A Comparative Study of Power Control Approaches for Device-to-Device Communications

Gabor Fodor*†, Demia Della Penda*, Marco Belleschi*, Mikael Johansson†, Andrea Abrardo‡
*Ericsson AB, E-mail: {gabor.fodor | marco.belleschi}@ericsson.com
†KTH, Royal Institute of Technology, E-mail: {mikaelj|gaborf}@kth.se
‡Department of Information Engineering, University of Siena, E-mail: {abrardo}@dii.unisi.it

***Abstract*—Device-to-device (D2D) communications integrated into cellular networks is a means to take advantage of the proximity of devices and thereby to increase the user bitrates and system capacity. D2D communications has recently been proposed for the 3GPP Long Term Evolution (LTE) system as a method to increase the spectrum- and energy-efficiency. Such systems support a wide range of power control schemes based on a combination of open-loop and closed-loop components and there is a need to set the associated control parameters such that spectrum- and energy- efficiency targets are met. In this paper we study the performance of various power control strategies applicable to D2D communications in LTE networks and compare them with a utility function maximization approach that balances spectrum efficiency and the total transmission power. Our reference scheme is based on a fully distributed algorithm that iteratively sets the signal-to-interference-plus-noise (SINR) targets and corresponding transmit power levels. We find that the LTE-based power control approach performs close to the optimal scheme provided that the associated parameters are properly set.** [1]

I. INTRODUCTION

Device-to-device (D2D) communications in cellular spectrum supported by a cellular infrastructure has the potential of increasing spectrum and energy efficiency as well as allowing new peer-to-peer services by taking advantage of the so called proximity and reuse gains [1], [2], [3], [4], In fact, D2D communications in cellular spectrum is currently studied by the 3^{rd} Generation Partnership Project (3GPP) to facilitate *proximity aware* internetworking services [5], national security and public safety applications [6] and machine type communications [7].

Obviously, D2D communications utilizing cellular spectrum poses new challenges, because relative to cellular communication scenarios, the system needs to cope with new interference situations. For example, in an orthogonal frequency division multiplexing (OFDM) system in which user equipments (UE) are allowed to use D2D (LTE direct mode) communication, D2D communication links may *reuse* some of the OFDM time-frequency physical resource blocks (RB). Due to the reuse, intracell orthogonality is lost and intracell interference can become severe due to the random positions of the D2D transmitters and receivers as well as of the cellular UEs communicating with their respective serving base stations (BS) [8], [9]. To realize the promises of D2D communications and to deal with intra- and intercell interference, the research community has proposed a number of important radio resource management (RRM) algorithms (see Figure 1).

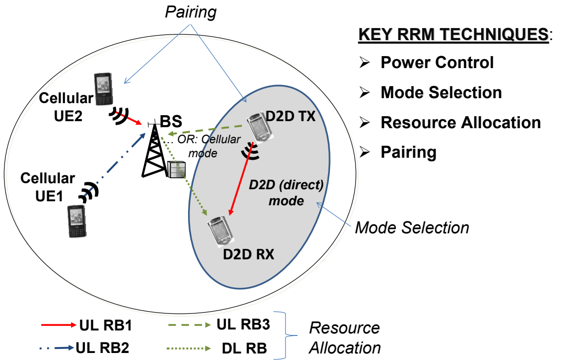

Figure 1. A D2D *candidate* pair consists of a D2D Transmitter and a D2D Receiver that are in the proximity of each other. The mode selection (MS) algorithm needs to decide on one of 3 possible communication modes:*cellular mode*, *D2D mode with dedicated resources*, or *D2D mode with reused resources*. This latter case involves a decision on which D2D pair(s) is (are) sharing resources with which cellular UE (pairing).

