Energy Efficient Spectrum Allocation and Mode Selection for Mission-Critical D2D Communications

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***Abstract*—Device-to-device (D2D) communications is considered as a key enabling technology in future cellular networks and thus, it has become an intriguing topic for research. It refers to an innovative technology that enables User Equipments (UEs) to communicate directly with each other without using the eNodeB. This is indeed a challenging technique for mission-critical communications, e.g. in public protection and disaster relief (PPDR) application. In such a critical application, energy efficiency is an important factor for long and reliable communication. This can be achieved using more spectrum applying the D2D paradigm in Heterogeneous Networks (HetNet). In this work, we simulate an LTE-Advanced (LTE-A) HetNet consisting of both macro and pico Base Stations (BSs). Spectrum allocation and mode selection is devised for the associated UEs in order to enhance their energy efficiency that will lead to higher lifetime. In particular, a number of Component Carriers (CC) are considered available for allocation to the BSs in order to utilize Carrier Aggregation (CA) of LTE-A while mode selection decisions are made by each BS in order to balance between power consumption minimization and UE target data rate achievement. Under this framework, a power minimization problem is formulated in order to provide a joint spectrum allocation and mode selection. This problem is solved using a state of the art optimization method known as proximal minimization algorithm. The obtained simulation results reveal the energy efficient spectrum allocation and mode selection according to channels' quality that can balance between achieving high data rate requirements and power minimization as an important factor to mission-critical applications such as PPDR services.**

Keywords*—Device-to-device, energy efficiency, mode selection, heterogeneous networks, spectrum allocation, LTE-Advanced, carrier aggregation, proximal minimization algorithm.

I. INTRODUCTION

Device-to-device (D2D) communications underlaying cellular networks is a recent trend and have been widely used in 3GPP LTE-Advanced (LTE-A) Release 12 under the name of Proximity Services (ProSe) [1]. Until now, in conventional cellular networks, two UEs were forced to communicate through the corresponding eNodeB, despite the size of the distance that separated them. As it seems, this is not efficient, especially in the case where the two UEs are located very close to each other. Establishing a wireless link between the UEs and allowing them to communicate directly without the presence of the eNodeB seems to be the solution. We expect that the overall capacity of the system will significantly improve as the network load reduces. This is beneficial for several types of services including mission-critical communications. In the context of 5G wireless networks, the D2D technology is employed for emergency situations, e.g. public protection and disaster relief. Key requirements for a PPDR system is to provide dynamic radio resource management in order to retain the lifetime of the end devices [2]. The D2D communication should be able to guarantee reliable communication in areas without network coverage for the case of public security provision [3]. Furthermore, D2D communications become more and more popular especially in wireless sensor networks (WSNs), where dense networks prevail and therefore, a big need exists for discharging the routing nodes. For future applications like smart cities, smart grid etc., the dense deployment of WSNs will be an integrated part pf 5G networks that will be enabled by employing D2D communication [4].

In such an application , the advanced network topology which brings the network closer to the mobile users is considered to be essential for the LTE-A, since it increases capacity in hot spots with high user demand and fills in areas not covered by the macro network, both outdoors and indoors. A HetNet deployment, similar to the multi-node WSN utilizing a diverse set of BSs, have attracted a lot of interest as an alternative way to improve spectral efficiency per unit area [5]. Such a topology can also increase the network performance and service quality by offloading traffic from the large macro-cells. The simplest deployment will be to use a dedicated carrier for the small cell layer. This will avoid interfering with the existing macro-cell network and avoids tight coordination or synchronization [6].

In the literature, a mode selection algorithm considering the D2D and cellular link quality and the interference situation of each transmission mode is described in [7]. Another solution considering power control is presented in [8] that studies one D2D pair and one cellular UE subject to spectral efficiency restrictions and maximum transmission power constraints. Proper power allocation allows more D2D links to share the same resources. In [9] the problem of mode selection, channel allocation and power assignment for OFDMA based D2D communications is studied jointly. The authors propose practical algorithms to assign subcarriers/power to the users while also deciding their operation mode. Results indicate that by jointly optimizing the related decisions, the total power consumption is reduced significantly. In [10] a joint spectrum allocation and mode selection algorithm for overlay D2D communications is presented. Each user decides individually its operation mode based on the interference level detected in the resources dedicated to D2D communications. An optimization problem that maximizes the D2D data rate subject to minimum cellular data rate constraints is formulated and solved by properly adjusting the carrier sensing threshold. Several works

