Efficient Resource Allocation in Device-to-Device Communication Using Cognitive Radio Technology

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***Abstract*—Device-to-device (D2D) communication is developed as a new paradigm to enhance network performance according to LTE and WiMAX advanced standards. The D2D communication may have dedicated spectrum (overlay) or shared spectrum (underlay). However, the allocated dedicated spectrum may not be effectively used in the overlay mode, while interference between the D2D users and cellular users cause impairments in the underlay mode. Can the resource allocation of a D2D system be optimized using the cognitive approach where the D2D users opportunistically access the underutilized radio spectrum? That is the focus of this paper. In this paper, the transmission rate of the D2D users is optimized while simultaneously satisfying *five sets of constraints* related to power, interference, and data rate, modeling D2D users as cognitive secondary users. Furthermore, a two-stage approach is considered to allocate the radio resources efficiently. A new adaptive subcarrier allocation scheme is designed first, and then, a novel power allocation scheme is developed utilizing geometric water-filling approach that provides optimal solution with low computation complexity for this nonlinear problem. Numerical results show that the proposed approach achieved significant performance enhancement than the existing schemes.**

***Index Terms*—Cognitive radio, device-to-device communication, power allocation, geometric water-filling, adaptive subcarrier allocation.**

I. Introduction

THE rapid development of wireless devices has stimulated increasing demand for spectrum in fourth and fifth generation (5G) mobile networks [22]. This poses a crucial challenge to the relatively scarce wireless resources and multitude of efforts are taken to overcome this spectrum crunch. When the Federal Communications Commission (FCC) observed that even the current licensed spectrum is significantly under utilized [12], there is much interest in the cognitive radio (CR) approach [21] to solve the under-utilization issue of the radio spectrum.

However, note that the classical CR technology mainly improves spectrum efficiency from the perspective of time and channel, neglecting the potential optimization from the space perspective [9]. Meanwhile, the D2D technology [26], [27] has been proposed as an effective solution for efficiently utilizing the scarce radio resources from the space perspective. Obviously both the CR and D2D communication systems must not harmfully interfere with the cellular networks. D2D communication can be categorized into: 1) in-band D2D either in underlay mode (shared spectrum) or in overlay mode (dedicated spectrum) and 2) out-of-band D2D where the unlicensed spectrum is adopted by other wireless technologies such as Wi-Fi direct or BlueTooth^{TM} [20]. In the overlay mode, however, still the dedicated spectrum for D2D users may not be efficiently utilized. On the other hand, in the underlay mode, the most critical part is the interference mitigation between the D2D users and cellular users due to the shared spectrum.

Now, the question arises. Can D2D communication be better optimized using the cognitive radio approach? Can D2D users be modeled as secondary cognitive users and opportunistically access the under-utilized radio spectrum to increase the spectral efficiency? This is the focus of this paper. Note that, there are key differences between CR and original D2D systems. Mainly, the D2D communication is mostly managed by the network (that provides the spectrum) while a CR system is managed by the CR terminals distributively by spectrum sensing and interference-aware decisions. We assume that a cognitive D2D user is capable of sensing the surrounding interference level on a given transmission channel. With this knowledge, a D2D user can take an intelligent decision on using a given channel while avoiding interference from nearby cellular transmissions (in uplink or downlink) [1], [25].

There have been several burgeoning research efforts found in the literature [3]–[6], [10], [17], [28], [33], [36] on the resource allocation schemes for CRNs. On the other hand, due to the benefit of D2D communication, International Mobile Telecommunications (IMT)- Advanced Standard systems, such as Long Term Evolution (LTE) and WiMax, allow D2D communication sharing the same radio resources with the cellular network to increase the spectral efficiency [9]. D2D communication is, in fact integrated into LTE-Advanced networks in [18], [19]. Radio resource allocation for D2D communication underlaying cellular networks are currently being extensively investigated by researchers in terms of spectral efficiency [11], [13], [34], [35], [37], [38] and in terms of energy efficiency [8], [15].

From the literature survey, it is found that, most of the recent works focus on how to exploit D2D communication in cellular networks under different constraints. However, only a few efforts [9], [16], [24], [29], [30], [32] have been made to incorporate D2D communication with CR technology to jointly

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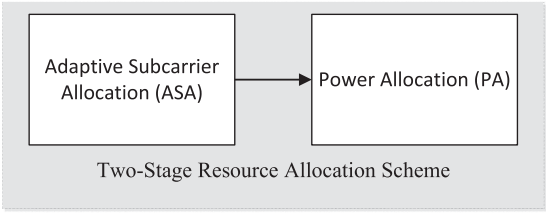

Fig. 1. The procedure for resource allocation scheme.

maximize the spectrum efficiency. In [9], the SUs mode selection strategies are optimized in a cognitive cellular network with D2D communication. A mixed overlay-underlay spectrum sharing method is proposed in [16] for CR-assisted D2D communications in a cellular network. Two spectrum access policies (random and prioritized) are investigated in [24] for cognitive and energy harvesting-based D2D communication in cellular networks. A resource allocation scheme based on CR approach for D2D underlay multicast communication is proposed in [32] to improve system performance. An optimal power allocation algorithm is presented in [30] for cognitive D2D communication assisted by two-way relaying. The joint use of full-duplex relay and D2D communication are investigated in [29] for CRNs.

In this paper, the resource allocation problem is studied by jointly employing CR technology and D2D communication in cellular networks. D2D users are modeled as cognitive secondary users where they can opportunistically access the spectrum. An orthogonal frequency division multiplexing (OFDM) based cognitive cellular network with D2D communication has been designed and analyzed using Lagrange formulation and then solved using geometric water-filling (GWF) method [14]. The optimization problem is characterized by the following five features in order to maximize the transmission rate of the D2D users: a) total power constraint, b) peak power constraint on each subcarrier, c) maximum power constraint of each D2D user, d) interference constraint to the PU band and e) minimum transmission rate requirements for the D2D users. To the best of the authors knowledge, the prior resource allocation researches did not consider the above five features simultaneously.

Furthermore, a two-stage approach is considered to allocate the radio resource efficiently. In the first stage, a new adaptive subcarrier allocation (ASA) scheme is designed based on three parameters that form a well-designed metric. These parameters are exploited as the weighting factors to make trade-off among the amount of power, interference and transmission rate. Then a novel power allocation (PA) scheme is developed utilizing proven GWF approach that can compute exact solution with efficient computation. The procedure for the resource allocation scheme is illustrated in Fig. 1.

The organization of the rest of this paper is as follows: Section II describes the system model and formulates the problem. Section III provides the proposed resource allocation scheme in detail. The performance of the proposed solutions are depicted in Section IV and finally Section V concludes the paper. Table I provides a list of frequently used variables and abbreviations.