Apart from resource allocation (i.e. RB selection), power control is a key technique to deal with intra- and intercell interference [10], [11], [12], [13]. References [10] and [11] analyze the single (isolated) cell scenario and provide some basic insight into the impact of power control and resource allocation. The authors of [12] study a multi-cell system focusing on a power control scheme that helps minimize the interference from the D2D layer to the cellular users assuming that D2D users that operate in D2D mode reuse the cellular resources. The work reported in [13] evaluates the LTE power control scheme for the hybrid cellular and D2D system and concludes that power control needs to be complemented by mode selection, resource scheduling and link adaptation to properly handle intra- and intercell interference.

In this paper we examine the performance of the LTE power control scheme when applied to the hybrid cellular D2D system and compare it with the performance of a distributed power control scheme based on utility maximization, where dynamic resource allocation and mode selection are also exercised by the network. The purpose of this examination is to gain insight into the applicability of LTE power control for D2D communications by quantifying its performance with respect to a utility optimal scheme.

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We structure the paper as follows. The next section is a brief overview of the LTE power control options that are applicable to D2D communications integrated in cellular systems. Next, in Section III, we describe our reference scheme that is based on a utility maximization approach. Section IV evaluates and compares results obtained with LTE schemes and those relying on the distributed optimization approach. Finally, Section V concludes the paper.

II. POWER CONTROL OPTIONS BASED ON LTE MECHANISMS

It is natural to base a power control (PC) strategy for D2D communications *underlaying* [2] an LTE network on the LTE standard uplink PC mechanisms. Building on the already standardized and widely deployed schemes facilitate not only a smooth introduction of D2D enabled user equipment (UE), but would also help to develop inter-operable solutions between different devices and network equipments. However, due to intracell interference and new intercell interference scenarios, the question naturally arises whether the available LTE power control is suitable for D2D communications integrated in an LTE network. Also, the ad-hoc networking community has proposed efficient distributed schemes suitable for D2D communications, including situations with or without the availability of a cellular infrastructure ([14] and [10], [13], [15] respectively). Such schemes can also serve as a basis for D2D power control design.

The LTE PC scheme can be seen as a 'toolkit' from which different PC strategies can be selected depending on the deployment scenario and operator preference [16]. It employs a combination of open-loop (OL) and closed-loop (CL) control to set the UE transmit power (up to a maximum level of $P_{MAX} = 24$ dBm) as follows:

$$P^{\text{UE}} = \underbrace{P_0 - \alpha \cdot G}_{\text{OL operating point}} + \underbrace{\Delta_{\text{TF}} + f\big(\Delta_{\text{TPC}}\big)}_{\text{dynamic offset}} + \underbrace{10 \cdot \log_{10} M}_{\text{BW factor}}, \quad (1)$$

where the OL operating point allows for *path loss (PL) compensation* and the dynamic offset can further adjust the transmit power taking into account the current modulation and coding scheme (MCS) and explicit transmit power control (TPC) commands from the network. The bandwidth factor takes into account the number of scheduled RBs (M). For the OL operating point, P_0 is a base power level used to control the SNR target and it is calculated as [17]:

$$P_0 = \alpha \cdot (\gamma^{tgt} + P_{IN}) + (1 - \alpha) \cdot (P_{MAX} - 10 \cdot \log_{10} M), \quad (2)$$

where α is the PL compensation factor, G is the path gain between the UE and the base station and P_{IN} is the estimated noise and interference power. For the dynamic offset, Δ_{TF} is the transport format (MCS) dependent component, $f\big(\Delta_{\text{TPC}}\big)$ represents the explicit TPC commands.

For the integrated D2D communications scenario, we consider the following options:

- No Power Control (NPC), reference case: With NPC, there is no fixed γ^{tgt}[2] and the transmit power of the cellular UEs and D2D transmitters is set to some fixed value $P_{fix} \leq P_{MAX}$ according to (1). For $M = 1$ this can be obtained by setting $\alpha = 0$ and $P_0 = P_{fix}$.
- Fixed SNR target (FST): FST fully utilizes the LTE path loss compensation capability by setting $\alpha = 1$ and $P_0 = \gamma^{tgt} + P_{IN}$, where γ^{tgt} is a predefined SNR target and P_{IN} is the interference plus noise power (in practice, for simplicity, P_{IN} can be assumed a fixed value, e.g. $P_{IN} \approx -121... - 116$ dBm).
- Open Loop with Fractional Path Loss Compensation (OFPC): The OFPC scheme allows users to transmit with variable power levels, depending on their path loss. In contrast to the FST-case, the OFPC compensates for the fraction of the path loss by setting α to some suitable value in the range $[0, 1]$, e.g. $0.4 \ldots 0.9$.
- Closed Loop PC (CL): CL extends the FST scheme by adding the dynamic offset or tuning step $f\big(\Delta_{\text{TPC}}\big)$ in (1) in order to compensate the measured SINR ($\hat{\gamma}$) at the receiver with the desired SNR target value. The tuning step can be computed as follows [13]:

$$f(\Delta_{\text{TPC}}) = \begin{cases} \left|\gamma^{tgt} - \hat{\gamma}\right|/2 & \text{if } \left|\gamma^{tgt} - \hat{\gamma}\right| > 2 \text{ dB} \\ 1 \text{ dB} & \text{otherwise} \end{cases} \quad (3)$$

For UEs communicating in cellular mode with their respective serving base stations, OFPC provides a well proven alternative, typically used in practice. It avoids the complexity and overhead associated with the dynamic offset of the CL scheme, but makes use of the fractional path loss compensation balancing between overall spectrum efficiency and cell edge performance [16]. Figure 2 illustrates the power control options for the D2D link, while we assume that the cellular link employs the de facto standard LTE fractional path loss compensating power control scheme.

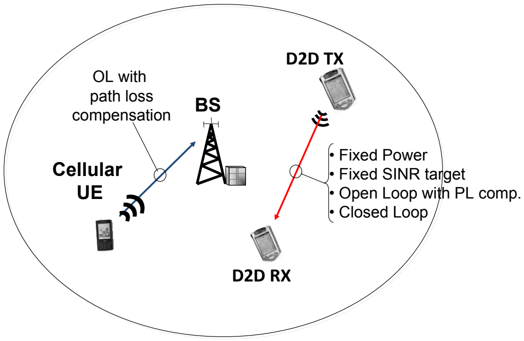

Figure 2. The UE communicating in cellular mode with its serving BS uses the de facto standard LTE fractional path loss compensating open loop power control. For the D2D link, we study various power control strategies that can all be easily deployed using the flexible LTE power control 'tool kit'.

III. POWER CONTROL OPTIONS BASED ON A DISTRIBUTED OPTIMIZATION APPROACH

A. System Model

In order to derive a reference scheme for network assisted D2D communications, we model the hybrid cellular-D2D

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[2] Note that (2) is valid only in the case when a γ^{tgt} value exists.

network as a set of L transmitter-receiver pairs. A transmitter-receiver pair can be either a cellular UE transmitting data to its serving base station or a D2D pair communicating in the cellular uplink spectrum[3]. The network topology is represented by a directed graph with connections labelled $l = 1, \ldots, L$. Associated with each link l is a function $u_l(\cdot)$, which describes the *utility* of communicating at rate s_l. The utility function u_l is assumed to be increasing and *strictly concave*, with $u_l \to -\infty$ as $s_l \to 0^+$. We let $\mathbf{c} = [c_l]$ denote the vector of link capacities, which depend on the communication bandwidth W and the achieved SINR of the links (γ_l). Obviously, the users rate vector $\mathbf{s}$ must fulfill the following set of constraints:

$$\mathbf{s} \preceq \mathbf{c}(\mathbf{p}), \qquad \mathbf{s} \succeq 0.$$

Let $G_{l,m}$ denote the effective link gain between the transmitter of pair m and the receiver of pair l (including path-loss and shadowing), σ_l is the thermal noise power at the receiver of link l and P_l is the transmission power. The SINR of link l can be written as

$$\gamma_l(\mathbf{p}) = \frac{G_{ll}P_l}{\sigma_l + \sum\limits_{m\neq l} G_{lm}P_m} = \frac{G_{ll}P_l}{\sigma_l + (P^{tot}_{l_{Rx}} - G_{ll}P_l)} \tag{4}$$

where $\mathbf{p} = [P_1, ..., P_L]$ is the power allocation vector, and $P^{tot}_{l_{Rx}}$ represents the total received power measured by the receiver of link l. Hence, the SINR in (4) can be computed by Receiver-l without knowing either the power used by other D2D pairs or cellular transmitters or any of the channel gains, except the one related to its corresponding Transmitter-l.