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like the one presented in [11] aim to interference to cellular users mitigation and throughput maximization. Considering the spectrum allocation problem, most solutions are based on auction theory [12]. In [13] D2D users bid for Resource Blocks (RBs) to the BS in order to facilitate spectrum allocation. A game theory approach for joint power control and channel allocation with D2D communication in HetNets has been studied in [14]. In [15], the D2D users assist the cellular transmissions to gain some spectrum released from the cellular system. The authors show that the number of the allowed accessing D2D pairs can be maximized by optimizing the D2D transmitters power of the proposed novel scheme. In [16], it is proposed a non-cooperative game theoretical model for spectrum allocation for multi-operator D2D communication. Each operator makes an offer about the amount of spectrum to contribute for multi-operator D2D communication considering only its individual performance.

The contribution of this work is to provide a framework under which, first, a number of CCs can be assigned to UEs of a HetNet that are associated with multiple BSs to provide cellular coverage to LTE-A UEs by employing CA. Second, a mode selection solution based on the channel quality between the D2D UEs and the associated BSs that aims to minimize the network's total power consumption, while also maintaining a target data rate threshold for each D2D link. This joint spectrum allocation and mode selection technique is incorporated into an energy efficient problem formulation that is solved using the proximal minimization algorithm found in [17]. Such a proximal minimization method is a key tool to introduce quadratic regularization into a smooth minimization problem. Thus, a dynamic radio resource management is accomplished for discovery both direct D2D and infrastructure based communication, so called mode selection algorithms D2D or cellular communication mode in order to increase the energy efficiency of the network. Such a solution is important for mission-critical communications like PPDR services.

The remainder of this paper is organized as follows. In Sec.II, we describe the system model of the HetNet with the considered D2D communication between the UEs. In Sec.III, we present the mathematical framework of a D2D enabled HetNet that is the basis of studying the data rate and power consumption performance of the proposed system. A centralized algorithm based on proximal optimization is then proposed in Sec.IV for the solution of the joint spectrum allocation and mode selection problem. In Sec.V we provide numerical results highlighting the performance of the proposed algorithm. Sec.VI provides a summary of this work.

II. System Model

The system model under study, consists of a macro cell that is served by a macro BS (MBS) and a small cell supported by a pico BS (PBS), which is used to increase spectral efficiency and offload the macro BS under the concept of HetNets. Fig.1 shows the concept of multi options for the available spectrum from the BSs to the users. We assume a set of $\mathcal{K}$ User Equipments (UEs) are spread between the macro and pico cells providing the opportunity of association to either one [1]. The

[1]The Fig.1 can be extended with more UEs that are omitted for sake of simplicity

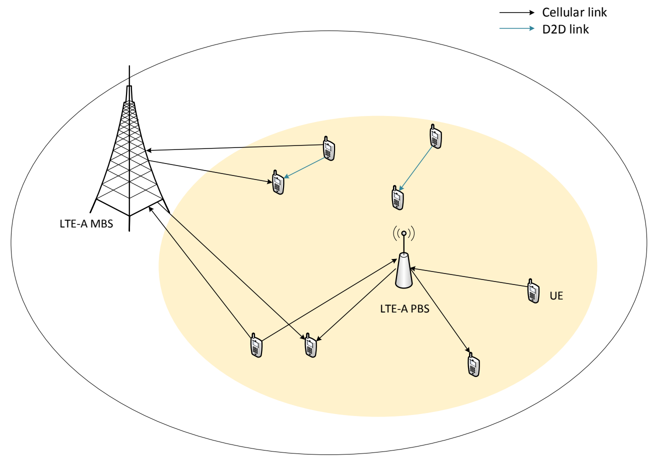

Fig. 1. The need for a joint spectrum allocation and mode selection in D2D communications.

