the set L_k.

After getting the set L_k in stage 2, the algorithm iterates over the PWHs in the set L_k. In each iteration, for every PWD m, the sum of the interference levels generated by the PWHs in the set L_k (on PWD m) is evaluated as $\Delta_m \leftarrow \sum_{l \in L_k} \eta(p_l^*,l,m), \forall m$. If the interference constraints, $\Delta_{m,k} \leq I_{m,\tilde{k}}^{max}, \forall m$ are satisfied then the capacity of the SWD $\tilde{k}$ is calculated for the PWHs in set L_k, and the assigned PWHs are removed from the sets L_k and Ψ. If the interference constraint is violated at any PWD, then we choose the PWH l (from the set L_k) that causes maximum sum interference (as given by Γ^l). The selection of PWH l is mathematically written as $\tilde{l} \leftarrow \arg\max_{l \in L_k} \Gamma^l$. The selected PWH l is removed from the set L_k and Ψ. Note that the retention of PWH l in the set Ψ may increase the capacity of the system but it also increases the complexity of our algorithm. By the end of first iteration over the set Ψ, the SWD $\tilde{k}$ has its assigned PWHs. The process is repeated till $\Psi \leftarrow \varnothing$.

C. Complexity Analysis

The main advantage of the above proposed algorithm is its low implementation complexity. In this section, we will compare the complexity of the proposed algorithm (IAGA) with the exhaustive search algorithm (ESA), which achieves an exactly optimal solution. The complexity of IAGA is measured in terms of flops and assignment operator take one flop[1] [52].

First, we will describe the complexity of the objective function and the constraints. The term inside the log in (1) requires approximately $11L$ flops. The interference constraint for each PWD requires $2L|P_L|$ flops. The sum interference $\sum_{m=1}^{M} \eta(p_l^*,l,m)$ for each PWH requires M flops. IAGA takes approximately $L(3M|P_L| + 2K + M + 2)$ flops

[1] A flop is defined as a real floating-point operation. A real addition, multiplication or division is counted as one flop. A complex addition is counted as two flops and a complex multiplication has four flops. The multiplication of a pq matrix with a qm matrix takes approximately $2pqm$ flops. Addition and removal of an element from a set takes one flop. The logical operator (e.g. comparison etc.) takes one flop.

for first stage and $11L^3 + L^2(K + 2M + 2) + L(K + 1)$ for second stage. Therefore, the total number of flops required by IAGA is

$$\begin{aligned}\text{Number of flops } &\approx 11L^3 + L^2(K + 2M + 2)\\ &\quad + L(3M|P_L| + 2K + M + 3)\\ &\approx O(L^3 + L^2K + L^2M).\end{aligned}$$

From the above complexity analysis, we conclude that IAGA has a polynomial-time complexity with respect to number of PWHs and number of SWDs. The computational complexity of exhaustive search algorithm (ESA) is $O(L^K)$.

IV. Simulation Results

In this section, we present some simulation results to demonstrate the performance and numerical convergence of the proposed iterative scheme. The impact of network parameters is also analyzed.

In all the simulations, the channel gain h is modeled as [53]

$$h = \Phi K_o \left(\frac{d_o}{d}\right)^{\beta}, \tag{10}$$

where K_o is a constant that depends on the antenna characteristic and average channel attenuation, d_o is the reference distance for the antenna far field, d is the distance between transmitter and receiver, β is the path loss constant and Φ is the Rayleigh random variable. Since this formula is not valid in the near field, in all the simulation results, we assume that d is greater than d_o. In all the results, $d_o = 10$m, $K_o = 50, \beta = 3$. The channel gain g is also modeled the same was as h in the simulation.

