What happens with a proportional fair cellular scheduling when D2D communications underlay a cellular network?

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***Abstract*—Device-to-Device (D2D) communications are seen as promising technology for future wireless systems. However, while underlying cellular networks they can negatively affect the performance of cellular communications when intra-cell spectrum sharing is enabled. The impact of D2D communications is not only seen on the cellular throughput, but also on the decision-making of the cellular scheduling policy. In this paper, we provide an impact assessment of D2D communications on the performance of Proportional Fair (PF) scheduling for a Long Term Evolution (LTE) multi-cell scenario through system-level simulations. Results show that due to excessive interference generated by D2D communications and depending on the accuracy of the link quality measure used to estimate the instantaneous data rate, a PF cellular scheduling policy may get stuck in an infinite loop and continuously selects the same User Equipments (UEs), which reduces the cellular throughput, or even approaches the performance of a Maximum Rate (MR)-based policy, thus affecting service coverage and fairness.**

I. Introduction

The main principle that underlies a Device-to-Device (D2D) communication is to exploit the User Equipments (UEs) proximity, which allows high data rates, low delays, and reduces the power consumption [1]. Moreover, while happening in cellular networks, the core network is offloaded from data transport and, at cell area boundaries, D2D links may be used to extend cell coverage [2]. D2D communications underlying cellular networks has been a topic of intense research in the last couple of years and appears as a relatively new area, that may offer tangible benefits for the future wireless systems. In fact, only recently D2D communications started to be considered inside 3rd Generation Partnership Project (3GPP) to facilitate Machine-to-Machine (M2M)/proximity aware services, and security/public safety applications [3].

Despite the aforementioned advantages, D2D communications introduce new challenges: the system must cope with new interference situations, especially the intra-cell or co-channel interference due to orthogonality loss [4]. Indeed, herein we focus on the *reuse gain* by tightening the system reuse factor (even for systems with unitary reuse), allowing D2D-capable UEs to directly transmit data by reusing radio resources of the cellular network, thus employing a shared spectrum mode [5].

The design of an efficient D2D network with minimal impact on cellular communications is the key problem evaluated in [6]. The impact assessment of D2D communications on the performance of cellular communications is provided in a scenario with favorable conditions for sharing resources, where a hotspot zone is located near the cell-edge and a Maximum Rate (MR) scheduler is used, that mostly selects cellular UEs located close to the Evolved Node B (eNB). Simulation results have shown that despite the overall system capacity being always improved when D2D communications are enabled, the performance of cellular communications is highly reduced in both Downlink (DL) and Uplink (UL), especially for dense scenarios such as the urban-microcell environment [7]–[9].

Nevertheless, using a MR scheduler is not considered to be practical. It starves the cell-edge UEs, which may be near hotspot zones, because of excessive interference. A more practical scheduling policy would also give transmission opportunity to cellular UEs near hotspot zones, or even inside them, which could harm the sharing of resources with D2D communications. The main contribution of this paper is to study the impact of D2D communications on the decision-making of a Proportional Fair (PF) cellular scheduling policy, in a multi-cell scenario and urban-microcell environment by means of system-level simulations.

This paper is organized as follows: in Section II, the system model is addressed; in Section III, Radio Resource Allocation (RRA) procedures used for D2D communications underlying a Long Term Evolution (LTE)-like cellular network are introduced; in Section IV, the main simulation results are presented and discussed; finally, in Section V, conclusions and perspectives are drawn.

II. System Model

In this section, the models adopted to evaluate the system performance are presented. Let us assume that each eNB is placed at the center of a site, which is represented by a regular hexagon. The considered scenario corresponds to a multi-cell system with eNBs uniformly distributed over it. The urban-microcell propagation environment is considered where each site is a single-cell [9]. It is also assumed that the multi-cell scenario has N_{CELL} cells and each one serves N_{UE} UEs. Also, each UE and eNB has an omnidirectional antenna.

The scenario also comprises rectangular hotspots located near the cell-edge in order to model a scenario in which D2D communications are likely to happen. A percentage of the total number of UEs within the cell is clustered inside the hotspot while the remaining UEs are uniformly distributed over the cell area. Considering that UEs within the hotspot zone are much close to each other and far away from most cellular UEs, D2D pairs of D2D-capable UEs are obtained by randomly pairing UEs in the hotspot. Fig. 1 exemplifies DL cellular and D2D communications with one hotspot.