UEs of $\mathcal{K}$ are divided in pairs that want to communicate with each other and thus exchange information data. We denote the set of possible D2D links as $\mathcal{L}$ the cardinality of which is $\frac{|\mathcal{K}|}{2}$ since all D2D links are pairs from set $\mathcal{K}$, so that one UE is serving as the transmitter and the other as the receiver. Suppose that the set of available Component Carriers (CC) for allocation is denoted by $\mathcal{N}$. Each BS is assigned with a subset of CCs that can allocate to the associated UEs either for D2D or cellular communication. We denote by $\mathcal{N}_1$ the set of CCs assigned to the macro BS and with $\mathcal{N}_2$ the corresponding value of the pico BS. Note that $\mathcal{N}_1 \cap \mathcal{N}_2 = \emptyset$. Each communicating pair l can be assigned with a number of CCs that are controlled by either BS and utilize them according to the corresponding BS's decision. Moreover, every UE is equipped with one omni-directional antenna used for both transmission and reception. Under this setup, every UE can provide Channel State Information (CSI) about each CC and also each operation mode (cellular or D2D). This is critical for the channel adaptation and CSI must be available to the LTE-A MBS that is in charge of performing spectrum allocation and mode selection decisions. Although D2D transmissions are enabled in order to enhance the system's performance, by reducing power consumption, such pairs may not always be able to communicate directly due to bad channel condition between the UEs and a potentially large data rate requirement that can be achieved by standard cellular communication.

III. Joint Spectrum Allocation and Mode Selection in D2D Communications

We aim to minimize the overall power consumption of the considered multi-user HetNet in order to provide spectrum allocation and mode selection for each CC, while respecting the UEs' data rate constraints. We begin the system analysis by providing the throughput experienced at each D2D receiver. For the wireless channel modeling and in order to calculate the received power at a D2D receiver, we use the following relation:

$$P_r = P_t d^{-a}, \tag{1}$$

where P_r is the received power, P_t is the transmit power, d is the distance between transmitter and receiver and a is the path loss coefficient. Transmit power is considered to be fixed and is denoted by P_{MBS}, P_{PBS} and P_{UE} when the transmitter is the macro BS, a pico BS or a UE in D2D mode respectively. P_{PBS} is typically smaller than P_{MBS}. The throughput performance of a D2D link l that utilizes a CC $n \in \mathcal{N}$ is described depending on the operation mode of the UE and the serving BS type as:

1) *D2D mode*: The D2D transmitter can utilize CC $n \in \mathcal{N}$, with transmit power equal to P_{UE}, so the throughput experienced at the respective receiver at distance d is:

$$R^n_{D2D}(l) = B_n \log(1 + \frac{P_{UE} d^{-a}}{\sigma^2}) \quad (2)$$

where B_n is the bandwidth of CC n and σ^2 is the power of the noise.

2) *Macro cell in cellular mode*: The throughput of a cellular link is limited to the minimum throughput between the links of transmitter-MBS and MBS-receiver. So the cellular mode transmission under CC $n \in \mathcal{N}_1$ provides a throughput to the cellular mode receiver that is:

$$R^n_{MBS}(l) = B_n \min\{\log(1 + \frac{P_{UE} d_1^{-a}}{\sigma^2}), \log(1 + \frac{P_{MBS} d_2^{-a}}{\sigma^2})\} \quad (3)$$

where d_1 and d_2 are the transmitter-MBS and MBS-receiver distances respectively.

3) *Pico cell in cellular mode*: In correspondence to the previous we calculate the achievable throughput as:

$$R^n_{PBS}(l) = B_n \min\{\log(1 + \frac{P_{UE} d_1^{-a}}{\sigma^2}), \log(1 + \frac{P_{PBS} d_2^{-a}}{\sigma^2})\} \quad (4)$$

where d_1 and d_1 are the transmitter-PBS and PBS-receiver distances respectively.

Note that both equations (3) and (4) represent cellular mode CCs but differ at the set of CCs that n belongs to. For eq. (3) it is $n \in \mathcal{N}_1$ while for eq. (4) it is $n \in \mathcal{N}_2$. Another difference lies in the transmit power of the BS. P_{PBS} is typically smaller than P_{MBS}.