Each link is seen as a Gaussian channel with Shannon-like capacity

$$c_l(\mathbf{p}) = W \log_2 \big(1 + K\gamma_l(\mathbf{p})\big) \tag{5}$$

which represents the maximum rate that can be achieved on link l. W is the system bandwidth and K models the SINR-gap reflecting a specific modulation and coding scheme. In the following we assume $K = 1$.

B. The SINR Target Setting and Power Control Problem

Assuming that the communication-mode has already been selected for the D2D candidates (i.e. *Cellular-Mode* or *D2D-Mode*), and all (cellular and D2D) links have been assigned a frequency channel or a RB, we formulate the problem of target rate setting and power control as:

$$\begin{array}{ll} \underset{\mathbf{p},\mathbf{s}}{\text{maximize}} & \sum_l u_l(s_l) - \omega \sum_l P_l \\ \text{subject to} & s_l \le c_l(\mathbf{p}), \quad \forall l, \\ & \mathbf{p}, \mathbf{s} \succeq 0 \end{array} \tag{6}$$

which aims at maximizing the utility while taking into account the transmit powers (through a predefined weight $\omega \in (0, +\infty)$ [20], so as to increase spectrum efficiency while reducing the sum power consumption. In this formulation, the $\mathbf{s}$ vector represents the vector of the rate *targets* which is in one-to-one correspondence with the SINR targets (γ_l^{tgt}), while the $\mathbf{c}$ vector represents the actual capacity achieved by the particular power vector $\mathbf{p}$.

C. Convexifying the Problem of Equation (6)

Unfortunately, Problem (6) is not convex, but exploiting the results presented in [20] and [21], we can transform it into the following equivalent form:

$$\begin{array}{ll} \underset{\tilde{\mathbf{s}},\tilde{\mathbf{p}}}{\text{maximize}} & \sum_l u_l(e^{\tilde{s}_l}) - \omega \sum_l e^{\tilde{P}_l} \\ \text{subject to} & \log(e^{\tilde{s}_l}) \le \log\big(c_l(e^{\tilde{\mathbf{p}}})\big) \quad \forall l, \end{array} \tag{7}$$

where $s_l \leftarrow e^{\tilde{s}_l}$ and $P_l \leftarrow e^{\tilde{P}_l}$. The transformed Problem (7) is proved to be convex (now in the $\tilde{s}_l$-s and $\tilde{P}_l$-s) since the utility functions $u_l(\cdot)$ are selected to be (log, x)-concave over their domains [20]. In this paper we use $u_l(x) \triangleq \ln(x), \forall l$. Under this condition, we can solve Problem (7) to optimality by means of an iterative algorithm where the $\tilde{s}_l$-s (or equivalently the SINR targets) are set by an outer loop. The transmit powers $\tilde{P}_l$-s that meet the particular SINR targets (set in each outer loop cycle) are in turn set by a Zander type iterative SINR target following inner loop [22]. The strength of this scheme is that it lends itself for a distributed execution in multicell systems, iteratively setting the utility optimal SINR targets, which are feasible and link-specific, with the corresponding power levels.