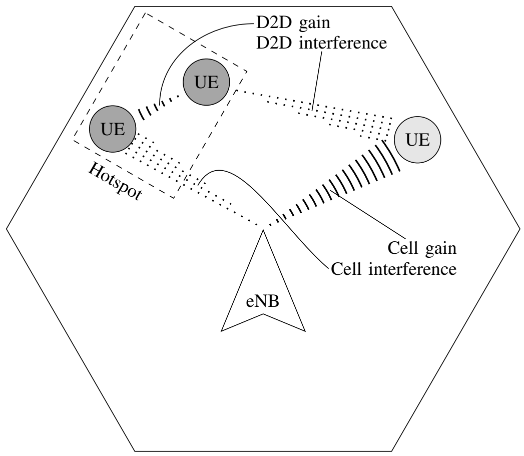


Fig. 1. DL cellular and D2D communications with hotspot near the cell-edge

The modeling of complex channel coefficients includes propagation effects on the wireless channel, namely, pathloss, shadowing, and fast fading. The distance-dependent pathloss is based on COST 231 Walfish-Ikegami model. Also, slow channel variations due to shadowing are modeled with a lognormal distribution of zero mean and standard deviation σ_{sh}. Further aspects of the fading model for urban-microcell environment are described in [7]–[9].

Due to practical reasons, subcarriers are grouped in blocks of 12 adjacent subcarriers spaced by $15\,\text{kHz}$, which gives a total bandwidth of $180\,\text{kHz}$ per block. At each Transmission Time Interval (TTI) or $1\,\text{ms}$, information is conveyed on that bandwidth over 7 Orthogonal Frequency Division Multiplexing (OFDM) symbols (one slot that lasts for $0.5\,\text{ms}$) and is modeled for transmission. This frequency-time block is designated as Physical Resource Block (PRB) and is the minimum allocable unit that can be scheduled in Orthogonal Frequency Division Multiple Access (OFDMA)-based LTE systems. However, and due to scheduling constraints, a UE when scheduled takes 14 OFDM symbols, i.e., two slots or a subframe [7], [8].

In our model, we consider a number of N_{PRB} PRBs available in each link direction that can be fully reused by all cells. Moreover, the channel response for each PRB is represented by the complex channel coefficient associated with its middle subcarrier and first OFDM symbol; and the channel coherence bandwidth is assumed to be larger than the bandwidth of a PRB, leading to a flat fading channel over each of them.

After scheduling, the total transmit power at eNB in DL, and of each cellular UE in UL and of each D2D transmitter in both phases, is equally divided by an Equal Power Allocation (EPA) scheme among the number of allocated PRBs.

III. Radio Resource Allocation Procedure

In this section, the assignment of available resources to cellular communications is dealt by the cellular scheduling policy and to D2D communications by the D2D grouping.

A. Cellular Scheduling

Based on some criterion/policy, scheduling of the available PRBs performs independently at each eNB and TTI for all UEs within the cell coverage area, including D2D-capable UEs inside hotspot zones, that may behave as conventional cellular UEs. Herein, we consider two criteria: MR and PF; which are both based on the estimation of instantaneous data rate.

1) MR Policy: Using the MR policy, the system capacity is maximized by assigning the PRB n to the UE $j^\star$ with the highest instantaneous data rate $\hat{R}_j^n$ on that resource, i.e.,

$$j^\star = \arg\max_j \left\{ \hat{R}_j^n \right\}. \tag{1}$$

As aforementioned in Section I, the usage of the MR policy provides a favorable scenario for sharing resources, since D2D pairs are within hotspot zones located near the cell-edge (as depicted in Fig. 1) and scheduled cellular UEs are usually close to the eNB. The MR scheduling policy is considered herein only for comparison purposes.