Let us also define a few more variables that will help in the problem formulation that follows. α^l_n denotes the portion of CC $n \in \mathcal{N}$ that is allocated to link l. This portion can be interpreted as a number of RBs or sub-carriers that are allocated to each link l, enabling as to perform the desired spectrum assignment to the UEs. α^l_n is defined as:

$$\alpha^l_n \in [0,1], \forall n \in \mathcal{N},\ \forall l \in \mathcal{L}. \quad (5)$$

In addition to the spectrum assignment, mode selection decisions are carried out, i.e. decisions about how the assigned spectrum must be utilized by each D2D link are accomplished. Thus, the decision of cellular or mode selection is provided per available spectrum that is useful in case of PPDR services [2],[4].

Moreover, μ^l_n denotes the portion from the assigned to link l spectrum on CC n, i.e. α^l_n, that will be exploited by direct D2D communication, while the rest of it will be reserved for cellular communication. By this notation if $\mu^l_n = 1$ for some n, l then the portion of spectrum of CC n that is assigned to link l, is utilized in D2D mode. μ^l_n is similarly defined as follows:

$$\mu^l_n \in [0,1],\ \forall n \in \mathcal{N}\ \forall l \in \mathcal{L}. \quad (6)$$

The overall data rate that is experienced by link $l \in \mathcal{L}$ utilizing multiple CCs and transmission modes is then defined as follows:

$$R(l) = \sum_{n \in \mathcal{N}_1} \alpha^l_n (\mu^l_n R^n_{D2D}(l) + (1-\mu^l_n) R^n_{MBS}(l)) + \sum_{n \in \mathcal{N}_2} \alpha^l_n (\mu^l_n R^n_{D2D}(l) + (1-\mu^l_n) R^n_{PBS}(l)). \quad (7)$$

The power consumed by link l at CC n is defined as follows:

$$p^l_n = \begin{cases} P_{UE} + (1-\mu^l_n) P_{MBS}, & \text{if } n \in \mathcal{N}_1 \\ P_{UE} + (1-\mu^l_n) P_{PBS}, & \text{if } n \in \mathcal{N}_2. \end{cases} \quad (8)$$

Each D2D transmitter requires P_{UE} power to transmit to the respective receiver in D2D mode plus a portion of $(1-\mu^l_n)$ of P_{MBS} or P_{PBS} if part of the resources is utilized through cellular mode.

IV. Energy Efficient Problem Formulation and Solution

In this section we describe the overall power minimization problem for the considered multi-user HetNet, which is subject to minimum target data rate constraints for the UEs based on the analysis of the previous section. The optimization problem is defined as follows:

$$\min_{\alpha^l_n, \mu^l_n} \sum_{n \in \mathcal{N}} \sum_{l \in \mathcal{L}} p^l_n, \quad (9)$$

subject to:

$$R(l) \geq r(l), \forall l \in \mathcal{L}, \quad (10)$$

$$\sum_{l \in \mathcal{L}} \alpha^l_n \leq 1,\ \forall n \in \mathcal{N}, \quad (11)$$

where $r(l)$ is the minimum throughput required by link l. The Eq. (11) is necessary so that the summation of the portions allocated to the D2D users reach the available number of resources.

The convex problem defined above can be solved using a *proximal algorithm* and in particular, the proximal minimization algorithm found in [17,Sec.4]. In fact, this algorithm employs quadratic regulation for easiest minimization by introducing a quadratic term in the objective function. Thus the problem is transformed into a strictly convex one by using an auxiliary variable x^l_n as also applied in [18] and other proximal optimization algorithm applications. The objective function now is obtained as follows:

$$\min_{\alpha_n^l,\mu_n^l,x_n^l} \sum_{n\in\mathcal{N}}\sum_{l\in\mathcal{L}} p_n^l + \sum_{n\in\mathcal{N}}\sum_{l\in\mathcal{L}} \frac{c}{2}(p_n^l - x_n^l)^2, \quad (12)$$

where c is a positive integer. The above function, when evaluated for fixed values of x_n^l, is a proximal operator [17]. For each iteration of the proximal algorithm the following problem is solved for a fixed value of x_n^l with standard convex optimization techniques such as solving the dual Lagrangian problem.

$$\min_{\alpha_n^l,\mu_n^l} \sum_{n\in\mathcal{N}}\sum_{l\in\mathcal{L}} p_n^l + \sum_{n\in\mathcal{N}}\sum_{l\in\mathcal{L}} \frac{c}{2}(p_n^l - x_n^l)^2 \quad (13)$$

that is subject to the constraints in eq. (10) and eq. (11).