D. Summary

This section presented the SINR target setting and power control tasks as a convex optimization problem (7). This problem can be approached by decomposing the problem to separate subproblems in $\tilde{\mathbf{s}}$ (Problem-I) and $\tilde{\mathbf{p}}$ (Problem-II) [23]. Problem-I can be solved by gradient iterations and using Lagrangian duality to obtain the SINR targets, while Problem-II can be solved by an iterative SINR target following inner loop. (The details are omitted due to space limitations.) In our case, we exploited the relationship between Problem-I and Problem-II such that the necessary Lagrange multipliers in the iterations of Problem-I are provided by solving Problem-II. In a practical setting, the SINR target setting outer loop and the transmit power setting inner loop can be started off by setting a low SINR target vector and running the inner loop to determine the transmit power levels and the corresponding $\lambda_i^\star$-s. The Lagrange multipliers are then used as the input values to the outer loop update rule (see Figure 3).

IV. NUMERICAL RESULTS

A. Simulation Setup and Parameter Setting

In this section we consider the uplink (UL) of a 7-cell system, in which the number of RB is 4 (per cell). In each cell, there are 2 cellular UEs transmitting to their respective serving base stations using a cellular UL RB and 4 D2D pairs also communicating in the uplink band. Because of the intracell orthogonality, two distinct RBs are allocated to the cellular UEs leaving two orthogonal RBs for the four D2D pairs in

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[3] It is advantageous to use uplink resources for the D2D link, because in some countries regulatory requirements may not allow to use downlink resources by user equipments. Therefore, in this paper we focus the case in which the D2D links use UL cellular resources, such as the uplink physical resource blocks in a cellular Frequency Division Duplexing system or the uplink time slots in a Time Division Duplexing system [3], [18], [19].

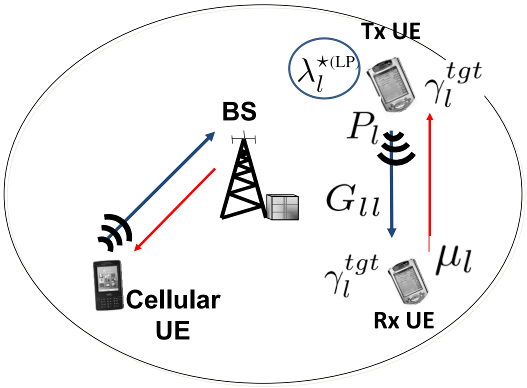

Figure 3. An example of a D2D pair sharing a resource block (RB) with a cellular UE. The D2D Tx node has a target SINR of γ_l^{tgt} set by the outer loop and runs the inner loop to set the necessary transmit power P_l. The D2D Rx node transmits on the backward channel also targeting an SINR target of γ_l^{tgt} and runs its inner loop to find the correct transmit power level of μ_l. μ is then used to find the Lagrange multiplier $\lambda_l^{\star}$ that is used to update the SINR targets. At the end of the outer loop convergence, the optimal SINR targets and associated transmit power levels are reached at all transmitters.

Table I

PARAMETERS OF THE 7-CELL SYSTEM UNDER STUDY

Parameter	***Value***
Layout	Hexagonal grid
Cell Radius	500m
Channel Model	Micro Urban [13]
System Bandwidth	10 MHz
Carrier Frequency	2GHz
P_{IN} (/MHz)	-116 dBm
P_0	-78 dBm
α	0.8
Max Tx Power	24 dBm
Fixed Tx Power for D2D	-10 dBm
Fixed SINR tgt for D2D	15 dB
Number of RB per user	1
Outer-Loop iterations	200
Inner-Loop iterations	10
ω	0.1 and 10
Distance between cellular UE and the BS	300 ± 50 m
Distance between D2D pairs	50 ± 25 m