2) PF Policy: The multi-carrier implementation of the PF scheduling for an OFDMA-based system performs dynamic channel allocations on a PRB basis [10]. To enable multi-user diversity gains in multi-carrier systems, data rates are adapted per frequency-time resource. The frequency-domain PF scheduling is dealt herein by estimating the instantaneous data rate in each PRB and updating the average data rate with an exponentially weighted low-pass filter for each cellular UE, after each TTI. Thus, the PF scheduling assigns sequentially each frequency-time resource on the considered PRB n at each TTI t to the UE $j^\star$ according to

$$j^\star = \arg\max_j \left\{ \frac{\hat{R}_j^n(t)}{T_j(t)} \right\}, \tag{2}$$

where $\hat{R}_j^n(t)$ is the estimated instantaneous data rate and $T_j(t)$ the average data rate. The low-pass filtered average data rate of each UE j after transmission at TTI t is given by

$$T_j(t+1) = \left(1 - \frac{1}{N_{\text{PF}}}\right) T_j(t) + \frac{1}{N_{\text{PF}}} R_j(t), \tag{3}$$

where $R_j(t)$ denotes the total received data rate of a UE j over all PRBs it got assigned to it at the TTI t and N_{PF} is the length of the exponentially weighted time window. The controllable trade-off between throughput and fairness attained by a generalized implementation of PF is out-of-scope work.

3) Instantaneous Data Rate: To follow channel variations inherent to wireless systems, link adaptation is utilized to match current channel conditions using link level curves for different Modulation and Coding Schemes (MCSs). But to perform link adaptation procedure, the instantaneous data rate $\hat{R}_j^n$ of the UE j on the PRB n is required to be estimated using a link quality measure.

Herein, the Signal to Noise Ratio (SNR) and Signal to Interference-plus-Noise Ratio (SINR) are used as link quality measures:

- **SNR:** it is only based on the instantaneous channel gain and noise power, which are assumed to be known by the serving cell of each UE;
- **SINR:** as the estimate value for total interference is measured and reported after each transmission, the last estimate may used as an interference margin [8].

Both link quality measures are still based on transmit power estimates. In DL, the full reuse of PRBs at eNB combined with EPA scheme allows an exact prediction of transmit power by the scheduling policy. However, in UL, each UE may be allocated with different levels of transmit power per PRB since it may be scheduled with different numbers of PRBs.

To estimate a link quality measure in UL, an estimate for the transmit power is required for instantaneous data rate calculations:

- **Max-PT:** it assumes that the total transmit power is used as an estimate for each PRB. This measure is significant for UEs near to cell-edge since they are usually assigned with one or just few PRBs and thus the transmit power effectively allocated by EPA is the maximum one or near to it;
- **Min-PT:** using EPA, the minimum possible power allocated to a given PRB is used, i.e., the total transmit power is equally divided among the total number of N_{PRB} PRBs in the bandwidth. This measure is more significant for UEs near the cell center, which get many PRBs at each TTI.

B. D2D Grouping

The fundamental idea behind D2D grouping is to schedule D2D pairs in favorable conditions to share resources with cellular UEs to obtain resource reuse gains while minimizing the impact on the performance of cellular communications.

After one cellular UE $j^\star$ is selected by the cellular scheduling policy, one D2D pair inside the hotspot zone is randomly grouped with the former UE. The grouping is performed inside each cell, for each PRB and TTI, and does not include any knowledge about the cellular UE previously scheduled [6].

In the following, Fig. 2 presents both cellular scheduling (MR or PF policies) and D2D grouping (random metric) in the algorithmic form for a better description of the RRA procedure.

```
for each TTI do
  for each PRB do
    for each cell do
      Selects a cellular UE according to a scheduling policy
      Selects randomly one D2D pair inside the hotspot
      Performs link adaptation of selected UEs
    end for
  end for
end for
```

Fig. 2. RRA procedure for cellular scheduling (MR or PF policies) and D2D pair grouping (random metric)

IV. Results

This section provides a performance assessment, through system-level simulations, of the coexistence of cellular and D2D communications in a multi-cell scenario. Simulations are aligned with the 3GPP LTE architecture [7]–[9] and their main parameters are summarized in Table I.