We also present the simulation results of the proposed IAGA. The performance of proposed IAGA algorithm is compared with (a) exhaustive search with upper bound (ESA-UB), (b) exhaustive search with discrete power allocation (ESA-Discrete) and (c) one-to-one exhaustive search assignment. For ESA-UB, a conventional convex optimization technique is used to determine the power of all the PWH assignment subsets. The disadvantage of this approach is that for ESA, we have to compute power allocation over all the possible PWH assignments. One-to-one ESA obtains an optimal solution for one-to-one PWH assignment. One-to-one PWH assignment is formulated by adding an additional constraint in (5) where a SWD can only receive data from one PWH–i.e., and a PWH can send data to only one SWD. Comparison between IAGA and one-to-one ESA helps us to show the effect of multiple PWH assignments in the cognitive radio system. Since the problem in (5) is a nonconvex MINLP NP-hard problem, an exact optimal solution is unknown. In this paper, we numerically compare the results of the proposed IAGA scheme with an exhaustive search algorithm. In all simulations noise variance is assumed to be one. The system parameters used for simulations are selected such that we can examine the effect of different system parameters (e.g., interference threshold level, number of primary users, number of secondary users, quantize power levels etc.) on the performance of the proposed schemes.

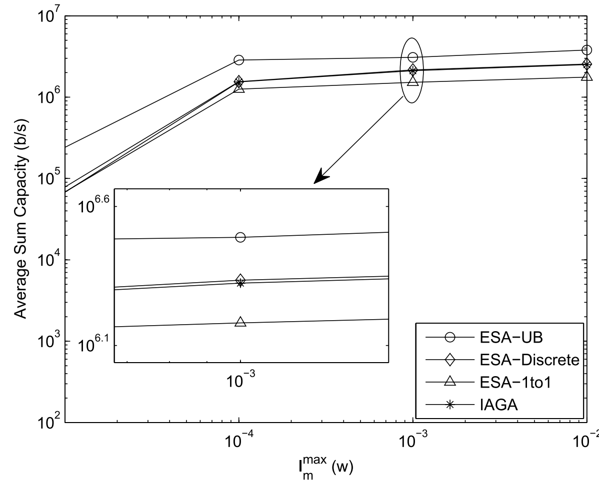


Fig. 5. Sum-rate capacity versus interference threshold (Watts). The parameters are $L = 6, K = 4, M = 4, \lambda = 1$.

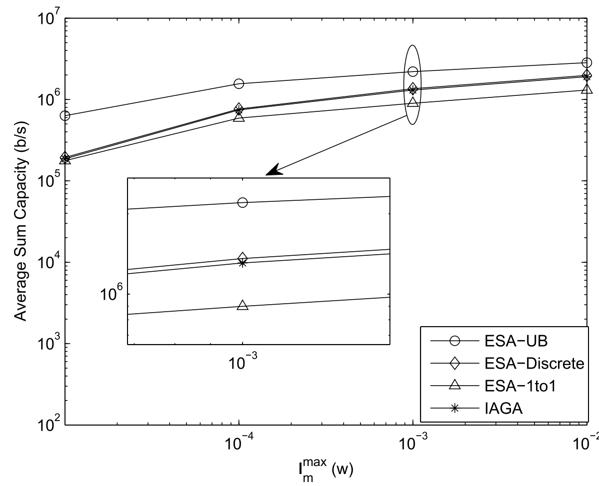


Fig. 6. Sum-rate capacity versus interference threshold (Watts). The parameters are $L = 5, K = 3, M = 4, \lambda = 2$.

In Figs. 5 and 6, we present the plot of sum-capacity versus interference threshold. We used the scenarios $(L, K, M, \lambda) =$ (6, 4, 4, 1) and (5, 3, 4, 2) where L is the number of PWHs, K is the number of secondary devices, M is the number of primary devices, and λ is number of discrete power levels. Bandwidth assigned to each SWD is 1 MHz. We observe that sum-capacity increases with the interference threshold because a feasible set of the optimization problem with lower interference threshold is a subset of a feasible set of the optimization problem with higher interference threshold. In other words, with the increase in the interference threshold, any SWD can transmit with more power. More power means high data rate. In both figures, the performance of IAGA is nearly equal to exhaustive search algorithm. In Figs. 7 and 8, we present the sum-capacity versus the number of PWHs. We used two different scenarios $(K, M, \lambda, I_{m,k}^{max}) =$ (4, 1, 1, 10mW) and (2, 4, 2, 1mW). From these results, we observe that the sum-capacity increases with the number of PWHs. This is because more PWHs in the system give more degrees of freedom in assigning the PWHs to the SWDs. More PWH means, more opportunities for the PWHs assignment to get less interference.