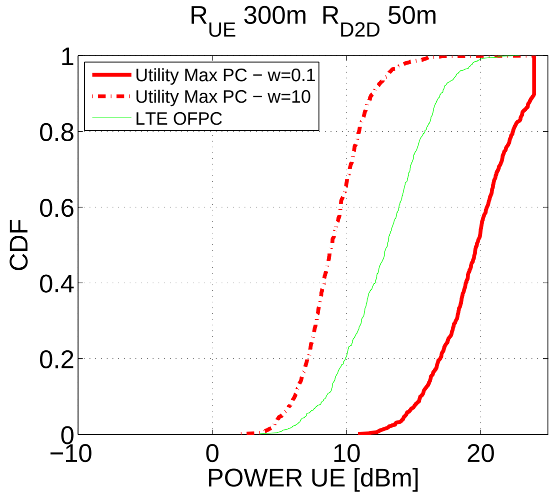

Figure 4. The transmit power distribution of the cellular UEs when using the LTA OFPC and the utility maximizing power control scheme by the cellular UEs. When $\omega = 10$, the utility-based approach results in significantly lower power levels for all UEs due to the conservative setting of the ω parameter in the utility function. In contrast, setting $\omega = 0.1$ encourages UEs to employ much higher transmit power levels.

each cell. This implies that two D2D candidates must select *direct mode with resource reuse*, while two D2D transmitters have the possibility to choose between *cellular mode*, *direct mode with dedicated resource* and *direct mode with resource reuse* (see Figure 1).

We perform Monte Carlo experiments to build some statistics over the used transmit power and achieved SINR by cellular UEs and D2D pairs when employing the LTE-based power control algorithms and the distributed optimization-based power control scheme respectively. For the LTE-based scheme, we assume that cellular UEs employ fractional path loss compensation (with $\alpha = 0.8$), while the D2D link uses one out of the four schemes described in Section II. For the utility maximization-based scheme (referred to as (optimal) SINR target-based PC), all transmitters execute the distributed outer and inner loop-based power control algorithm as described in Section III.

The main simulation parameters are given in Table I. We note that P_0 is set according to Equation (2) to correspond to $\gamma^{tgt} = 12.5$ dB.

B. Numerical Results

Recall that in our study we compare the utility-based algorithm (UM-PC) applied to all users, to four different PC schemes in which the cellular UEs always use the LTE OFPC power control (irrespective of the D2D power control method). Accordingly, Figure 4 shows the distribution of the transmit power levels of the cellular UEs for the LTE OFPC case and for the utility maximizing case. Here we see that when $\omega = 10$ the utility-based approach results in much lower UE power consumption, especially for the regions above 10 dBm. However, when $\omega = 0.1$, the UE power consumption is much less penalized and therefore the overall UE power consumption increases. Figure 5 shows the distribution of the D2D transmit power levels. Here we can see that for the very low power region (< 0 dBm), the LTE-based schemes use less power than the utility-based scheme. However, for higher power D2D transmitters (> 5 dBm), the optimization-based scheme uses less power than any of the LTE-based methods (with the exception of the fixed transmit power case). From a practical point of view, the important region is the one above 5 dBm, since UEs below this power level do not utilize their available power resources to improve their SINR levels. For UEs above 10 dBm, the utility-based scheme and the LTE OFPC schemes perform similarly, while the fixed SINR target and the closed loop scheme sets significantly higher D2D transmit power levels. Notice that the "Fixed Tx Power" setting applies to D2D UEs that actually use the D2D mode, while D2D candidate UEs using cellular mode use the LTE OFPC scheme, which explains the "Fixed Tx Power" distribution curve in Figure 5.

The SINR distribution of the cellular UEs are shown in Figure 6. We see that the utility- based scheme results in a somewhat lower SINR basically for all UEs, but this difference

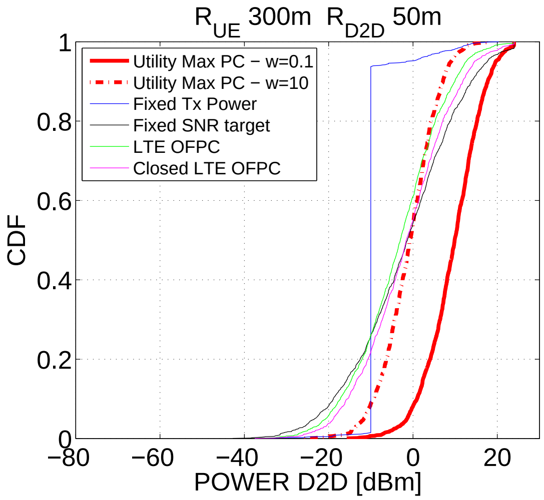

Figure 5. The transmit power distribution of the D2D UEs when using one of the 4 LTE-based power control schemes and the utility-based scheme. The utility maximizing scheme uses somewhat higher power in the low power ($<$ 0...5 dBm) region ($\omega = 10$), but uses lower power for UEs transmitting with higher power levels. Again, setting $\omega = 0.1$ encourages D2D UEs to employ higher transmit power levels. This figure should be examined together with Figure 9 to get an insight into the D2D power usage under the studied PC approaches.