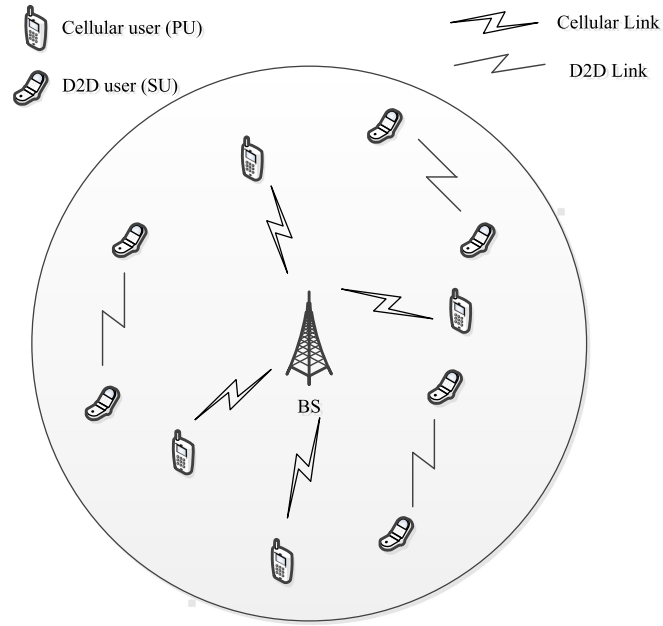

Fig. 2. A D2D enabled cognitive radio system.

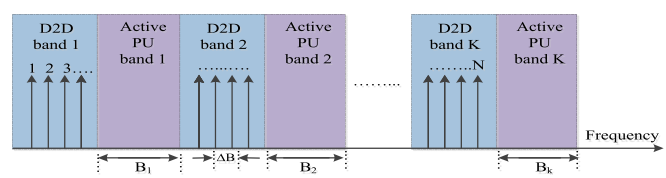

Fig. 3. Spectrum distribution of PUs and D2D users in OFDM based cognitive D2D system.

II. System Model and Problem Formulation

A. System Model

In this work, we considered the downlink of a single cell OFDM cognitive cellular system with multiple cellular users (PUs) and multiple D2D users (SUs) as shown in Fig. 2.

In spectral domain, we utilized the side-by-side CR access model as shown in Fig. 3. It is assumed that the frequency bands with bandwidth B (B_1, B_2, ..., B_K in Hz), are occupied by K PUs (1, 2, ..., K). The unoccupied bands that can be sensed by the M D2D users (1, 2, ..., M) for possible transmission, is located on both sides of the PU bands. Note that, it may look like the considered D2D communication is using overlay mode (dedicated frequency band) in Fig. 2. However, it is not the case. In this paper, the D2D users are allowed to opportunistically utilize those unused spectrum left by the PUs. This is done by the D2D users sensing the environment and then cognitively adapting their radio parameters accordingly [25].

Let, $\mathcal{K}$ be the set for PUs where $\mathcal{K} = \{1, 2, ..., K\}$ and $\mathcal{M}$ be the set for D2D users where $\mathcal{M} = \{1, 2, ..., M\}$. The frequency band which is available for CR transmission, is divided into N subcarriers and each subcarrier occupies a bandwidth of ΔB Hz.

Note, each subcarrier experiences a fading channel where channel gain is impaired by the effects of propagation path loss,

TABLE I
LIST OF FREQUENTLY USED VARIABLES AND ABBREVIATIONS

Group	Variable	Meaning
Index	k	index of PUs, for $k = 1, 2, \cdots, K$
	m	index of D2D users, for $m = 1, 2, \cdots, M$
	l	index of other active D2D users, for $l = 1, 2, \cdots, M$
	n	index of subcarriers, for $n = 1, 2, \cdots, N$
	B	index of PUs bandwidth B_1, B_2, ..., B_K in Hz
Set	$\mathcal{K}$	set of PUs $\{1, 2, \cdots, K\}$
	$\mathcal{M}$	set of D2D users $\{1, 2, \cdots, M\}$
	$\mathcal{N}$	set of subcarriers $\{1, 2, \cdots, N\}$
	$\mathcal{N}_m$	set of subcarriers allocated to the mth D2D user $\{1, 2, \cdots, N_m\}$
	$\bar{N}_m$	number of subcarriers allocated to the mth D2D user
	λ	set of subcarriers that exceeds the peak power constraint
	Ω	set of subcarriers that need to be reallocated
Channel related term	$h^{dd}_{m,n}$	channel gain between the mth D2D user's transmitter and receiver
	$h^{dp}_{m,k}$	channel gain between the mth D2D user's transmitter and the kth PU's receiver
	$h^{pd}_{k,m}$	channel gain between the kth PU's transmitter and the mth D2D user receiver
	$\Gamma_{m,n}$	channel gain-to-noise ratio
	d_m	link distance between the devices of D2D user
	η	path attenuation factor
	σ^2_{AWGN}	additive white Gaussian noise variance
Bandwidth related term	$d^{(k)}_{m,n}$	spectrum distance between the nth subcarrier of the mth D2D user and the kth PU band
	ΔB	bandwidth of each subcarrier in Hz
Power related term	$P_{m,n}$	transmit power for the mth D2D user allocated to the nth subcarrier
	S_m	total allocated power for the mth D2D user
	E_m	extra power for the mth D2D user
	R_m	remaining power for the mth D2D user that needs to be reallocated in the next round
Interference related term	$\Upsilon^k_{m,n}$	interference introduced by the nth subcarrier of the mth D2D user to the kth PU band
	$I^k_{m,n}$	interference factor for the mth D2D user between the nth subcarrier and the kth PU band
	$\rho^k_{m,n}$	interference introduced by the kth PU signal to the mth D2D user on the nth subcarrier
	$L_{l,n}$	interference signal comes from other active D2D users.
	$\mathcal{I}_{agg}$	aggregated interference
Transmission rate related term	$\Re_{m,n}$	transmission rate for the mth D2D user on the nth subcarrier
	$\bar{\Re}_{m,n}$	transmission rate when peak power constraint is considered
Constraint Group	P_T	total power constraint
	$P_{m,max}$	maximum power constraint of the mth D2D user
	$\bar{P}_{m,n}$	peak power constraint for the mth D2D user at the nth subcarrier
	I^k_{th}	interference threshold of the kth PU band
	$\Re_{m,min}$	minimum transmission rate requirements for the D2D users
	$x_{m,n}$	binary decision variable of subcarrier allocation
Others	$\alpha, \beta, \gamma, \delta, \psi$	Lagrange multipliers
	$\Pi_{m,n}$	proposed metric for subcarrier allocation
	w_1, w_2, w_3	weighting factors for subcarrier allocation
Reference Level	μ	water level
	j^*	water level step (highest step under the water)
Matrix	$\mathbf{X}$	$M \times N$ matrix of subcarrier allocation
	$\mathbf{P}$	$M \times N$ matrix of allocated power
	$\mathbf{T}$	$M \times N$ matrix of allocated power when binary decision variable is considered
Abbreviations	PSD	power spectrum density
	ASA	Adaptive subcarrier allocation
	PA	Power allocation
	GWF	Geometric water-filling
	GWFPP	Geometric water-filling with peak power constraint

multipath fading and shadowing. Hence, the D2D users need to detect the channel state information (CSI), i.e., the channel gain $h^{dd}_{m,n}$, $h^{dp}_{m,k}$ and $h^{pd}_{k,m}$, by an appropriate channel estimation mechanism before transmission. In practice, CSI on the D2D users own channel can be obtained via the classical channel estimation methods. However, the CSI from the D2D user to the PU is not directly available. This can be obtained in two steps. First the D2D user estimates the reversed channel from the PU to the D2D user. Then, under the assumption of channel reciprocity D2D to PU channel can be estimated by the D2D user. Here, $h^{dd}_{m,n}$ denotes the channel gain between the mth D2D user's transmitter and receiver; $h^{dp}_{m,k}$, is the channel gain between the mth D2D user's transmitter and the kth PU's receiver; and $h^{pd}_{k,m}$, is the channel gain between the kth PU's transmitter and the mth D2D user's receiver. The subscript of index n denotes the nth subcarrier.

