Interference Mitigation using Band Selection for Network-assisted D2D Communications

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***Abstract*—For systems with reuse factor less than one, the co-channel interference can drastically reduce the gain of primary networks, which limits the whole system performance. This paper exploits the selection of Downlink (DL) or Uplink (UL) band to be reused by a Device-to-Device (D2D) link. The band selected by the method is based on a radio distance metric, such as received power. Despite being a simple concept, results have shown that band selection can effectively mitigate the interference caused by D2D communications in a Long Term Evolution (LTE) network. Therefore, the coexistence of cellular and D2D communication modes becomes possible in time, frequency, and space.**

I. Introduction

Device-to-Device (D2D) communication is a type of direct wireless communication between two or more network nodes, hereafter generally referred as User Equipments (UEs), similar to direct-mode operation in professional mobile radio systems (colloquially, walkie talkies) or the bluetooth technology, that has attracted increasing attention of scientific community in the last couple of years, mostly because of its flexibility [1]: D2D communications can be deployed in Industrial, Scientific and Medical (ISM) bands for the unlicensed spectrum use, such as Wireless Local Area Networks (WLANs), or in cellular networks for a licensed use [2].

Particularly, for communications happening in a cellular network, it is evidently resource inefficient (both in terms of energy and bandwidth) to communicate via a 3rd entity (cell tower) when nature provides a direct path between two closely located UEs [3]. Therefore, the main principle that underlays each D2D communication is to exploit the proximity of UEs, which provides the hop gain (direct path), reducing energy consumption, while allowing very high throughputs and low delays [2]. Moreover, the network operator does not need to be involved in the actual data transport (except for session setup signaling, charging, and policy enforcement) [4], which offloads the core network; and at cell boundaries, D2D links may be used as relays to extend the coverage area [1], [5].

As such, due to their deployment flexibility and aforementioned advantages, D2D communications are currently being considered inside 3rd Generation Partnership Project (3GPP) to facilitate Machine-to-Machine (M2M)/proximity aware services, and security/public safety applications, becoming part of Long Term Evolution (LTE) standards [6]. In this context, conventional cellular and D2D communications can be respectively referred as primary and secondary communications.

D2D communications are particularly attractive considering the reuse gain obtained when D2D-capable UEs are allowed to directly transmit data by reusing either Downlink (DL) or Uplink (UL) radio resources from the cellular network [7]. However, operating in the in-band shared spectrum mode [8], secondary communications pose new challenging interference situations, such as the co-channel interference, due to orthogonality loss [9], which can drastically reduce the performance of primary communications [10].

Some of the already studied solutions to deal with this problem and improve the overall network throughput include, e.g., power control, spatial diversity, robust centralized/distributed resource allocation, mode selection and grouping, or network coding [7], [8]. In this paper we investigate the interference mitigation by using an intelligent selection of the transmission band, either DL or UL, for the D2D link when sharing spectrum resources with an LTE network. Nevertheless, the method is still valid for a time-based duplexing scheme and other types of wireless systems. Also, differently from most of state-of-art publications that focus on interference mitigation, herein we consider a realistic multi-user/cell scenario, with wrap-around, and both communication directions.

The remaining sections of the paper are organized as follows: in Section II the principle behind band selection technique is presented and explained in detail, Section III has the description of system model and realistic models used for simulations, in Section IV the principal results are shown and analyzed, lastly conclusions are drawn in Section V.

II. Band Selection

A. The Principle Overview

The main principle behind band selection for interference mitigation is to either select DL or UL band for the D2D link using a radio distance metric, like the received power, Pr. The decision-taking procedure verifies if the received power from the serving Evolved Node B (eNB) of the transmitter within D2D pair[1] is above a given threshold, Pr_{TH}, and if it yields true, the DL band is selected; otherwise, the UL band is used.

The Pr is measured from the serving eNB (eNB-UE link), not within the D2D pair (UE-UE link), and attempts to map the position of the interferer (D2D-capable UE that acts as

[1]A pair formed by two D2D-capable UEs (transmitter and receiver) that use the direct path to communicate.