It can be easily observed that if $x_n^l = p_n^{l*}$ where p_n^{l*} is the optimal solution of (9), problems (9) and (13) are equivalent. Variable x_n^l is used in order to iteratively approximate the optimal solution p_n^{l*} by solving (13) for fixed values of x_n^l, only to use the solution $p_n^l(t)$ acquired at iteration t as the fixed value of x_n^l for the next iteration (setting $x_n^l(t+1) = p_n^l(t)$) and resolving (13).

Let us define the Lagrangian of (13) as:

$$\begin{aligned} L(\boldsymbol{\alpha},\boldsymbol{\mu},\boldsymbol{\kappa},\boldsymbol{\lambda}) = \sum_{n\in\mathcal{N}}\sum_{l\in\mathcal{L}} p_n^l + \sum_{n\in\mathcal{N}}\sum_{l\in\mathcal{L}} \frac{c}{2}(p_n^l - x_n^l)^2 - \\ \sum_{l\in\mathcal{L}} \kappa_l (R(l) - r(l)) + \sum_{n\in\mathcal{N}} \lambda_n (\sum_{l\in\mathcal{L}} \alpha_n^l - 1) \end{aligned} \quad (14)$$

where $\boldsymbol{\alpha},\boldsymbol{\mu}$ are vectors containing the values of α_n^l and μ_n^l and $\boldsymbol{\kappa},\boldsymbol{\lambda}$ are the vectors of the dual variables κ_l and λ_n of the problem's constraints. In order to minimize L we firstly calculate the gradients of L with respect to α_n^l and μ_n^l and end up with the following equations:

$$\nabla_{\alpha_n^l} L = \kappa_l(\mu_n^l R_{D2D}^n(l) + (1-\mu_n^l) R_{MBS}^n(l)) + \lambda_n = 0 \quad (15)$$

and:

$$\begin{aligned} \nabla_{\mu_n^l} L = P_{MBS}[c(P_{UE} + \mu_n^l) + x_n^l - 1] - \\ \kappa_l \alpha_n^l (R_{D2D}^n(l) - R_{MBS}^n(l)) = 0 \end{aligned} \quad (16)$$

In addition, the problem's constraints provide us with:

$$\kappa_l(\sum_{n\in\mathcal{N}_1} \alpha_n^l(\mu_n^l R_{D2D}^n(l) + (1-\mu_n^l) R_{MBS}^n(l)) - r(l)) = 0,\ \forall l \in \mathcal{L} \quad (17)$$

and:

$$\lambda_n(\sum_{l\in\mathcal{L}} \alpha_n^l - 1) = 0,\ \forall n \in \mathcal{N}_1 \quad (18)$$

Solving the nonlinear system of equations (15)-(18) we can obtain a solution for $\alpha_n^l, \mu_n^l, \kappa_l, \lambda_n$ as a function of c, x_n^l and the data rates: $R_{D2D}^n(l), R_{MBS}^n(l), R_{PBS}^n(l)$. Note that in equations (15)-(18) it is assumed that $n \in \mathcal{N}_1$ and thus $R_{MBS}^n(l)$ is used throughout the equations. In the other case $R_{PBS}^n(l)$ is used instead. After this step, p_n^l is evaluated using equation (8) and the power minimization step is concluded.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
a	3
P_{UE}	30 dBm
P_{MBS}	43 dBm
P_{PBS}	40 dBm
σ^2	-100 dBm
B_n	20 MHz
c	1
$x_n^l(0)$	10
ϵ	0.01

Algorithm 1 Proximal Algorithm

Require: c and $x_n^l(1)$
  $t = 1$
  for each iteration t **do**
    Calculate $p_n^l(t)$ using Algorithm 2
    if $|x_n^l(t) - p_n^l(t)| < \epsilon$ **then**
      break
    else
      $x_n^l(t+1) \leftarrow p_n^l(t)$
    end if
    $t = t + 1$
  end for