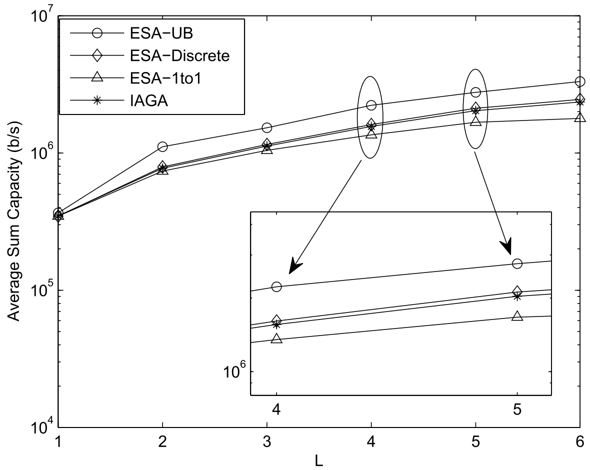


Fig. 7. Sum-rate capacity versus number of PWHs. The parameters are $K = 4, M = 1, \lambda = 1, I_{m,k}^{max} = 10mW$.

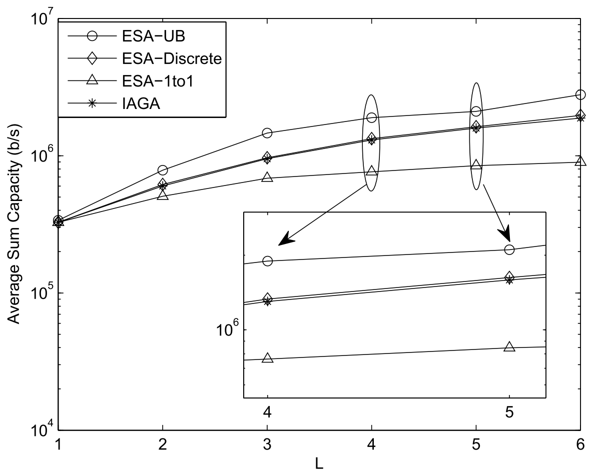


Fig. 8. Sum-rate capacity versus number of PWHs. The parameters are $K = 2, M = 2, \lambda = 2, I_{m,k}^{max} = 1mW$.

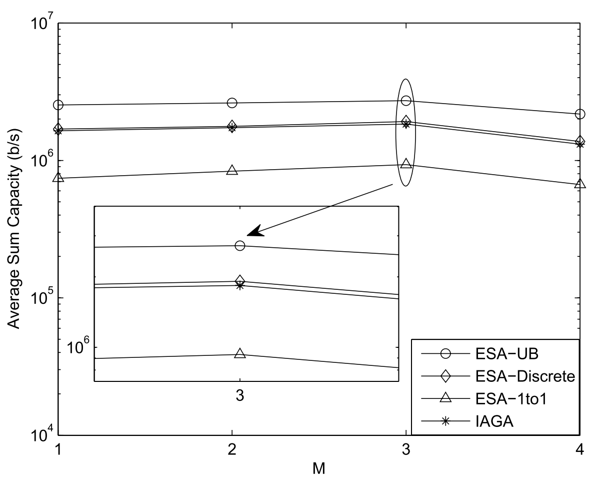


Fig. 9. Sum-rate capacity versus number of PWDs. The parameters are $K = 2, L = 5, \lambda = 1, I_{m,k}^{max} = 1mW$.