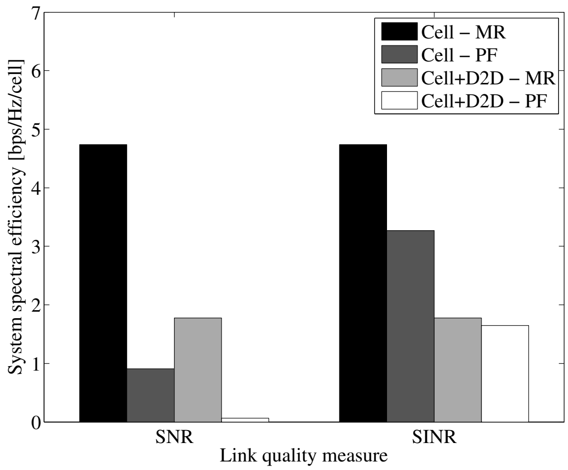
TABLE I
SIMULATION PARAMETERS

Parameter	**Value**	**Ref.**
Number of eNBs (N_{CELL})	7 (with wrap-around)	
Cellular environment	Urban-microcell	[9]
Inter-site distance	$500\,\text{m}$	[9]
eNB transmit power	$38\,\text{dBm}$	[7]
UE transmit power	$24\,\text{dBm}$	[7]
Cellular pathloss model	$34.5 + 38\log_{10}(\text{distance})$	[7]
Shadowing std. dev.	$10\,\text{dB}$	
Horizontal antenna pattern	$A(\theta) = 1$ (omnidirectional)	[7]
Fast fading model	3GPP SCM	[9]
Average user speed	$3\,\text{km/h}$	[7]
Hotspot size	$50 \times 120\,\text{m}$	
Percentage of hotspot UEs	$50\,\%$	
D2D pathloss model	$37 + 30\log_{10}(\text{distance})$	[8]
Central carrier frequency	$1.9\,\text{GHz}$	[9]
System bandwidth	5 MHz DL/UL (25 PRBs each)	[7]
Noise power	$-116.4\,\text{dBm}$	
Link adaptation	LTE (15 MCSs)	[11]
Required cell-edge SNR	$-6.2\,\text{dB}$	[11]
Traffic model	Full buffer	[9]
Effective TTI duration	1 ms	
Monte Carlo realizations	1 000	
Snapshot duration	1 s	

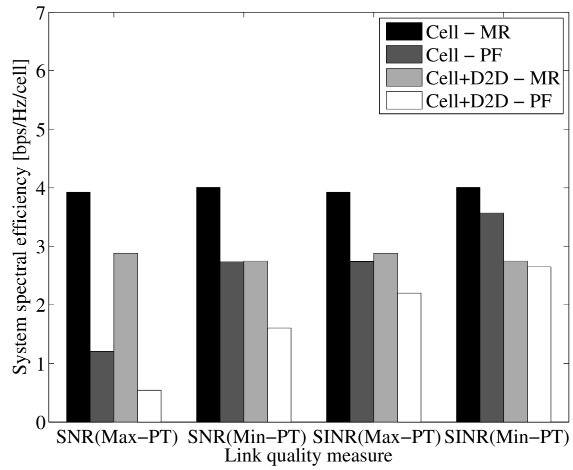
The impact of D2D communications on the decision-making of the scheduling policy is evaluated by means of cellular throughput, fairness and service coverage. The nomenclatures **Cell** and **Cell+D2D**, hereafter just mentioned as modes, are used in figure legends to refer, respectively, the cellular network without and with D2D communications occurring in parallel. In Cell+D2D mode, D2D communications are enabled by the D2D grouping procedure described in Section III-B.

Fig. 3 shows the system spectral efficiency of cellular communications for both DL and UL with 16 UEs/cell. As depicted in Fig. 3(a), cellular communications have their performance reduced due to additional interference in Cell+D2D mode, mainly when using the SNR-based link quality measure. However, when SINR-based link quality measure is used instead, the PF performance is improved, and approaches that of the MR policy. For the UL, the Min-PT estimate is able to improve PF performance compared to the Max-PT estimate for both SNR and SINR measures.