Algorithm 2 Lagrangian Minimization

Require: $c, x_n^l, r(l), R_{D2D}^n(l), R_{MBS}^n(l), R_{PBS}^n(l), \forall n, l$
  Calculate $\alpha_n^l, \mu_n^l, \kappa_l, \lambda_n$ using eq. (15)-(18)
  Evaluate p_n^l from eq. (8)
  return p_n^l

The entire procedure is briefly described in Algorithm 1. After initializing c and $x_n^l(1)$ the iterative proximal algorithm begins by calculating p_n^l using Algorithm 2. Then a test is made in order to check if the algorithm has converged to the optimal solution by comparing x_n^l and p_n^l. If convergence has not been achieved, x_n^l is updated with the current step solution prior to the next iteration. Algorithm 2 simply solves the nonlinear system (15)-(18) in order to calculate p_n^l and return the result to Algorithm 1.

V. SIMULATION RESULTS

In this section we track the performance of the proximal algorithm and also evaluate the performance of the resulted solution for a set of use cases. The simulation parameters used for the results presented in this section are displayed in Table I.

The sum power of the network versus the proximal algorithm iterations is displayed in Fig. 2. The different cases presented are characterized by the number of CCs N and the number of D2D links L. For simplicity it is assumed that $N/2$ carriers belong to set $\mathcal{N}_1$ and the rest $N/2$ to set $\mathcal{N}_2$. It can be seen clearly that as N and L increase, the required number of iterations, for the proximal algorithm to converge is also increased. Another thing worth mentioning is the increasing

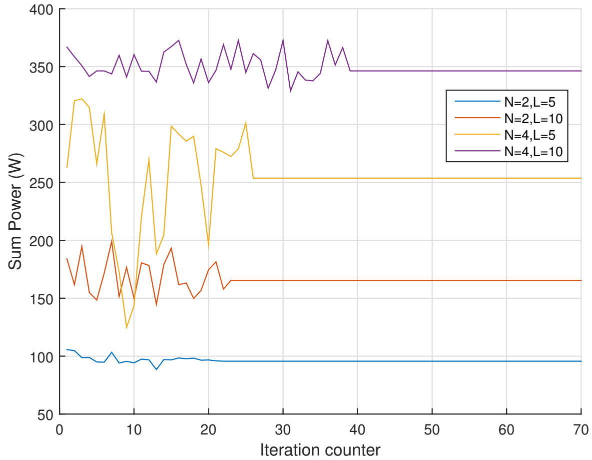

Fig. 2. Sum power of all D2D links versus the proximal algorithm iteration step.

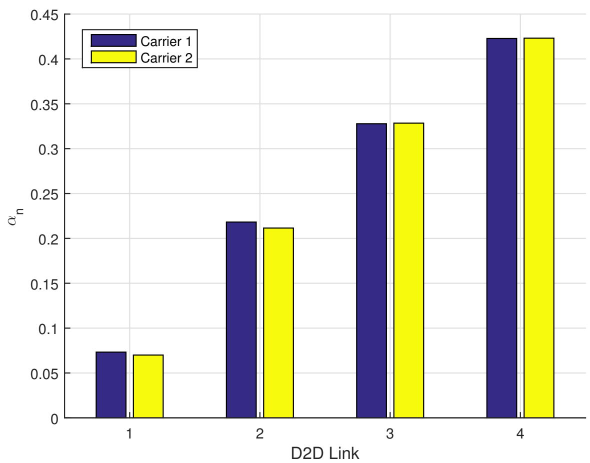

Fig. 3. Resulted α_n for each link l. Target rates are given by $r = [1, 3, 5, 8]Mbps$.

convergence sum power as N and L increase. The fluctuations observed before the convergence do not mean much as they are solutions of (13) and not (9).

Next in Figures 3 and 4 the results of α_n^l and μ_n^l are displayed for a scenario of $N = 2$ carriers and $L = 4$ links. In Fig. 3 we measure $\alpha_n = [\alpha_{n_1}^l, \alpha_{n_2}^l]$ for each link $l \in [1, 2, 3, 4]$. The links for this measurement require a target data rate r_l increasing to their index, i.e. $r_l > r_{l-1}$. We notice that our solution assigns bigger portions of spectrum from both carriers to the links with higher data rate demands, which was to be expected.