Due to the coexistence of PU and D2D users in the side-by-side bands, mutual interference is introduced. Now, the mutual interference introduced by the nth subcarrier of the mth D2D

user to the kth PU band can be written as [31]

$$\Upsilon_{m,n}^{(k)} = |h_{m,k}^{dp}|^2 P_{m,n} T_s \int_{d_{m,n}^{(k)}-W_k/2}^{d_{m,n}^{(k)}+W_k/2} \left(\frac{\sin \pi f T_s}{\pi f T_s}\right)^2 df \quad (1)$$

where, $P_{m,n}$ is the transmit power for the mth D2D user allocated to the nth subcarrier, T_s is the symbol duration, $d_{m,n}^{(k)}$ represents the spectrum distance between the nth subcarrier of the mth D2D user and the kth PU band and W_k represents the occupied bandwidth by the kth PU.

Let $I_{m,n}^{(k)} = |h_{m,k}^{dp}|^2 T_s \int_{d_{m,n}^{(k)}-W_k/2}^{d_{m,n}^{(k)}+W_k/2} (\frac{sin \pi f T_s}{\pi f T_s})^2 df$, be the interference factor for the mth D2D user between the nth subcarrier and the kth PU band. Then (1) can be rewritten as

$$\Upsilon_{m,n}^{(k)} = P_{m,n} \cdot I_{m,n}^{(k)}. \quad (2)$$

Now, with an ideal coding scheme, the transmission rate for the mth D2D user on the nth subcarrier, is given by the following formula,

$$\Re_{m,n}(P_{m,n}, d_m) = \Delta B \log\left(1 + \frac{P_{m,n}\,|h_{m,n}^{dd}|^2\, d_m^{-\eta}}{\mathcal{I}_{agg}}\right) \quad (3)$$

where, d_m represents the link distance between the devices of D2D user and η is the path attenuation factor. In (3), $\mathcal{I}_{agg} = \sigma_{AWGN}^2 + \sum_{k=1}^{K} \rho_{m,n}^k + \sum_{l=1, l\neq m}^{M} L_{l,n}$ denotes the aggregated interference, where σ_{AWGN}^2 denotes the additive white Gaussian noise (AWGN) variance, the second term be the interference introduced by the kth PU signal to the mth D2D user on the nth subcarrier and the third term represents the interference signal comes from other active D2D users.

Let $\Gamma_{m,n} = \frac{|h_{m,n}^{dd}|^2\, d_m^{-\eta}}{\mathcal{I}_{agg}}$ represents the channel gain-to-noise ratio, then (3) can be rewritten as

$$\Re_{m,n}(P_{m,n}, d_m) = \Delta B \log\left(1 + P_{m,n}\Gamma_{m,n}\right). \quad (4)$$

In this paper, a transmission rate constraint associated with the maximum modulation order limitation on each subcarrier is considered. It leads to a peak power constraint ($\bar{P}_{m,n}$) for the mth D2D user on the nth subcarrier which can be written from (4) as,

$$\bar{P}_{m,n} = \frac{2^{\bar{\Re}_{m,n}} - 1}{\Gamma_{m,n}} \quad (5)$$

where, $\bar{\Re}_{m,n}$ is the corresponding transmission rate when $\bar{P}_{m,n}$ is considered.

Let $x_{m,n}$ be a binary decision variable of channel (subcarrier) allocation. If subcarrier n is allocated to D2D user m, then $x_{m,n}$ is equal to 1; otherwise it is equal to zero. Since each subcarrier is exclusively allocated to one D2D user, we can write,

$$\sum_{m=1}^{M} x_{m,n} = 1,\ n = 1, 2, ..., N. \quad (6)$$

Now, the total system transmission rate is given by

$$\Re(\mathbf{X}, \mathbf{P}) = \Delta B \sum_{m=1}^{M}\sum_{n=1}^{N} x_{m,n} \log\left(1 + P_{m,n}\Gamma_{m,n}\right) \quad (7)$$

where, $\mathbf{X}$ is a $M \times N$ matrix of subcarrier allocation indices $x_{m,n}$, and $\mathbf{P}$ is a $M \times N$ matrix of allocated power $P_{m,n}$.

B. Problem Formulation

Our objective of resource (subcarrier and power) allocation is to maximize the total downlink transmission rate of the D2D system under both power and interference constraints along while meeting the minimum rate requirement. Therefore, the optimization problem can be formulated as follows

$$\max_{\mathbf{X},\mathbf{P}} \Delta B \sum_{m=1}^{M}\sum_{n=1}^{N} x_{m,n} \log\left(1 + P_{m,n}\Gamma_{m,n}\right)$$

subject to:

$$C1: \sum_{m=1}^{M} x_{m,n} = 1,\ x_{m,n} \in \{0,1\};\ \forall n \in \mathcal{N}$$

$$C2: \sum_{m=1}^{M}\sum_{n=1}^{N} x_{m,n} P_{m,n} \leq P_T, P_{m,n} \geq 0;$$

$$C3: \sum_{n=1}^{N} x_{m,n} P_{m,n} \leq P_{m,max};\ \forall m \in \mathcal{M}$$

$$C4: x_{m,n} P_{m,n} \leq \bar{P}_{m,n};\ \forall m \in \mathcal{M},\ \forall n \in \mathcal{N}$$

$$C5: \sum_{k=1}^{K}\sum_{n=1}^{N} x_{m,n} \Upsilon_{m,n}^{(k)} \leq I_{th};\ \forall m \in \mathcal{M}$$

$$C6: \sum_{n=1}^{N} x_{m,n} \Re_{m,n} \geq \Re_{m,min};\ \forall m \in \mathcal{M} \quad (8)$$

where, constraint C1 depicts that each subcarrier can not be reused by more than one D2D user. Constraint C2, C3 and C4 denote total power constraint (e.g. P_T), maximum power constraint for each D2D user (e.g. $P_{m,max}$), and peak power constraint on each subcarrier (e.g. $\bar{P}_{m,n}$) respectively. Constraint C5 describes interference constraint where I_{th} denotes the total interference threshold by the K PU bands. Lastly, constraint C6 provides minimum transmission rate requirements for the D2D users.