The Jain's index is used in Fig. 4 as a performance metric of data rate fairness for UEs employing cellular communications in both DL and UL with 16 UEs/cell. From Fig. 4(a), using SINR as link quality measure, the PF policy is able to provide



(a) DL



(b) UL

Fig. 3. System spectral efficiency of cellular communications for both DL and UL with 16 UEs/cell

satisfactory levels of fairness in the cellular network. However, when D2D communications are enabled, the data rate fairness is drastically reduced, achieving values under 10 % and near to the MR fairness levels. Using the SNR link quality measure, as the system spectral efficiency of PF approaches zero most of UEs also have an average UE data rate near zero, contributing to the higher fairness levels observed in Fig. 4(a). Unlikely of what was observed in Fig. 3(b), where the Min-PT estimate was responsible to improve the system spectral efficiency for UL, the usage of the Min-PT estimate reduced the data rate fairness, as seen in Fig. 4(b).

From the analyzes of Fig.'s 3 and 4, two important conclusions shall be noticed concerning the PF policy:

1) The cellular throughput tends to be lower for a SNR-based link quality measure, especially in DL;
2) The performance in terms of throughput and fairness tends to approach the MR one for a SINR-based measure. In UL, it happens especially for Min-PT.

The impact of D2D communications on the performance of cellular communications for 16 UEs/cell are summarized in Table II. Herein, the impact is shown as the percentage decrease of throughput or fairness in comparison to performance achieved by the cellular network acting only in Cell mode.

TABLE II
PERCENTAGE DECREASE ON THE THROUGHPUT AND FAIRNESS OF CELLULAR COMMUNICATIONS (CELL+D2D MODE, 16 UEs/CELL)

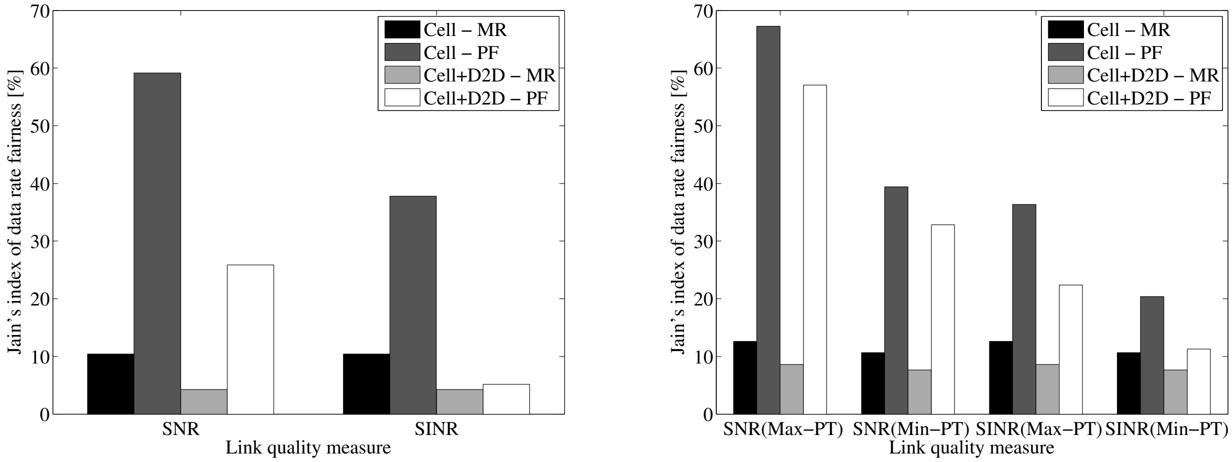
	DL: SNR/UL: SNR(Max-PT)				**DL: SINR/UL: SINR(Min-PT)**			
	Throughput		**Fairness**		**Throughput**		**Fairness**	
	MR	PF	MR	PF	MR	PF	MR	PF
DL	63 %	93 %	60 %	56 %	63 %	50 %	60 %	86 %
UL	27 %	55 %	32 %	15 %	31 %	26 %	28 %	45 %

Looking at the summary presented in Table II, the impact due to interference generated by D2D communications on throughput and fairness is always higher in DL for both scheduling criteria and link quality measures. Also, those two conclusions previously highlighted for PF policy are extended:

1) Comparing SNR- and SINR-based link quality measures, the impact on cellular throughput is higher for a SNR-based measure, while impact on fairness is higher for the SINR-based measure;
2) Comparing PF and MR for a SINR-based link quality measure, the impact on the cellular throughput is higher for a MR-based scheduling policy than for a fair policy. Unlikely of what happens with the cellular throughput, the impact on fairness is higher by using a fair policy than the MR-based policy.