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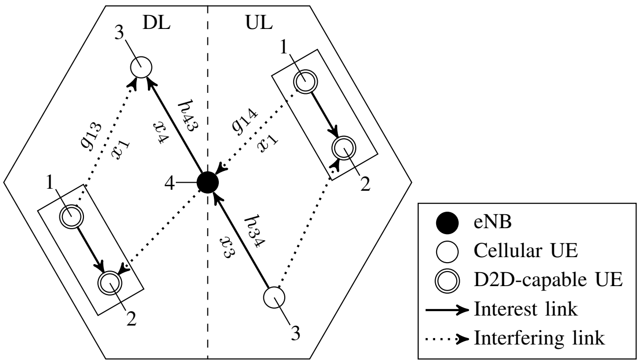

Fig. 1. Simplified scenario illustrating the urban-microcell environment with hotspot for DL and UL communication directions: source 1, 3, and 4 transmit signals x_1, x_3, and x_4 with power P_1, P_3, and P_4, respectively; h_{34} and h_{43} represent the channel between sources 3 and 4 in both directions, while g_{13} and g_{14} represent the interfering channels because of D2D communication originated from source 1

transmitter) within the cell, since the real location is most of the times unavailable (see Fig. 1). The greater is the received power, the lower is the distance to eNB. Thus, above threshold means "near eNB", while below the threshold translates "at cell-edge" position (see Fig. 2).

Furthermore, the method must be applied for all D2D pairs in each Transmission Time Interval (TTI) because of channel variations. Also, we refer as active pairs the ones with the same selected band as the current communication phase, i.e., reuse DL band in DL phase or reuse UL band in the UL phase.

For LTE networks, the band selection technique is performed per Physical Resource Block (PRB) and also includes the grouping of one active pair (selected randomly or by any other mean) with the primary scheduled cellular UE to either reuse the DL or UL PRBs (see Fig. 3). In this situation, system-specific measures like Reference Signal Receive Power (RSRP), Received Signal Strength Indicator (RSSI), or even Reference Signal Receive Quality (RSRQ) may be used alone or combined as radio distance metric.

B. The Underlying Concept

Consider the picture in Fig. 1, where h and g denote the complex channel coefficients, respectively associated with desired and interfering gains. These channels are assumed to be asymmetric, i.e., DL and UL channels may have different gains. The simplified scenario represented therein also suffers outside interference from the surrounding cells that are using the same PRB. That interference channel can be generally designated as i_k, where k refers to the index of the interferer I_k (eNB or UE). Also, each receiver is subject to experience additive white Gaussian noise $n_3, n_4 \sim \mathcal{CN}(0, \sigma^2)$. Moreover, the transmitted data symbols are represented as x, and we assume that $|x_1|^2 = |x_3|^2 = |x_4|^2 = |x_{I_k}|^2 = 1$. Thereby, the received signals at sources 3 and 4 are given as follows

$$y_3 = \underbrace{\sqrt{P_4} h_{43} x_4}_{\text{desired signal}} + \underbrace{\sum_k \sqrt{P_{I_k}} i_k x_{I_k}}_{\text{outside interf. signal}} + \underbrace{\sqrt{P_1} g_{13} x_1}_{\text{D2D interf. signal}} + n_3,$$

$$y_4 = \underbrace{\sqrt{P_3} h_{34} x_3}_{\text{desired signal}} + \underbrace{\sum_k \sqrt{P_{I_k}} i_k x_{I_k}}_{\text{outside interf. signal}} + \underbrace{\sqrt{P_1} g_{14} x_1}_{\text{D2D interf. signal}} + n_4.$$

Taking the power ratio of desired signal over interference and noise, the Signal to Interference-plus-Noise Ratio (SINR) values at sources 3 and 4 are calculated as

$$\gamma_3 = \frac{|h_{43}|^2}{\frac{\sum_k P_{I_k} |i_k|^2}{P_4} + \frac{P_1}{P_4}|g_{13}|^2 + \frac{\sigma^2}{P_4}}, \quad (1)$$

$$\gamma_4 = \frac{|h_{34}|^2}{\frac{\sum_k P_{I_k} |i_k|^2}{P_3} + \frac{P_1}{P_3}|g_{14}|^2 + \frac{\sigma^2}{P_3}}. \quad (2)$$

Our goal is to reduce the interference that comes from D2D communications (the outside interference is hard to be avoided) so that the SINR is higher.

In DL all PRBs available within the cell, N_{PRB}, are used, and in UL the PRBs per UE depend on the scheduling policy. Hence, $P_4 = P_{\text{eNB}}/N_{\text{PRB}}$ and $P_{\text{UE}}/N_{\text{PRB}} \le P_1, P_3 \le P_{\text{UE}}$, where P_{eNB} and P_{UE} are the total transmit power of eNB and UEs, respectively. In addition, normally $P_3, P_4 \gg \sigma^2$, which makes the system being mostly limited by interference, i.e., $\sigma^2/P_4 \approx 0$ and $\sigma^2/P_3 \approx 0$.