The optimization problem in (8) is nonconvex due to the binary decision variable $x_{m,n}$. This variable can be relaxed by applying a time sharing approach to allow any value in the interval $(0, 1]$ instead of $\{0, 1\}$ set. This approach allows multiple users to transmit on a certain subcarrier during a defined scheduled period. Let $t_{m,n} = x_{m,n} P_{m,n}$, then the optimization problem in (8) can be rewritten as follows:

$$\max_{\mathbf{X},\mathbf{T}} \Re(\mathbf{X}, \mathbf{T}) = \Delta B \sum_{m=1}^{M}\sum_{n=1}^{N} x_{m,n} \log\left(1 + \frac{t_{m,n}}{x_{m,n}}\Gamma_{m,n}\right)$$

subject to:

$$C1: \sum_{m=1}^{M} x_{m,n} = 1,\ x_{m,n} \in (0,1];\ \forall n \in \mathcal{N}$$

$$C2: \sum_{m=1}^{M}\sum_{n=1}^{N} t_{m,n} \leq P_T,\ t_{m,n} \geq 0;$$

$$C3: \sum_{n=1}^{N} t_{m,n} \leq P_{m,max},\ \forall m \epsilon \mathcal{M}$$

$$C4: t_{m,n} \leq \bar{P}_{m,n};\ \forall m \epsilon \mathcal{M},\ \forall n \epsilon \mathcal{N}$$

$$C5: \sum_{k=1}^{K}\sum_{n=1}^{N} t_{m,n} I_{m,n}^{(k)} \leq I_{th};\ \forall m \epsilon \mathcal{M}$$

$$C6: \sum_{n=1}^{N} x_{m,n} \Re_{m,n} \geq \Re_{m,min};\ \forall m \epsilon \mathcal{M} \tag{9}$$

Now, the problem in (9) is convex which is equivalent to the original problem in (8) when the condition on $x_{m,n}$ is relaxed for D2D user m and subcarrier n. Finding the optimal pair $(x_{m,n}^*, t_{m,n}^*) = (x_{m,n}^*, x_{m,n}^* P_{m,n}^*)$ leads to the same solution as finding $(x_{m,n}^*, P_{m,n}^*)$.

The analytical solution of the problem in (9) is

$$P_{m,n}^* = \left[\frac{1+\psi_m}{\ln\left(\alpha_n + \beta_m + \gamma_n + \sum_{k=1}^{K} \delta_k I_{m,n}^{(k)}\right)} - \frac{1}{\Gamma_{m,n}}\right]^+. \tag{10}$$

Please see the **Appendix** for the solution.

The $P_{m,n}^*$ denotes the optimal power allocation for the mth D2D user on the nth subcarrier when $m = m^*$. Thus, the indices of the subcarrier allocation matrix X will be

$$x_{m,n} = \begin{cases} 1 & m = m^* \text{ for } n = 1, 2, ..., N \\ 0, & \text{otherwise.} \end{cases} \tag{11}$$

The power allocation strategy in (10) is indeed corresponding to the conventional water-filling (CWF) strategy [23] and depends on the Lagrange multipliers associated with the per user power and interference constraints. By using the CWF, the optimal power allocation strategy can be calculated. However, several iterations may be involved in finding the optimal value. Also the complexity of getting the optimal solution is high. Therefore, in this paper, GWF approach [14] is utilized to solve the CWF problem which is described in the following section. It has two advantages: 1) The geometric approach can compute the exact solution to the CWF, including the weighted case, with less computation. This is done without determining the water level through solving the non-linear system. 2) Mechanism of the proposed geometric approach can overcome the limitations of the CWF algorithm to include more stringent constraints.

III. Proposed Resource Allocation Scheme

An efficient resource allocation scheme is proposed in this section to address the problem defined in (8), based on the analysis in Section II. A two-stage approach is considered to solve (8) efficiently. Specifically, the resource allocation scheme is divided into two individual procedures: adaptive subcarrier allocation (ASA) and power allocation (PA). In the first stage, each subcarrier is assigned to one D2D user with the minimum value of the proposed metric that is adaptive in nature. In the second stage, power is allocated among all the D2D users to maximize the transmission rate.

A. Adaptive Subcarrier Allocation (ASA)

Most of the recent works regarding subcarrier allocation strategy to the D2D users is based on the greedy approach [11], [37]. However, we have proposed an adaptive metric based on the amount of power, interference and transmission rates to optimally assign subcarriers to the D2D users in this paper.

Let $\mathcal{N}$ be the set of subcarriers where $\mathcal{N} = \{1, 2, ..., N\}$, $\mathcal{N}_m$ be the set of subcarriers allocated to the mth D2D user and $\bar{N}_m$ denotes the number of subcarriers allocated to the mth D2D user. Now, the transmission rate increment due to one more subcarrier allocation to the mth D2D user can be written as,

$$\Delta\Re_{m,n} = \Re_{m,n}\left(\frac{P_{m,n}}{\bar{N}_m + 1}, d_m\right) - \Re_{m,n}\left(\frac{P_{m,n}}{\bar{N}_m}, d_m\right), n\epsilon\mathcal{N}_m. \tag{12}$$

The power increment for transmitting one more step increment in transmission rate $\Delta\Re$ on subcarrier n of the mth D2D user can be written as,

$$\Delta P_{m,n} = \frac{(2^{\Re_{m,n} + \Delta\Re_{m,n}} - 2^{\Re_{m,n}})}{\Gamma_{m,n}}. \tag{13}$$

The interference increment caused by subcarrier n of the mth D2D user for the kth PU can be written as,

$$\Delta\Upsilon_{m,n}^{(k)} = \Delta P_{m,n} \cdot I_{m,n}^{(k)}. \tag{14}$$

A metric composed of three parts for the nth subcarrier of the mth D2D user is described as,

$$\Pi_{m,n} = w_1\left(\frac{\Delta P_{m,n}}{P_{m,max} - P_{m,used}}\right) + w_2\left(\sum_{k=1}^{K}\frac{\Delta\Upsilon_{m,n}^k}{I_{th} - \Upsilon_{m,used}^k}\right) + w_3\left(\frac{\Delta\Re_{m,n}}{\Re_{m,used} - \Re_{m,min}}\right) \tag{15}$$

where, $P_{m,used}$ is the amount of power that has been utilized for the mth D2D user, $\Upsilon_{m,used}^k$ is the interference that has been initiated to the kth PU, and $\Re_{m,used}$ is the corresponding transmission rate of the mth D2D user. The first part consists of the amount of the power increment for one more increment in the transmission rate and the amount of the unused power. The second part includes the amount of interference to be used for computing the interference constraints. Finally, the third part is associated with the minimum transmission rate requirement among the D2D users. Three non-negative weighting factors (w_1, w_2, and w_3) are used to manage the trade-offs between the power, the interference constraints and, the minimum rate requirement in the subcarrier allocation process. This is the reason why this subcarrier assignment strategy is named as adaptive subcarrier allocation (ASA).

For a specific D2D user, a subcarrier n^* with the minimum value of the metric (15), is assigned to that selected D2D user m^*. A subcarrier with a lower value depicts that the power and interference increments for providing one more increment in

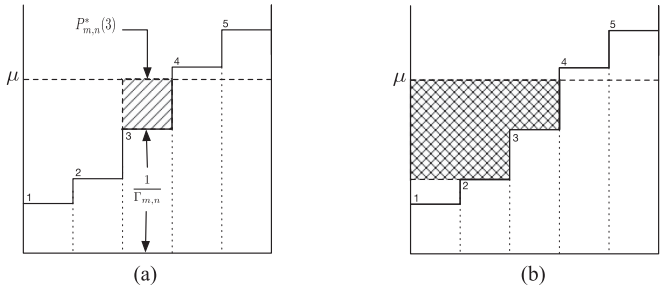

Fig. 4. Illustration for the GWF algorithm (a) illustration of water level step $j^* = 3$, allocated power for the third step $P^*_{m,n}(3)$, and step depth is $\frac{1}{\Gamma_{m,n}}$ and (b) illustration of $P(j)$ (shadowed area, representing the total power above step j) when $j = 2$.

Algorithm 1: Adaptive Subcarrier Allocation (ASA).