In order to understand the higher impact on cellular throughput when PF is using a SNR-based link quality measure, and why PF approaches the MR performance in terms of system spectral efficiency and fairness when it is using a SINR-based measure in DL, the service coverage is evaluated in the following. To analyze the service coverage in DL, Fig. 5 presents the MCS usage and Cumulative Distribution Function (CDF) of the average UE throughput of cellular communications.

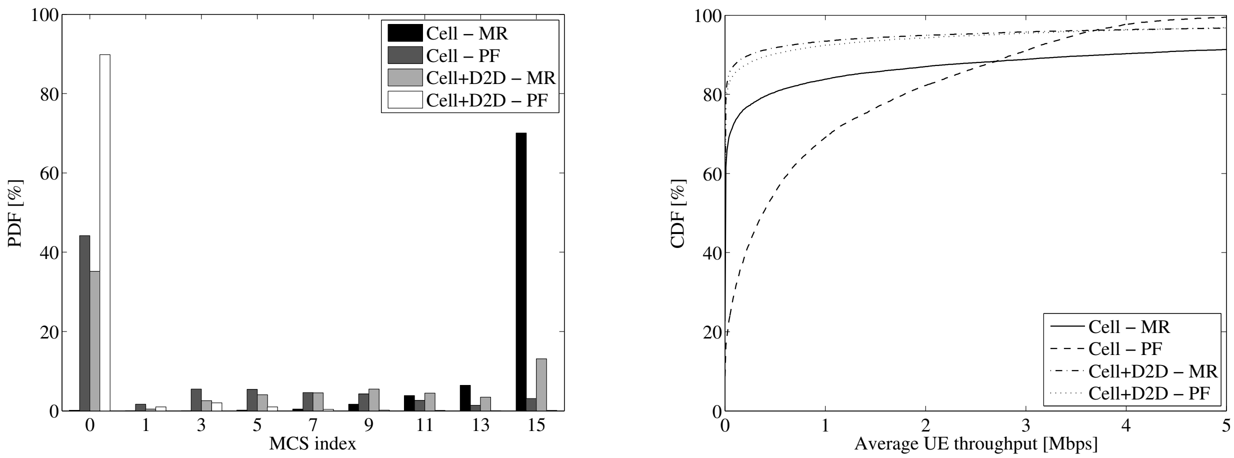
As seen in Fig. 5(a), both schedulers achieve high usage of high MCSs in the Cell mode, especially MR, and a lower usage of high MCSs in the Cell+D2D mode, especially PF. Also, 35 % and 90 % of transmissions set by, respectively, MR and PF schedulers in the Cell+D2D mode are not able to achieve the minimum SINR to establish communication. It means that an instantaneous data rate based on SNR used by the PF policy, which is unaware of the interference generated by D2D communications, is not useful for scheduling in the Cell+D2D mode. In fact, it overestimates the instantaneous data rate of



(a) DL

(b) UL

Fig. 4. Jain's index of data rate fairness of cellular communications for both DL and UL with 16 UEs/cell