Now, let us assume the worst case scenario[2], where 1) the D2D transmitter is always close to the cellular receiver, either eNB in UL phase or celular UE in DL phase, being the dominant interferer; 2) so the interfering channel is always good, i.e., $|g_{13}|^2 \to 1^-$ and $|g_{14}|^2 \to 1^-$ (or $0\,\text{dB}$).

Regarding the phases in communication, four situations may happen: we are in DL and the cellular UE is near eNB (ST1) or the cellular UE is at cell-edge (ST2); or we are in UL and the cellular UE is near eNB (ST3) or the cellular UE is at cell-edge (ST4). Without loss of generality, let us just focus on the urban-microcell scenario with a bandwidth of $5\,\text{MHz}$. Thus, $P_{\text{eNB}} - P_{\text{UE}} = 14\,\text{dB}$ (P_{eNB} is around 25 times greater than P_{UE}) and $N_{\text{PRB}} = 25$ PRBs [11]. As such, the order of magnitude for desired signals and D2D-generated interference in Eq.'s (1) and (2) is heuristically compared as follows

ST1: $|h_{43}|^2 \to 1^-$; $0.04 \lessapprox (P_1/P_4)|g_{13}|^2 \lessapprox 1$; $\Rightarrow$ reuse DL
ST2: $|h_{43}|^2 \to 0^+$; $0.04 \lessapprox (P_1/P_4)|g_{13}|^2 \lessapprox 1$; $\Rightarrow$ reuse UL
ST3: $|h_{34}|^2 \to 1^-$; $1 \le (P_1/P_3)|g_{14}|^2 \le 25$; $\Rightarrow$ reuse DL
ST4: $|h_{34}|^2 \to 0^+$; $1 \le (P_1/P_3)|g_{14}|^2 \le 25$; $\Rightarrow$ reuse DL

Clearly, for the ST2, ST3, and ST4 situations, selecting an orthogonal band, i.e., $|g_{13}|^2 = |g_{14}|^2 = 0$, shall represent a huge impact, reducing the overall interference suffered by the cellular receiver. For ST1, since the cellular (desired) channel is good and $(P_1/P_4)|g_{13}|^2$ is most of the times less than the unity, there is no particular need to select an orthogonal band. As a summary, regardless the communication direction, the band selection principle does apply: if D2D communications happen close to eNB (ST1, ST3, and ST4) then the DL band is reused, otherwise the UL band is reused (ST2).

[2]It can be very restrictive, but while proved for the worst case scenario, it is proved for all other cases.

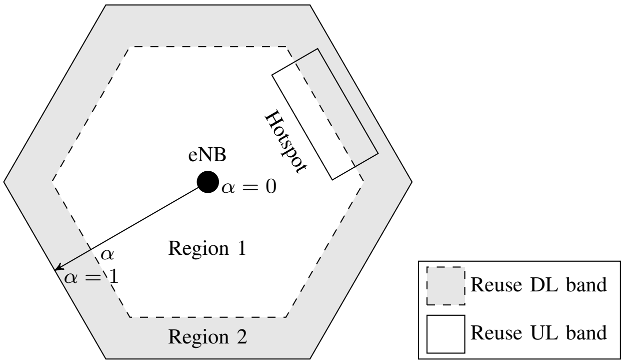

Fig. 2. Variation of eNB threshold according the band factor α: region 1 means "near eNB" thus DL band is reused, and region 2 translates in "at cell-edge" therefore UL band is reused

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for each TTI, cell, and PRB do
    Select one cellular UE using the PF scheduling policy
    for each D2D pair do
        Determine the band (DL or UL) to be used in the D2D link
        Set pair as active if selected band equals the comm. direction
    end for
    Randomly group an active D2D pair with the cellular UE
    Perform the link adaptation of selected UEs
end for
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Fig. 3. RRA simulation procedure

C. Setting the Threshold

The selection of any band is dependent on the established threshold for each eNB, Pr_{TH}. A possible approach, only considering large scale fading effects (path loss and shadowing), is to define a band factor $\alpha \in [0, 1]$ which is multiplied by the cell radius (cell radius fraction). The received power at that new distance from eNB is the new threshold, as shown in Fig. 2. In real networks, a campaign of field measures can be used instead, where by following the trial and error strategy described below, different best thresholds are set, depending on the place where D2D communications happen.

