Location-based Power Control Mechanism for D2D Communication Underlaying a Cellular System

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Abstract — The paper presents a location-based approach to controlling the power of device-to-device (D2D) underlay of a frequency reuse-1 cellular system. The system allows for direct communication to share uplink resources with cellular users. As a result, both D2D and cellular users are experiencing additional interferences in the system. By controlling the output power of the devices, these interferences can be mitigated and the performance of the network can be improved in terms of better spectral and energy efficiency. The proposed location-based target signal-to-interference ratio power control scheme for D2D communications utilizes information about users' locations to estimate the interference level experienced by the receiver of the direct link. Based on this estimation, an appropriate transmit power can be determined. The performance of the proposed power control solution is investigated via system level simulations.

Keywords — context-awareness, device-to-device, frequency reuse-1, power control

1. Introduction

In recent years, device-to-device (D2D) communication operating as an underlay in cellular networks has attracted a lot of attention within the research community. It is believed that it can ensure better spectral efficiency of the system and is capable of reducing power consumption, thus improving energy efficiency. Moreover, such a communication solution can enable new types of multimedia services [1]–[3]. Working as an underlay, D2D communications may use the same radio resources as those relied upon by other cellular users. Such an approach allows to increase the frequency reuse factor (FRF) even above the level achieved by the reuse-1 scheme [3].

However, enabling D2D communications that share the spectrum with a cellular telecommunication system poses some new challenges. For instance, new interference patterns emerge which have to be managed, typically with the help of power control or resource allocation mechanisms. This leads to improved performance of the network in terms of better spectral and energy efficiency.

The remainder of the paper is organized as follows. In Section 2, a short review of other works is presented. Section 3 describes the system model under consideration. In Section 4, the proposed power control solution is described, with an analysis of its performance given in Section 5. The paper is concluded in Section 6.

2. Related Work

Numerous studies have been conducted on mitigating interference in D2D communications, i.e. [1], [2], [4]–[9]. The most commonly used approaches involve power control and resource allocation solutions. For example, in [4] a D2D power reduction method was introduced to control interference affecting cellular users. Interference mitigation solutions based on resource allocation often exploit slow-scale parameters, such as path-loss or shadowing, to perform interference-aware resource allocation, as proposed in [7].

Some papers explore the possibility of using location information for resource allocation and for selecting users sharing those resources, i.e. [10]–[13]. In [10] and [11], an interference limited area (ILA) control strategy was proposed. It is employed in addition to a power control mechanism to ensure that the outage probability of D2D communications, caused by interference from cellular users, is lower than a predetermined threshold. Meanwhile, in [12], an interference limited area control method is applied to restrict interference before the resource allocation process. In [13], the distance-constrained resource-sharing criterion (DRC) was introduced to limit the set of cellular users that can share resources with D2D users, resulting in a significant reduction in the D2D link's outage probability. Furthermore, DRC does not require cellular users to reduce their transmission power, thereby avoiding degradation of the cellular link's performance.

3. System Model

In this paper, we consider an FRF-1 cellular system in which a D2D underlay is operational, as presented in Fig. 1. The system allows for D2D communications to share uplink resources with co-channel cellular users (CUEs). Consequently, additional interferences are introduced in the system. Interference affecting the receiving D2D device (DUE) is caused when CUEs transmit relying the same resource. On the other hand, from the point of view of CUEs, interference is caused