Input: The set $\mathcal{N} = \{1, 2, ..., N\}$
initialization: $\mathcal{N}_m = \phi, \bar{N}_m = 0, \Re_{m,used} = 0,$
$P_{m,used} = 0, \Upsilon^k_{m,used} = 0;\ \forall m \epsilon \mathcal{M},\ \forall n \epsilon \mathcal{N},\ \forall k \epsilon \mathcal{K}$
for $n \epsilon \mathcal{N}$ **do**
  compute $\Delta P_{m,n}$ using (13),
  $\Delta \Upsilon^{(k)}_{m,n}$ using (14)
  and $\Delta \Re_{m,n}$ using (12);
  calculate $\Pi_{m,n}$ using (15);
  $(m^*, n^*) = \arg\ \min\ \Pi_{m,n}$;
  $\mathcal{N} = \mathcal{N} - \{n^*\}, \mathcal{N}_{m^*} = \mathcal{N}_m \cup \{n^*\}, \bar{N}_m = \bar{N}_m + 1;$
  update $P_{m,used}, \Upsilon^k_{m,used}, \Re_{m,used}$
end

transmission rate are relatively small compared to other subcarriers. The ASA strategy is well described in Algorithm 1.

B. Power Allocation (PA)

After the subcarriers are assigned as described in the previous section, power allocation is performed for the selected subcarrier n^* of the D2D user m^*. For the selected subcarrier n^* of the D2D user m^*, the value of x_{m^*,n^*} becomes 1 and then the power allocation problem in (8) can be solved using GWF approach. Fig. 4 gives an illustration of the GWF approach.

Instead of trying to determine the common water level μ (real nonnegative number) in CWF, we introduce the highest water level step, denoted by j^*, which is an integer number to find the solutions for power allocation. Let $P(j)$ denotes the water volume above step j or zero, whichever is greater and the value of $P(j)$ can be found as:

$$P(j) = \left[P_T - \left\{ \sum_{n=1}^{j-1} \left(\frac{1}{\Gamma_{m,j}} - \frac{1}{\Gamma_{m,n}} \right) \right\} \right]^+ ; \forall j \epsilon \mathcal{N}_m \quad (16)$$

where, $\frac{1}{\Gamma_{m,n}}$ is the "step depth" of the nth stair. Due to the definition of $P(j)$ being the power (water volume) above step j, it cannot be a negative number. Therefore we use $\{.\}^+$ in (16) to assign 0 to $P(j)$ if the result inside the bracket is negative. The corresponding geometric meaning is that the j^{*th} level is above water.

According to [14], the explicit solution for power allocation is:

$$P_{m,n} = \begin{cases} P_{m,j^*} + \left(\frac{1}{\Gamma_{m,j^*}} - \frac{1}{\Gamma_{m,n}} \right) & 1 \le n \le j^* \\ 0, & j^* < n \le N_m, \end{cases} \quad (17)$$

where the water level step j^* is given as

$$j^* = \max \{ j | P(j) > 0, 1 \le j \le N_m \} \quad (18)$$

and the power level for this step is

$$P_{m,j^*} = \frac{1}{j^*} P(j^*). \quad (19)$$

In order to allocate power to the selected subcarriers for each D2D user, first we perform geometric water-filling with peak power constraint (GWFPP) [14] for all the subcarriers and calculate $\{P_{m,n}\}$ using (17), (18) and (19). Now, let λ is defined by the set $\{n | P_{m,n} > \bar{P}_{m,n}, n \epsilon \mathcal{N}_m\}$. If λ is an empty set, then $P_{m,n}$ will be the output, otherwise, $P_{m,n}$ will be set by the individual peak power $\bar{P}_{m,n}$. Everytime we need to update the set $\mathcal{N}_m$ and the total power P_T at the end of each iteration. Since the finite set $\mathcal{N}_m$ is getting smaller and smaller until the set λ is empty. The required steps to apply the algorithm GWFPP is summarized below:

Algorithm GWFPP

Input: vector $\{\frac{1}{\Gamma_{m,n}}\}, \{\bar{P}_{m,n}\}\ \forall n \epsilon \mathcal{N}_m$ and P_T.

1) Compute $\{P_{m,n}\}$ using (17), (18) and (19).

2) The set λ is defined by the set $\{n | P_{m,n} > \bar{P}_{m,n}\}, n \epsilon \mathcal{N}_m$. If λ is the empty set, output $\{P_{m,n}\}^{N_m}_{n=1}$; else, $P_{m,n} = \bar{P}_{m,n}$, as $n \epsilon \lambda$.

3) Update $\mathcal{N}_m$ and P_T. Then return to 1) of the GWFPP.

The next step is to compute the summation of allocated power for all D2D users. Let S_m be the total allocated power for the mth D2D user, E_m be the extra power for the mth D2D user when S_m exceeds the device's maximum power ($P_{m,max}$) and R_m be the remaining power for the mth D2D user that needs to be reallocated in the next round. In order to satisfy device's maximum power constraint, three cases are considered: 1) $S_m = P_{m,max}$, 2) $S_m > P_{m,max}$ and 3) $S_m < P_{m,max}$. For the first case, after checking the interference and minimum rate requirement constraints, we can have the allocated power vector for those D2D users directly. For the second case, we first perform GWFPP with the corresponding $P_{m,max}$ and then, check the interference and minimum rate requirement constraints to get their power allocation vectors. In this case, we also calculate all the E_m that needs to be reallocated in the next round. Finally, for the third case, in order to perform GWFPP less number of times, we start with those D2D users where we can allocate the remaining power most while satisfying the required constraints. In each case, if any violation of the interference or minimum rate constraint happens, this algorithm creates a set of Ω for those subcarriers and the amount of the R_m that needs to be reallocated in the next round. The process continues until all the reallocation being completed while satisfying all the constraints. The required steps for performing the power allocation are described in Fig. 5 and the detailed algorithm is well depicted in the Algorithm 2 description.

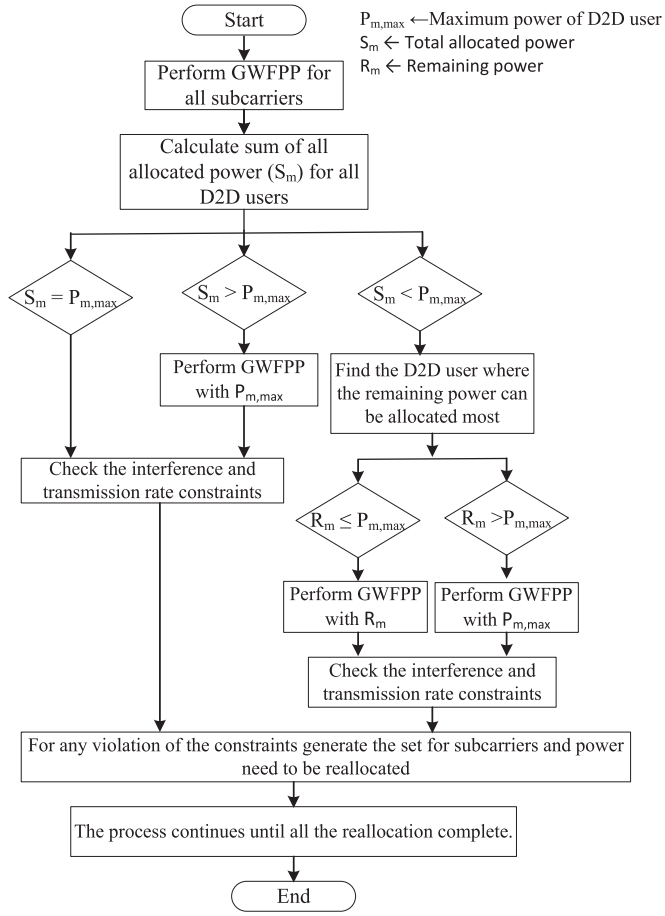

Fig. 5. Flow chart of PA algorithm.