While turning on the band selection technique, the D2D-generated interference on cellular communications is reduced (i.e., they become protected). In such conditions, the cellular gain increases which inevitably is reflected in an increased cellular interference on D2D communications, reducing the D2D gain. Hence, a best threshold shall be selected so that the whole system benefits from both communication modes.

For that, the band factor α is varied and thresholds are set for each eNB and all PRBs. Next, the band selection method is applied at every TTI, and the system performance results collected for both cellular and D2D communications in DL and UL. Let us denote Ψ as the system performance with D2D communications but without band selection, and Φ_j as the system performance with D2D communications and band selection enabled for α_j (the communication direction and mode were omitted in the notation for simplicity). So the best band factor $\alpha^\star$ is obtained as follows

$$\alpha^\star = \arg\max_j \left(\frac{C_j}{D_j} \right), \forall \alpha_j, \tag{3}$$

where, for α_j,

$$C_j = \max\left(|\Psi - \Phi_j|_{\text{DL}}, |\Psi - \Phi_j|_{\text{UL}} \right)_{\text{Cell}}, \tag{4}$$

$$D_j = \max\left(|\Psi - \Phi_j|_{\text{DL}}, |\Psi - \Phi_j|_{\text{UL}} \right)_{\text{D2D}}, \tag{5}$$

and

$$A = \{0, 0.1, \ldots, 1\} \text{ and } j = 1, 2, \ldots, \#A \text{ and } \alpha_j \in A.$$

In the case of cellular communications we desire to maximize C_j (Eq. (4)), i.e., find $(\Phi_j)_{\text{Cell}} \gg \Psi_{\text{Cell}}$, because on such situation the gain provided by cellular communications is maximum in the presence of D2D communications. On the other hand, when band selection is not enabled, the gain of D2D communications is maximum, but it has a strong impact on cellular communications; thus maximizing D_j (Eq. (5)), i.e., finding $(\Phi_j)_{\text{D2D}} \ll \Psi_{\text{D2D}}$, is the same as minimizing the D2D gain or the generated interference. The best trade-off between system performance and interference mitigation is then ensured by maximizing the ratio C_j/D_j (Eq. (3)).

III. System Model and Simulation Framework

In previous sections a simplified signal model was used. In this one, realistic models that were employed to evaluate the system performance are described. Hence, consider an LTE-like network based on the urban-microcell propagation environment, where each eNB is placed in the center of a site (a single-cell) represented regular hexagon [12]. This scenario corresponds to a multi-cell network with N_{Cell} cells regularly distributed over it and each cell serves N_{UE} UEs.

Also, there is a hotspot per cell where D2D communications happen. A percentage of the total number of UEs within the cell is clustered inside the hotspot zone while the remaining UEs are uniformly distributed over the cell area. Moreover, the D2D pairs are obtained by a simple random pairing of UEs inside the hotspot. However, in our model, UEs within the hotspot may be chosen by the scheduling policy at each TTI, therefore acting as cellular UEs. Fig. 1 exemplifies both cellular and D2D communications.

The modeling of complex channel coefficients follow a PRB basis, including the propagation effects on wireless channels, namely, pathloss, shadowing, and fast fading [11]–[13]. Additionally, we consider a number of N_{PRB} PRBs available in each link direction (determined by the system bandwidth) that can be fully reused by all cells.

As presented in Fig. 3, after one cellular UE is selected by the Proportional Fair (PF) cellular scheduling policy, one D2D pair inside the hotspot is randomly grouped with the former UE to share the same PRB, in the predetermined DL or UL band. Moreover, after scheduling, the total transmit power of eNB in DL and cellular UE in UL, and D2D transmitter in both communication directions, is equally divided among the number of allocated PRBs.

Furthermore, the link adaptation procedure selects the Modulation and Coding Scheme (MCS) that yields the maximum SINR threshold [14], and packets are error-free received. The main simulation parameters are summarized in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Ref.
Number of eNBs (N_{Cell})	7 (with wrap-around)	
Cellular environment	Urban-microcell	[12]
Inter-site distance	500 m	[12]
Minimal UE-eNB link distance	20 m	
eNB transmit power	38 dBm	[11]
UE transmit power	24 dBm	[11]
Cellular pathloss model [dB]	$34.5 + 38\log_{10}(d)$, d in meter	[12]
Shadowing std. dev.	10 dB	[11]
Fast fading model	3GPP SCM	[12]
Average UE speed	3 km/h	[11]
Antenna gain	6 dBi	[11]
Antenna configuration	SISO, omnidirectional	
Hotspot size (width × height)	120 × 50 m	
Number of UEs per cell (N_{UE})	16	
Percentage of hotspot UEs	50 %	
D2D pathloss model [dB]	$37 + 30\log_{10}(d)$, d in meter	[13]
Central carrier frequency	1.90 GHz	[12]
System bandwidth (N_{PRB})	5 MHz DL/UL (25 PRBs each)	[15]
Noise power at eNB/UE	−116.40 dBm/−112.40 dBm	
Link adaptation	LTE (15 MCSs)	[14]
Required cell-edge SNR	−6.20 dB	[14]
Scheduling policy	PF	
Traffic model	Full buffer	
Number of TTIs	1000	