In Fig. 9, we present the sum-capacity versus number of PWDs. The parameters are $(L, K, \lambda, I_{m,k}^{max}) = (5, 2, 1, 1\text{mW})$. Fig. 9 illustrates the variation in sum-capacity with the increase in the number of PWDs. In this result, we observe that sum-capacity decreases as the number of PWDs increases. This is because the PWH assignment needs to satisfy more interference constraints as the number of PWDs increases. From the numerical results, we can see that IAGA converges to within 86% of that obtained by ESA-Discrete algorithm at low interference threshold and 96% percent at high interference threshold.

V. Conclusion

In this paper, we presented an iterative joint PWH assignment and power allocation (IAGA) algorithm for cognitive radio based systems in hospital buildings. The proposed iterative algorithm has low computational complexity, and its performance is close to that of the exhaustive search algorithm. Simple underlying concept and ease of implementation with low-complexity make this iterative algorithm a suitable candidate for multiple PWH assignment and power allocation problem. In future, we will extend this algorithm to different channel models and the case where the channel knowledge is imperfect.

Appendix
Proof of Concavity of Upper Bound

Proof: We need to establish the concavity of function $f : \mathbb{R}^L \rightarrow \mathbb{R}$, defined as $f(p_1, \ldots, p_l) = \frac{(\sum_l |h_k^l|^2 \beta_l^2 p_l)}{1+\sum_l (|h_k^l|^2 \beta_l^2 p_l)} = \frac{\sum_l x_l}{1+\sum_l x_l}$, where $x_l = |h_k^l|^2 \beta_l^2 p_l$. From the definition, function f is concave if **dom** f is a convex set and if for all $\boldsymbol{x}, \boldsymbol{y} \in \textbf{dom} f$, and λ with $0 \leq \lambda \leq 1$, we have

$$f(\lambda \boldsymbol{x} + (1 - \lambda \boldsymbol{y})) \geq \lambda f(\boldsymbol{x}) + (1 - \lambda) f(\boldsymbol{y})$$

Let us define a linear function $g : \mathbb{R}^L \rightarrow \mathbb{R}$ as $g(x_1, \ldots, x_L) = \sum_l x_l$ and a concave function $h : \mathbb{R} \rightarrow \mathbb{R}$ as $h(z) = \frac{z}{1+z}$. We know that composition of a concave function with an affine mapping is concave, that is, $h(g(\boldsymbol{x}))$ is concave. Therefore,

$$h(g(\lambda \boldsymbol{x}) + g((1 - \lambda \boldsymbol{y}))) \geq \lambda h(g(\boldsymbol{x})) + (1 - \lambda) h(g(\boldsymbol{y})) \tag{11}$$

Further, we observe that

$$\begin{aligned} h(g(\lambda \boldsymbol{x}) + g((1 - \lambda \boldsymbol{y}))) &= \frac{\lambda \sum_l x_l + (1 - \lambda \sum_l y_l)}{1 + \lambda \sum_l x_l + (1 - \lambda \sum_l y_l} \\ &= f(\lambda \boldsymbol{x} + (1 - \lambda \boldsymbol{y})) \end{aligned}$$

and

$$\lambda h(g(\boldsymbol{x})) + (1 - \lambda) h(g(\boldsymbol{y})) = \lambda f(\boldsymbol{x}) + (1 - \lambda) f(\boldsymbol{y})$$

Hence, from (11), we conclude that $f(\lambda \boldsymbol{x} + (1 - \lambda \boldsymbol{y})) \geq \lambda f(\boldsymbol{x}) + (1 - \lambda) f(\boldsymbol{y})$, which establishes that function is concave. □

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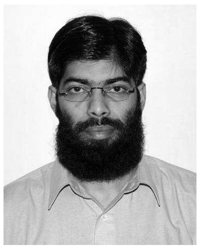

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