IV. Performance Evaluation

A. Simulation Setup

In order to evaluate the performance of the subcarrier assignment and power allocation algorithm for D2D communications, we simulated a multiuser single cell system with radius 100 m where base station (BS) is located in the center of the cell. All cellular users (PUs) and D2D users (SUs) are randomly distributed with uniform distribution within the cell. The distance between D2D pairs varies depending on their relative position in the cell. All other simulation parameters are considered according to Table II. The simulation results are evaluated over different realization of PUs and D2D user locations, interference conditions and channel gains. Average transmitted data rates for different algorithms under consideration are obtained from several independent simulation runs.

In order to evaluate the performance of the proposed algorithm, we compared our algorithm with the classical schemes: uniform power loading, water-filling schemes [23], and ladder/triangular profile power allocation [2], [7]. In the uniform power loading scheme, uniform power is loaded into each subcarrier. With the total power as the power constraint, the power profile follows the water-filling scheme as in [23]. In ladder profile scheme [2], power is distributed in such a fashion so that the subcarriers that are adjacent to the PU bands, are given less power where as the subcarriers that are far away to the PU bands, are given more power. According to the triangular power allocation scheme in [7], power allocated to the subcarriers near the PUs is smaller and gradually increase as moving towards the middle. Thus maximum power is allocated to the middle most subcarrier. Since the idea behind the schemes (ladder

Algorithm 2: Power Allocation (PA).

Input: vector $\{P_{m,max}\}\forall m\epsilon\mathcal{M}$, P_T;
initialization
$A = \{m|m\epsilon\mathcal{M}\}, B = \{n|n\epsilon\mathcal{N}_m\}$
$C = \{m|\text{sorted D2D user}\}, \Omega = \phi$;
for $n \epsilon B$ **do**
  compute $\{P_{m,n}\}$ using **GWFPP** with P_T
end
for $m \epsilon A$ **do**
  calculate total allocated power, $S_m = \sum_{n=1}^{N_m} P_{m,n}$
  if $S_m = P_{m,max}$ **then**
    Interference-Rate Check($\Upsilon_m, \Re_m$);
  end
  if $S_m > P_{m,max}$ **then**
    Extra power, $E_m = S_m - P_{m,max}$;
    compute $\{P_{m,n}\}$ using **GWFPP** with $P_{m,max}$;
    Interference-Rate Check($\Upsilon_m, \Re_m$);
  end
  if $S_m < P_{m,max}$ **then**
    calculate $\{P_{m,max} - S_m\}$;
  end
end
sort $\downarrow \{P_{m,max} - S_m\}$;
for $m \epsilon C$ **do**
  total power need to be reallocated, $R_m = S_m + E_m$;
  $\mathcal{N}_m = \mathcal{N}_m \cup \{n\}, n \epsilon \Omega$;
  if $R_m \leq P_{m,max}$ **then**
    compute $\{P_{m,n}\}$ using **GWFPP** with R_m;
    Interference-Rate Check($\Upsilon_m, \Re_m$);
  else
    Extra power, $E_m = S_m - P_{m,max}$;
    compute $\{P_{m,n}\}$ using **GWFPP** with $P_{m,max}$;
    Interference-Rate Check($\Upsilon_m, \Re_m$);
  end
end
return $\{P_{m,n}\}$
Function `Interference-Rate Check`($\Upsilon_m, \Re_m$):
  calculate total interference, $\Upsilon_m = \sum_{n=1}^{N_m} P_{m,n} I_{m,n}^{(k)}$
  calculate total transmission rate, $\Re_m = \sum_{n=1}^{N_m} \Re_{m,n}$
  if $(\Upsilon_m \leq I_{th})$ && $(\Re_m \geq \Re_{min})$ **then**
    output: $\{P_{m,n}\}$;
    $E_m = 0$;
  end
  If($!\mathcal{N}_m$)
  $\Omega \longleftarrow \mathcal{N}_m \setminus n, E_m = \sum_{n=1}^{N_m} P_{m,n}$
  return $\{P_{m,n}\}, E_m, \Omega$

TABLE II
Simulation Parameters

Parameters	Values
Total no. of D2D users	5–35
Total no. of PUs	12–24
Total no. of subcarriers	5–50
Subcarrier bandwidth (ΔB)	1.5 KHz
Total bandwidth (B)	10 KHz
The value of T_s	1 μs
Path loss factor	4
The value of δ_d^2	10^{-12}
Max D2D T_x power	0.1W
Max PU T_x power	0.25W

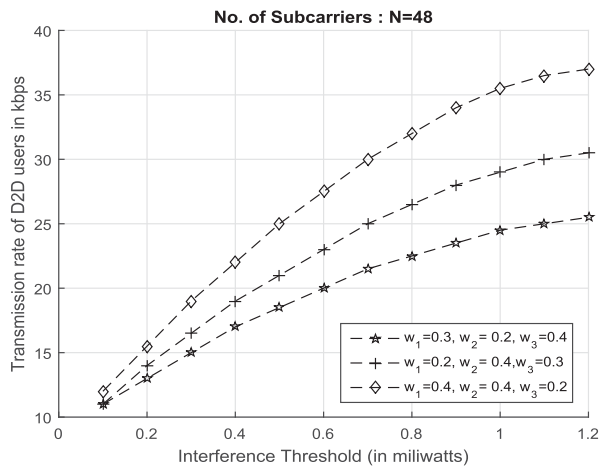

Fig. 6. Illustration of the behavior for the proposed subcarrier assignment with different values of the weighting factors (w_1, w_2, w_3).

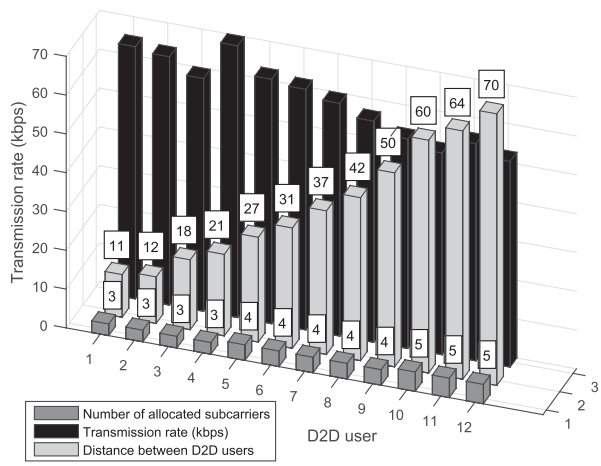

Fig. 7. Effect of the distance between the D2D users on subcarrier allocation.

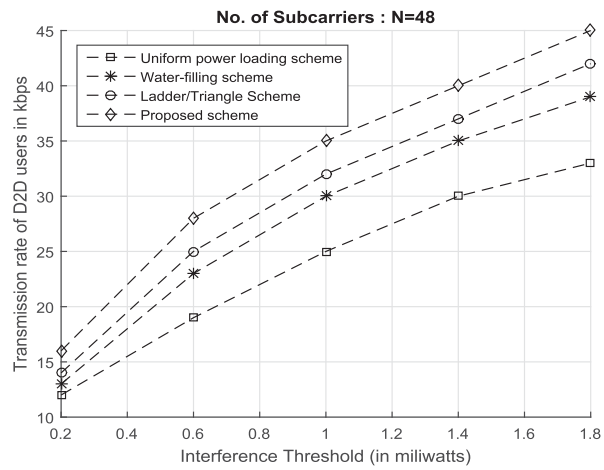

Fig. 8. Transmission rate of D2D users versus interference threshold to the PUs for different schemes.