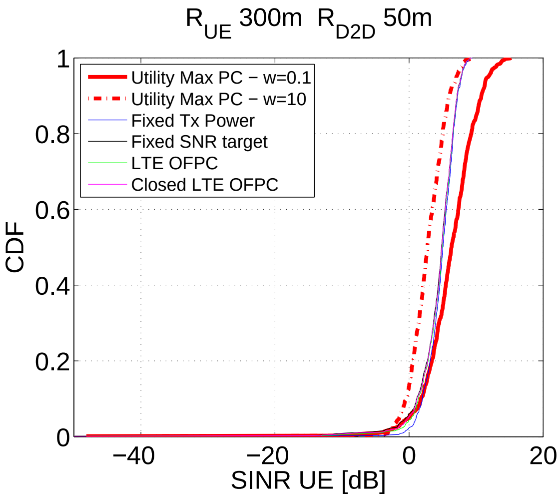

Figure 6. The SINR distribution of the cellular UEs. Because of the conservative UE transmit power setting (see Figure 4), the resulting SINR with the utility maximizing scheme is somewhat lower ($\omega = 10$) or somewhat higher ($\omega = 0.1$) than with the LTE-based PC schemes.

is not large (around 2-3 dB). The underlying reason is that in this setting ($\omega = 10$), the utility-based algorithm is somewhat conservative in terms of using higher power levels, since high ω values tend to punish high power consumption.

The SINR levels of the D2D users are shown in Figure 7. Here the utility-based power control outperforms the LTE-based power control, except for the lowest SINR users. The SINR gain is especially significant for the high SINR users, where only the fixed transmit power scheme yields higher SINR values than the utility-based approach. However, the fixed transmit power method is clearly unacceptable from a fairness perspective.

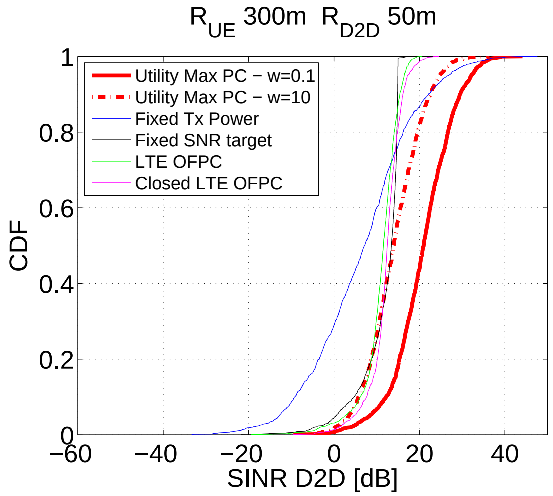

Figure 7. The SINR distribution of the D2D users. For most D2D users, the utility-based scheme gives significantly higher SINR (especially with $\omega = 0.1$) than the LTE-based schemes.