In order to measure μ_n^l it is required that the links have different channel states in D2D and cellular mode rather than different target rates. In Fig. 4 as the link index increases, each link experiences better condition in D2D mode and worse condition in cellular mode. The results are obtained for 3 cases of target rate ($r = 2, 5, 8Mbps$, common for all links). It is evident that when D2D mode provides very high SNR and

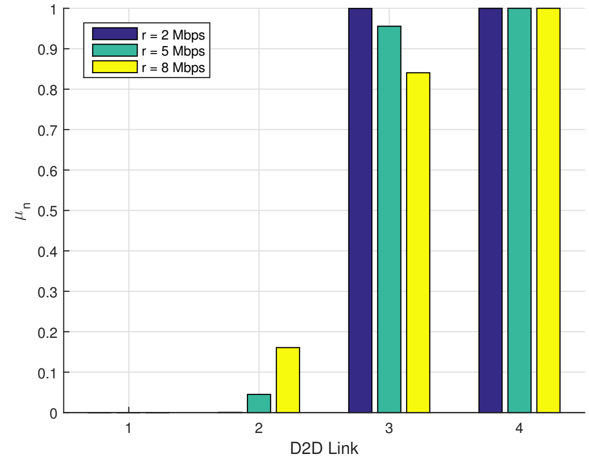

Fig. 4. Resulted μ_n for each link l. The SNR situation of each link is as follows: $SNR_1 = [5, 20]dB$, $SNR_2 = [10, 15]dB$, $SNR_3 = [15, 10]dB$, $SNR_4 = [20, 5]dB$. The first value corresponds to D2D SNR while the second, to cellular mode for each link.

cellular mode very low (link 4), we have $\mu_n = 1$, meaning full D2D utilization of the assigned spectrum, while on the contrary (link 1), $\mu_n = 0$. In less extreme cases (links 2,3), the results are not absolute and μ_n leans towards the mode with better SNR. Moreover, as the target SNR increases, μ_n is higher or lower according to which mode offers higher SNR.

Variable μ_n^l is the one that impacts power consumption. The proposed algorithm aims in total power minimization, so intuitively the higher the proportion of allocated spectrum is utilized for D2D communication, i.e. μ_n^l, the less power is consumed. Depending on the D2D and cellular SNRs, μ_n^l is decided in order to satisfy the data rate demand $r(l)$. The effect on power consumption is displayed in Fig. 5. As the D2D mode SNR increases, the gain from enabling D2D mode is greater, and power consumption is quickly diminished to its minimum value (1 W) when the link is fully in D2D mode. The transition from cellular to D2D mode occurs for higher D2D SNR values, as the cellular mode SNR increases.

VI. Conclusion

In this work, we propose a framework for energy efficient D2D communications in mission-critical applications like PPDR services for the 5G networks, where HetNet and CA applications are deployed to the BSs and the UEs respectively. In such a setup, spectrum allocation and mode selection decisions are provided jointly so that users are assigned with multiple CCs that are utilized in different operation modes. An overall network power minimization problem for the considered multi-user HetNet is devised imposing minimum data rate constraints. This problems is then solved using state of the art proximal minimization algorithm incorporating quadratic regulation. Indicative results were obtained that reveal fair spectrum allocation decisions according to the users target rates, as well as proper mode selection depending on the channel states of D2D and cellular links towards minimizing power consumption. In this way, energy efficient spectrum allocation is guaranteed for mission-critical communications, e.g. PPDR

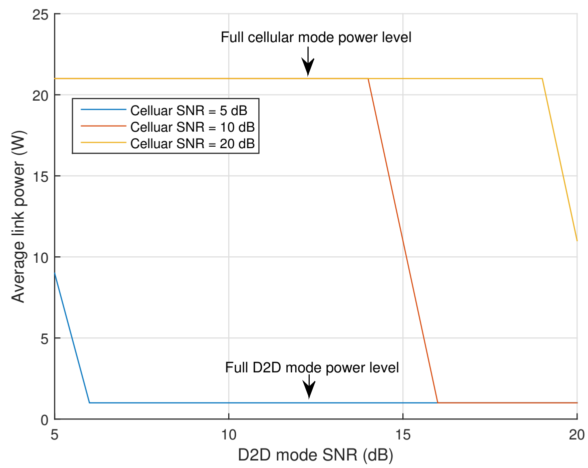

Fig. 5. Average link power consumption versus the D2D mode SNR.

services, that are enabled by D2D type of communication.