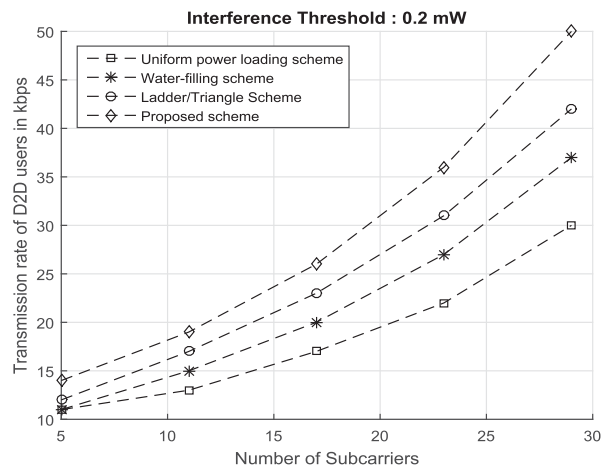

Fig. 9. Transmission rate of D2D users versus number of subcarriers with fixed interference threshold for different schemes.

profile and triangular power allocation) is the same, thus we name these schemes as ladder/triangle scheme.

The behavior of the proposed subcarrier assignment strategy with different values of the weighting factors in (15) is illustrated in Fig. 6. The effect of the different weighting factors (w_1, w_2, w_3) is revealed in the performance curves. The simulation results show that an appropriate value of the weighting factors for the threer parts in the proposed indicator can achieve superior performance. We select the values of the weighting factors (w_1, w_2, w_3) to be (0.4, 0.4, 0.2) in the following simulation, since this combination returns the highest summation of the transmission rates of the D2D users in the simulation range.

Fig. 7 shows the effect of the distance between the D2D users on subcarrier allocation where the minimum rate requirement is 50 kbps. Here, the first row represents the number of allocated subcarriers, the second row denotes the distance between the D2D users and the third row shows the transmission rate. It can be observed from Fig. 7 that the distance between the D2D user plays an important role on the total number of subcarriers allocated to one D2D user. To satisfy the minimum rate requirements of the D2D users, closely located D2D users require less number of subcarriers compared to the distantly located D2D users. Fig. 7 depicts the scenario where D2D users located within 20 meters need three subcarriers to satisfy the minimum rate requirement whereas D2D users located within 70 to 80 meters range need at least five subcarriers to satisfy the minimum rate requirement.

In Fig. 8, we plotted the transmission rate of D2D users versus the interference threshold introduced to the PUs band for different schemes. As we see, the transmission rate for all the schemes increases as the interference threshold increases. Also the transmission rate achieved by the proposed scheme outperforms other three existing schemes. The reason is that the proposed scheme maintains both the power and interference constraints at all stages of the operation. The transmission rate of the uniform power loading scheme is significantly lower than the other schemes due to the violation of both of these constraints.

Fig. 9 shows the transmission rate achieved by the D2D users versus the number of subcarriers for the different schemes. It is obvious that as the number of subcarriers increases, the proposed scheme provides better transmission rate for D2D users than the other existing methods. The reason is that our proposed ASA

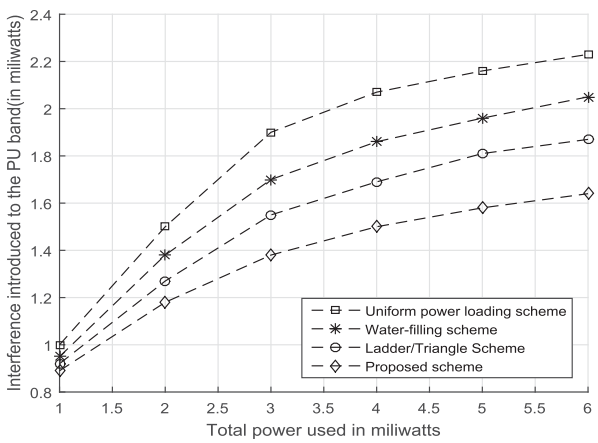

Fig. 10. Total power budget versus interference introduced to the PU band for different schemes.

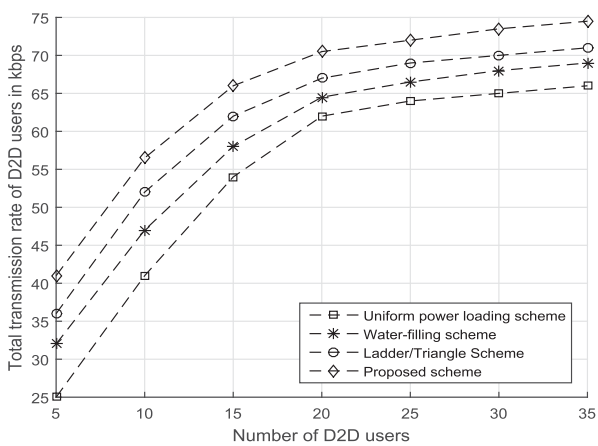

Fig. 11. Total transmission rate versus number of D2D users for the different schemes.

scheme is adaptive in nature due to the three different parts in the used metric.

Fig. 10 presents the interference introduced to the PU band versus total power budget for different schemes. As the total power budget increases, the interference generated to the PU band by the uniform power loading and water-filling schemes are severe. This is because these algorithms did not take the interference constraints into account. On the other hand, our proposed scheme is able to load power into multi-D2D users providing increased transmission rate while always keeping the interference introduced to the PU band below a specified threshold.

Fig. 11 illustrates the scenario of the total transmission rate versus the number of D2D users for the different schemes. It can be observed that as we increase the number of D2D users, the total transmission rate of our proposed scheme outperforms the other existing schemes while meeting the given constraints. When the number of D2D users remain small, the total transmission rate graph for all the schemes follow the linear pattern with a steep slope. However, for large number of D2D users, the total transmission rate graph for all the schemes become slowly saturated. This is as expected since, as we increase the number

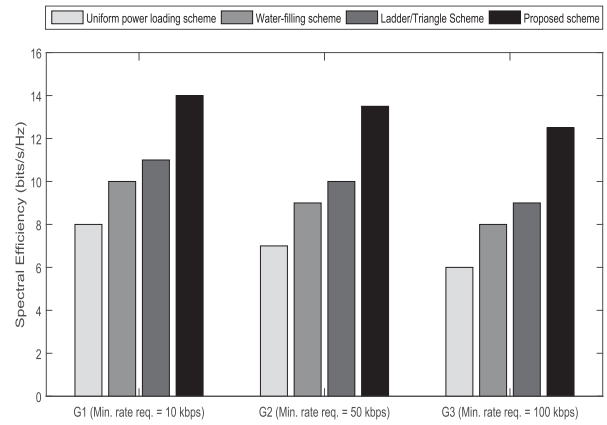

Fig. 12. Performance of different schemes for different minimum rate requirements.