TABLE II
AVERAGE SYSTEM SPECTRAL EFFICIENCY (BPS/HZ/CELL)

	Cellular comm.		D2D comm.		Total		
	DL	UL	DL	UL	DL	UL	Agg.
Hotspot near eNB†							
No D2D comm.	3.88	4.80	–	–	3.88	4.80	8.68
No band sel.	1.67	3.03	1.65	1.48	3.32	4.51	7.83
$\alpha = 0.0$	3.34	3.29	0.37	1.40	3.71	4.69	8.40
$\alpha = 0.2$	2.35	4.15	1.17	0.96	3.52	5.11	8.63
$\alpha = 0.4$	1.86	4.61	1.51	0.49	3.37	5.10	8.47
$\alpha = 0.6$	1.74	4.71	1.59	0.26	3.33	4.97	8.30
$\alpha = 0.8$	1.70	4.75	1.62	0.15	3.32	4.90	8.22
$\alpha = 1.0$	1.69	4.77	1.63	0.09	3.32	4.86	8.18
Hotspot at cell-edge†							
No D2D comm.	2.60	3.54	–	–	2.60	3.54	6.14
No band sel.	1.48	2.56	2.85	2.10	4.33	4.66	8.99
$\alpha = 0.0$	2.58	2.56	0.03	2.10	2.61	4.66	7.27
$\alpha = 0.2$	2.56	2.65	0.51	2.06	3.07	4.71	7.78
$\alpha = 0.4$	2.24	2.87	1.40	1.87	3.64	4.74	8.38
$\alpha = 0.6$	1.96	3.06	1.96	1.62	3.92	4.68	8.60
$\alpha = 0.8$	1.79	3.20	2.28	1.36	4.07	4.56	8.63
$\alpha = 1.0$	1.69	3.29	2.47	1.14	4.16	4.43	8.59

† Hotspot near eNB or at cell-edge means, respectively, that the hotspot center is 50 and 200 m from eNB

IV. RESULTS AND DISCUSSION

The system performance results in terms of spectral efficiency are presented in Table II, considering only cellular communications and both communication modes without and with band selection technique for different band factors. In addition, the hotspot is moved from challenging to more favorable conditions for D2D communications to happen: "hotspot near eNB" and "hotspot at cell-edge", respectively.

TABLE III
AVERAGE CELLULAR OUTAGE PROBABILITY (%)

	Hotspot near eNB		Hotspot at cell-edge	
	DL	UL	DL	UL
No D2D comm.	5.42	0.72	10.81	1.40
No band sel.	13.40	17.87	30.31	12.39
$\alpha^{\star\dagger}$	10.69	5.00	22.53	5.17

† For hotspot near eNB $\alpha^\star = 0.2$ and at cell-edge $\alpha^\star = 0.8$

Results show that when band selection is not being used, the D2D-generated interference has a strong impact on cellular communications, yet its relevance is higher when hotspot is positioned near the eNB, with 2.21 bps/Hz/cell (or 57 %) and 1.77 bps/Hz/cell (or 37 %) of loss considering, respectively, DL and UL cellular spectral efficiency.

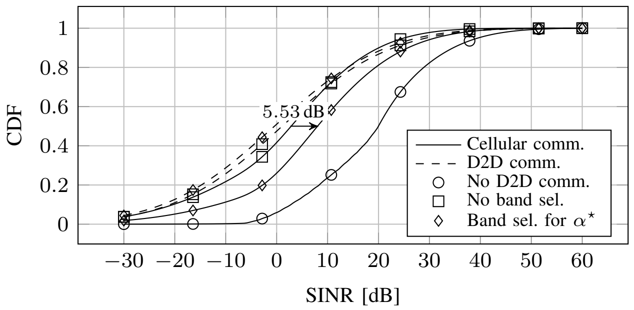
Nevertheless, the aforementioned advantages of D2D communications, clearly justify their use. For that, compare the total aggregated spectral efficiency achieved with and without D2D communications when hotspot location is at cell-edge; the achieved gain is 2.85 bps/Hz/cell (or 46 %). But, when hotspot is placed too much close to eNB, the higher co-channel interference drastically limits the whole system performance, reducing it 0.85 bps/Hz/cell (or 10 %).