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References

[1] K. Zheng, F. Hu, W. Wang, W. Xiang, and M. Dohler, "Radio resource allocation in lte-advanced cellular networks with m2m communications," *Communications Magazine, IEEE*, vol. 50, no. 7, pp. 184–192, 2012.

[2] G. Fodor, S. Parkvall, S. Sorrentino, P. Wallentin, Q. Lu, and N. Brahmi, "Device-to-device communications for national security and public safety," *Access, IEEE*, vol. 2, pp. 1510–1520, 2014.

[3] Ericsson, "Rws-120003 lte release 12 and beyond," tech. rep., June 2012.

[4] M. Usman, A. Gebremariam, U. Raza, and F. Granelli, "A software-defined device-to-device communication architecture for public safety applications in 5g networks," *Access, IEEE*, vol. 3, pp. 1649–1654, 2015.

[5] D. Lopez-Perez, S. Güvenç, G. De la Roche, M. Kountouris, T. Q. Quek, and J. Zhang, "Enhanced intercell interference coordination challenges in heterogeneous networks," *Wireless Communications, IEEE*, vol. 18, no. 3, pp. 22–30, 2011.

[6] E. Seidel, "Lte-a hetnets using carrier aggregation," *NoMoR Research GmbH, Munich, Germany, June*, 2013.

[7] K. Doppler, C.-H. Yu, C. Ribeiro, and P. Janis, "Mode selection for device-to-device communication underlaying an lte-advanced network," in *Wireless Communications and Networking Conference (WCNC), 2010 IEEE*, pp. 1–6, April 2010.

[8] C.-H. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen, "Resource sharing optimization for device-to-device communication underlaying cellular networks," *Wireless Communications, IEEE Transactions on*, vol. 10, pp. 2752–2763, August 2011.

[9] C. Gao, X. Sheng, J. Tang, W. Zhang, S. Zou, and M. Guizani, "Joint mode selection, channel allocation and power assignment for green device-to-device communications," in *Communications (ICC), 2014 IEEE International Conference on*, pp. 178–183, June 2014.

[10] B. Cho, K. Koufos, and R. Jantti, "Spectrum allocation and mode selection for overlay d2d using carrier sensing threshold," in *Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2014 9th International Conference on*, pp. 26–31, June 2014.

[11] C.-H. Yu, O. Tirkkonen, K. Doppler, and C. Ribeiro, "Power optimization of device-to-device communication underlaying cellular communication," in *Communications, 2009. ICC '09. IEEE International Conference on*, pp. 1–5, June 2009.

[12] A. Jilani, "Spectrum allocation methods: Studying allocation through auctions," *Journal of Economics, Business and Management*, vol. 3, no. 7, 2015.

[13] A. Li, X. Liao, and D. Zhang, "A spectrum allocation algorithm for device-to-device underlaying networks based on auction theory," in *Wireless Communications and Signal Processing (WCSP), 2014 Sixth International Conference on*, pp. 1–6, Oct 2014.

[14] Y. He, F. Wang, and J. Wu, "Resource management for device-to-device communications in heterogeneous networks using stackelberg game," *International Journal of Antennas and Propagation*, vol. 2014, 2014.

[15] Z. Dai, J. Liu, and C. Wang, "Qos-based device-to-device communication schemes in heterogeneous wireless networks," *Communications, IET*, vol. 9, no. 3, pp. 335–341, 2015.

[16] B. Cho, K. Koufos, R. Jäntti, Z. Li, and M. A. Uusitalo, "Spectrum allocation for multi-operator device-to-device communication," *arXiv preprint arXiv:1502.04186*, 2015.

[17] N. Parikh and S. Boyd, "Proximal algorithms," *Foundations and Trends in Optimization*, vol. 1, no. 3, pp. 127–239, 2014.

[18] X. Lin and N. Shroff, "Utility maximization for communication networks with multipath routing," *Automatic Control, IEEE Transactions on*, vol. 51, pp. 766–781, May 2006.