TABLE III
IMPROVEMENT (IN %) OF THE PROPOSED SCHEME ON SPECTRAL EFFICIENCY COMPARED TO OTHER SCHEMES

Groups	Other schemes	Improvement
G1 (Min. rate req. 10kbps)	Uniform power loading	43%
	Water-filling	29%
	Ladder/Triangle	22%
G2 (Min. rate req. 50kbps)	Uniform power loading	48%
	Water-filling	33%
	Ladder/Triangle	26%
G3 (Min. rate req. 100kbps)	Uniform power loading	52%
	Water-filling	36%
	Ladder/Triangle	28%

of D2D users, the interference becomes dominant and the rate of transmission rate increment decreases. However, throughout the simulated region, our proposed scheme provides superior performance than the other schemes.

Fig. 12 investigates the performance of different algorithms for different minimum rate requirements. Here, three groups (e.g., G1, G2 and G3) are formed with three minimum rate requirement values (e.g., 10 kbps, 50 kbps and 100 kbps) to evaluate the algorithms performance in terms of spectral efficiency. Spectral efficiency (bits/s/Hz) is defined as the total transmission rate divided by the bandwidth allocated to the D2D users per second. Figure shows that the spectral efficiency decreases due to the increase in the minimum rate requirement, with the same constraints. This is because less number of D2D users are admitted due to high minimum rate requirement. Again, the proposed scheme outperforms the other schemes which is well depicted in Table III.

V. CONCLUSION

In this paper, we have studied how efficiently D2D communication can be employed with a cognitive radio approach in order to improve spectrum usage. An OFDM based cognitive cellular network with D2D communication has been modeled and analyzed using Lagrange formulation and solved using GWF approach. An adaptive subcarrier allocation scheme is designed based on a metric with three terms related to transmission

power, interference and transmission rate. The proposed power allocation scheme is developed using GWF to maximize the total downlink transmission rate of the D2D system under both power and interference constraints along with minimum rate requirements. Our simulation results show the proposed allocation scheme outperforms the existing schemes under different operating conditions. The performance of cognitive spectrum access in D2D-enabled cellular networks can be further improved (e.g., in terms of both spectrum efficiency and energy efficiency) by using more advanced resource allocation methods as well as emerging communication techniques such as full-duplexing, and also radio frequency energy harvesting techniques. Furthermore, future research shall consider the uplink scenario that has few basic differences and of course multicellular environment.

In order to find the solution of the optimization problem depicted in (9), Lagrange multipliers $(\alpha, \beta, \gamma, \delta, \psi)$ are used corresponding to the five constraints. The Lagrange can be formed as

$$\begin{aligned} L(\mathbf{X}, \mathbf{T}, \alpha, \beta, \gamma, \delta, \psi) &= \Delta B \sum_{m=1}^{M} \sum_{n=1}^{N} x_{m,n} \log\left(1 + \frac{t_{m,n}}{x_{m,n}} \Gamma_{m,n}\right) \\ &- \sum_{m=1}^{M} \sum_{n \epsilon \mathcal{N}_m} \alpha_n \left(\sum_{m=1}^{M} \sum_{n=1}^{N} t_{m,n} - P_T \right) \\ &- \sum_{m=1}^{M} \beta_m \left(\sum_{n=1}^{N} t_{m,n} - P_{m,max} \right) \\ &- \sum_{m=1}^{M} \sum_{n \epsilon \mathcal{N}_m} \gamma_n \left(t_{m,n} - \bar{P}_{m,n} \right) \\ &- \sum_{k=1}^{K} \delta_k \left(\sum_{m=1}^{M} \sum_{n=1}^{N} t_{m,n} I_{m,n}^{(k)} - I_{th} \right) \\ &- \sum_{m=1}^{M} \psi_m \left(\Re_{m,min} - \sum_{n=1}^{N} x_{m,n} \Re_{m,n} \right). \end{aligned} \tag{20}$$

The Lagrangian dual problem can be rewritten as follows:

$$\begin{aligned} D(\alpha, \beta, \gamma, \delta, \psi) &= \max_{\mathbf{X}, \mathbf{T}} \sum_{m=1}^{M} \sum_{n=1}^{N} \Bigg\{ (1 + \psi_m) x_{m,n} \\ &\log\left(1 + \frac{t_{m,n}}{x_{m,n}} \Gamma_{m,n}\right) - \left(\alpha_n + \beta_m + \gamma_n + \sum_{k=1}^{K} \delta_k I_{m,n}^{(k)}\right) t_{m,n} \Bigg\} \\ &+ \sum_{m=1}^{M} \sum_{n \epsilon \mathcal{N}_m} \alpha_n P_T + \sum_{m=1}^{M} \beta_m P_{m,max} + \sum_{m=1}^{M} \sum_{n \epsilon \mathcal{N}_m} \gamma_n \bar{P}_{m,n} \\ &+ \sum_{k=1}^{K} \delta_k I_{th} - \sum_{m=1}^{M} \psi_m \Re_{m,min} = \max_{\mathbf{X}} \sum_{m=1}^{M} \sum_{n=1}^{N} \max_{\mathbf{P}} \Bigg[x_{m,n} \Bigg\{ (1 \\ &+ \psi_m) \log\left(1 + P_{m,n} \Gamma_{m,n}\right) - \left(\alpha_n + \beta_m + \gamma_n + \sum_{k=1}^{K} \delta_m I_{m,n}^{(k)}\right) \\ &\times P_{m,n} \Bigg\} \Bigg] + \sum_{m=1}^{M} \sum_{n \epsilon \mathcal{N}_m} \alpha_n P_T + \sum_{m=1}^{M} \beta_m P_{m,max} \\ &+ \sum_{m=1}^{M} \sum_{n \epsilon \mathcal{N}_m} \gamma_n \bar{P}_{m,n} + \sum_{k=1}^{K} \delta_k I_{th} - \sum_{m=1}^{M} \psi_m \Re_{m,min} \\ &= \max_{\mathbf{X}} \sum_{m=1}^{M} \sum_{n=1}^{N} \max_{\mathbf{P}} \left\{ x_{m,n} \Psi(P_{m,n}) \right\} + \sum_{m=1}^{M} \sum_{n \epsilon \mathcal{N}_m} \alpha_n P_T + \sum_{m=1}^{M} \beta_m \\ &P_{m,max} + \sum_{m=1}^{M} \sum_{n \epsilon \mathcal{N}_m} \gamma_n \bar{P}_{m,n} + \sum_{k=1}^{K} \delta_k I_{th} - \sum_{m=1}^{M} \psi_m \Re_{m,min} \end{aligned} \tag{21}$$

with $\Psi(P_{m,n})$ being defined as follows:

$$\Psi(P_{m,n}) = (1 + \psi_m) \log\left(1 + P_{m,n} \Gamma_{m,n}\right) - \left(\alpha_n + \beta_m + \gamma_n + \sum_{k=1}^{K} \delta_k I_{m,n}^{(k)}\right) P_{m,n}. \tag{22}$$

To maximize (21) for any given $x_{m,n}$, (22) is differentiated with respect to $P_{m,n}$ and set the result to 0. This yields

$$P_{m,n}^{*} = \left[\frac{1 + \psi_m}{\ln\left(\alpha_n + \beta_m + \gamma_n + \sum_{k=1}^{K} \delta_k I_{m,n}^{(k)}\right)} - \frac{1}{\Gamma_{m,n}} \right]^{+}. \tag{23}$$

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