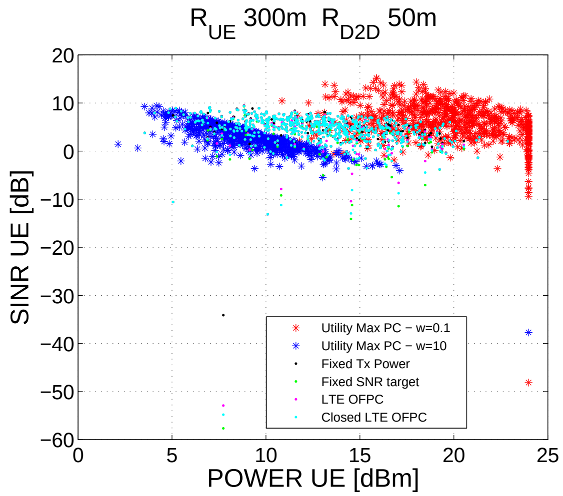

Figure 8. Scatter plot of the used transmit power of the cellular UEs and the resulting SINR values when using different schemes for the cellular UEs and the D2D pairs. The clear tendency is that the utility-based scheme gives similar SINR values but typically with much less transmit power.

To gain some insights into the relation between the used power levels and the resulting SINR values for the power control approaches under study, we are interested in the scatter plots of Figure 8 and Figure 9. Figure 8 represents each dropped UE in a Monte Carlo experiment with a dot indicating the used cellular UE power and resulting SINR value for that particular UE. Because of the resource reuse between cellular and D2D users, the SINR of the cellular UEs depend on the power control scheme of the D2D users, as clearly visible in Figure 8. Here we can clearly see that the general trend is that the utility-based scheme with $\omega = 10$ uses lower power levels for similar UE SINR performance. In other words, similar quality of service level can be maintained by lower UE power levels when relying on the dynamic SINR target adjusting algorithm.

Figure 9 shows the relation between the D2D transmit power levels and the D2D SINR values. It is interesting to observe

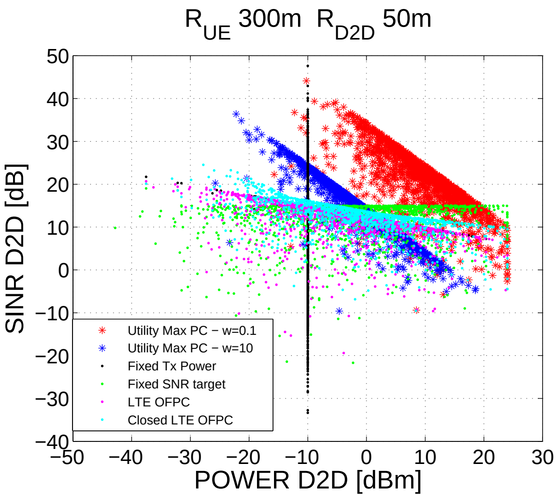

Figure 9. Scatter plot of the used transmit power of the D2D UEs and the resulting SINR values when using different schemes for the cellular UEs and the D2D pairs.

that the utility maximizing scheme tends to allocate higher power levels to lower SINR users, so in that sense it is (tries to be) 'fair' by compensating poor users by allocating somewhat higher power. In a sense this is the opposite of the (extreme unfair) fixed Tx power approach (horizontal line) but not as fair as the LTE OFPC scheme in the sense of SINR equalization (close to being 'horizontal' in the power-SINR plane).

V. CONCLUSIONS

In this paper we studied the performance of D2D communications when the D2D power control is based on the available LTE power control methods, namely fixed transmit power, fixed SINR target, open loop path loss compensation and closed loop schemes. As a reference case, we used a utility maximization scheme that is based on SINR measurements reporting and an iterative SINR target and transmit power level setting algorithm. The numerical results indicate that the LTE PC gets close to the utility-based scheme, both in terms of used transmit power levels by the cellular as well as the D2D users and the resulting SINR values. The only significant gain with the optimization-based approach is the SINR obtained by the high performing D2D users. On the other hand, the LTE OFPC scheme, (depending on the ω parameter of the utility-based method) can produce somewhat higher SINR values for the cellular UEs. These results tend to suggest that the flexible LTE power control scheme is well prepared for network assisted D2D communications, especially for the cellular UEs. However, for the D2D pairs, the utility based scheme can provide gains in terms of SINR distribution and total transmit power consumption. Therefore, as a future work, a hybrid scheme, in which cellular UEs use LTE power control, whereas D2D UEs use a utility-based approach can be investigated.

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