While enabling band selection and based on the approach that was described in Section II, the best trade-off between system performance and interference mitigation is achieved for $\alpha^\star = 0.2$ when hotspot is near eNB, and for $\alpha^\star = 0.8$ when hotspot is at cell-edge. In both cases, the losses in cellular communications are reduced: from 57 to 39 % in DL and from 37 to 14 % in UL for the former case; and from 43 to 31 % in DL and from 28 to 10 % in UL for the latter case.

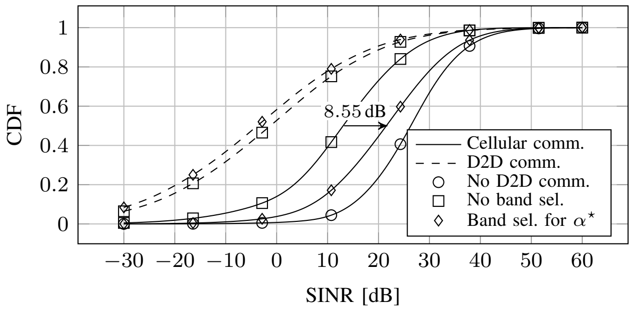
In general, band selection improves the gains of cellular communications and limits the gains of D2D communications both in DL and UL phases, regardless the hotspot position. This translates in an improvement of 10 % in the total aggregated spectral efficiency with hotspot near eNB and a tiny reduction of 4 % with hotspot at cell-edge.

In order to better understand how the band selection impacts on the whole system, let us look to the Cumulative Distribution Function (CDF) of SINR, which is presented in Fig. 4 for the hotspot near eNB, i.e., the most demanding conditions. Regardless the communication direction, the method improves the SINR curve of cellular communications making it tend to the one without D2D communications, compensating the slightly degrades in the SINR curve of D2D communications. When hotspot is at cell-edge (not shown here due to space limitations), the same conclusion applies as before. However, for that case the cellular interference on D2D communications, especially in DL, is reduced making the D2D gain higher.

The outage probability is a figure of merit for the system. It can be interpreted as the fraction of time in average that a UE stays out of service due to fading or, in other words, as the probability of UE's SINR falls below a given minimum, i.e., $\mathrm{P}(\gamma \leq \Gamma_{min}) = \int_{-\infty}^{\Gamma_{min}} f_\gamma(t)\,\mathrm{d}t = F_\gamma(\Gamma_{min})$, where $f_\gamma(\cdot)$ and $F_\gamma(\cdot)$ are the Probability Density Function (PDF) and



(a) DL direction



(b) UL direction

Fig. 4. Hotspot near eNB, where $\alpha^\star = 0.2$: in the 50th percentile a gain of 5.53 and 8.55 dB is achieved for cellular communications in DL and UL directions, respectively

CDF of SINR, respectively. In LTE networks, Γ_{min} is the SINR threshold to ensure the lowest MCS. Thus, the outage probability may also be measured as the number of UEs that have zero throughput over the total UEs in the system.

As it can be observed in Table III comparing the results without and with the use of band selection technique (rows four and five, respectively), the cellular outage probability is always reduced, which reveals the protection provided by the method against harmful interference.

V. Conclusion

In this paper we investigated a novel interference mitigation technique that enables the coexistence of cellular and D2D communications in wireless systems that have in-band spectrum sharing (i.e., reuse factor less than one). Besides being simple formulated, the band selection technique has permitted gains in the DL and UL communication phases along with the protection of cellular network from excessive co-channel interference; which surely extends the recommendation of just reusing the UL band for D2D links [16].

The radio distance metric is prone to errors, especially if fast channel variations happen, since it in fact represents the link quality between the eNB and D2D transmitter rather than the real distance between them. To ensure better location accuracy of D2D transmitter, the radio distance metrics of its neighbors from discovery phase can be reported and combined in eNB or use the Global Positioning System (GPS).

Finally, associating the band selection with proper grouping techniques, e.g., minimum distance between D2D transmitter and receiver, instead of using a random grouping, may provide further gains for the whole system. But this study will be left for future publications.

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