(a) MCS usage for instantaneous data rate based on SNR

(b) Average UE throughput for instantaneous data rate based on SINR

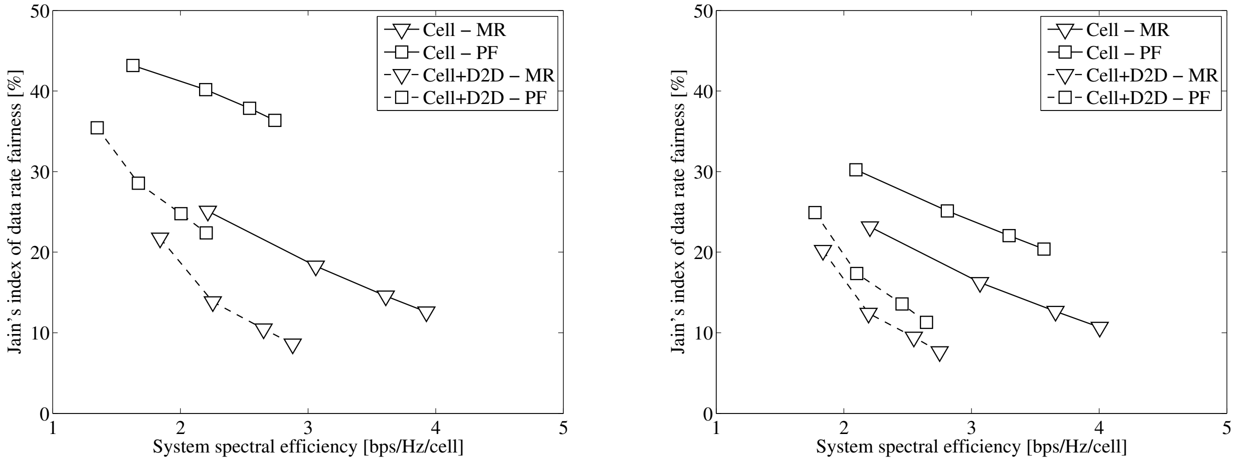
Fig. 5. Service coverage analyzes for cellular communications in DL with 16 UEs/cell

cellular UEs near to cell-edge, which configure a bad situations for sharing resources but that are more often scheduled by the PF policy than by the MR policy. From Fig. 5(b), while only 11 % of all UEs are out of service when using the PF policy, 49 % are never scheduled by the MR policy in the Cell mode. But when D2D communications are enabled, almost 50 % of all UEs are never scheduled. And other almost 30 % of them have average throughput practically zero. It is the reason why the SINR-based PF approaches very much the MR performance. As in the Cell+D2D mode interfering sources are close to cellular UEs, the high interference from D2D communications is responsible to nullify the achievable instantaneous data rate estimated by the PF for most of UEs and thus they are never (or only a few times) scheduled.

Fig. 6 presents the impact on the trade-off between cellular throughput and fairness of PF considering different transmit power estimates in UL for a SINR-based link quality measure and for several offered loads in terms of number of UEs/cell. By comparing Max-PT- and Min-PT-based PF performances in Fig. 6(a) and Fig. 6(b), respectively, it is possible to see that the PF performance with Min-PT-based is near the MR one not only in the Cell+D2D mode, but also in the Cell mode, while with Max-PT-based it provides a better trade-off between throughput and fairness. Thus, more realistic predictions of link quality may improve the PF performance in UL.

V. Conclusions

The main objective of this paper was to study the impact of D2D communications on the decision-making of a PF cellular scheduling policy in a multi-cell scenario. Results have



(a) Instantaneous data rate based on SINR(Max-PT)

(b) Instantaneous data rate based on SINR(Min-PT)

Fig. 6. Trade-off between throughput and fairness of PF considering different transmit power estimates in UL with 4, 8 12 and 16 UEs/cell

shown that due to excessive interference generated by D2D communications, a fair scheduling policy such as the PF is getting stuck in an infinite loop by continuously scheduling cellular UEs which have overestimated instantaneous data rates and is approaching the performance of an unfair MR-based scheduling when its instantaneous data rate is underestimated in UL or even perfectly estimated in DL. Also, while the cellular throughput was greatly reduced in DL, a lower impact was observed in UL.

When the instantaneous data rate of cellular UEs near hotspot zones, which are in bad situations for sharing resources, is overestimated although they are not able to achieve the minimum required MCS, they may be scheduled once and again in subsequent TTIs by the PF policy, since their historical data rates are not improved. However, it is important to highlight that in this work we ignored dropping mechanisms at several layers of the protocol stack, as it is frequently done in literature. In real world implementations, no user would be infinitely scheduled, but they would be dropped after a certain amount of time. The aim of our approach was just to show that the cellular throughput is drastically reduced for an unrealistic link quality measure which ignores effects of interference.

For a link quality measure based on SINR, as the outage rate in PF policy is greatly increased by considering the total interference, its performance in terms of system spectral efficiency, fairness and service coverage is approximated by those obtained by the MR.

To ensure reliable communications for cellular UEs in a D2D-assisted cellular network, some constraints on throughput and fairness would be required to protect cellular communications. As such, in the future, we intend to investigate the problem of jointly and dynamically schedule D2D communicating pairs with cellular UEs sharing the same resources, in order to control or even avoid the interference situation on cellular network.

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