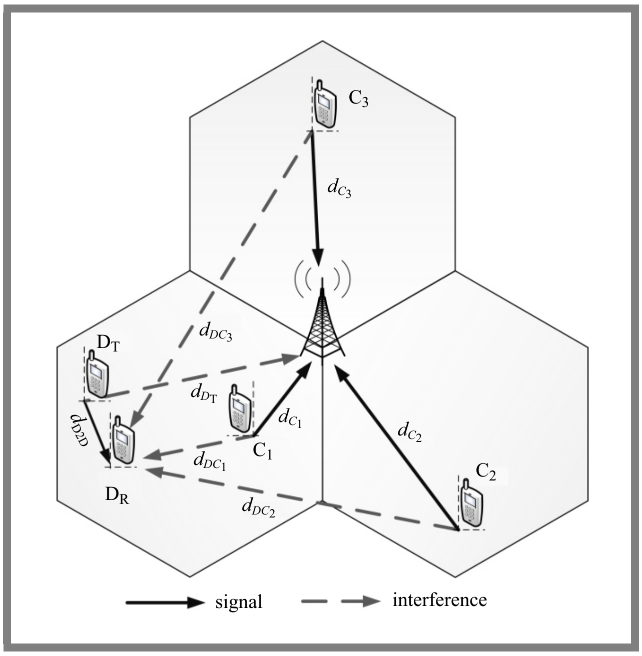

Fig. 1. System model.

by transmitting DUEs and is experienced by the serving base station. The signal-to-noise and interference ratio (SINR) for the DUE receiver γ_D and the BS for a cellular user $k(\gamma_{C_k})$ are given by:

$$\gamma_D = \frac{h_D(d)P_D}{\sum\limits_{i=1}^{N} h_{DC_i}(d)P_{C_i} + N_0} \tag{1}$$

and

$$\gamma_{C_k} = \frac{h_{C_k}(d)P_{C_k}}{\sum\limits_{i=1, i\neq k}^{N} h_{C_i}(d)P_{C_i} + h_D(d)P_D + N_0}, \tag{2}$$

where N is the number of adjacent cells using the same frequency (that includes the cell where the D2D pair is located). $h_D(d)$ and $h_{C_i}(d)$ are the distance dependent losses on the path between D2D users and between the DUE receiver and the CUE transmitter I, respectively, $h_{C_k}(d)$, $h_{C_i}(d)$ and $h_D(d)$ are the losses on the path between cellular transmitters k and i and the base station and on the path between the DUE transmitter and the base station, respectively. The additive white Gaussian noise (AWGN) variance is denoted by N_0. P_D defines the transmit power and the transmitted signal of DUE and P_{C_i} stands for the transmit power and transmitted signal of the i–th CUE transmitter.

In the considered system an open-loop power control (OLPC) mechanism is utilized for the CUE's power settings. The transmit power of the cellular users is given by:

$$P_C = \min\left(P_0 + A \cdot h(d), P_{max}\right), \tag{3}$$

where P_0 is the initial power level of the UE, A is a path-loss compensation factor and $h(d)$ is the path-loss between the BS and the CUE. The maximum transmit power is limited by P_{max}. In the system model, we assume that the base station has knowledge about the location of the devices it serves. With the increasing popularity of location-based services (LBS), the acquisition of UEs' location is becoming less troublesome and applicable data may be obtained in various ways, e.g., via the satellite-based GNSS positioning system.

4. Location-based Power Control for D2D

In this paper, we propose a location-based target signal-to-interference ratio (SIR) power control (LTSIPC) scheme for D2D communications. The mechanism utilizes information about users' locations to estimate the interference experienced by the D2D receiver. The proposed LTSIPC is a centralized approach, where the base station is acting as the central unit which, through its own power control mechanism, such as OLPC, obtains information about the transmitting powers of cellular user devices that interfere with the D2D receiver. Using the positions of those devices, the host entity can estimate the distance between them and, consequently, the interference caused to the D2D receiver. Since the proposed LTSIPC is based solely on distance and location, it requires no knowledge of channel coefficients, which allows to reduce the number of channel quality reports in the system.

The SIR of the D2D receiver can be expressed as:

$$\zeta_D = \frac{|h_{D2D}|^2 P_D d_{D2D}^{-\alpha}}{\sum\limits_{i=1}^{N} |h_{DC_i}|^2 P_{C_i} d_{DC_i}^{-\alpha}}, \tag{4}$$

where h_{D2D} and h_{DC_i} are channel coefficients of the D2D and D2D-CUE links considered, d_{D2D} and d_{DC_i} are the distances between D2D devices and the D2D receiver and the cellular user i, respectively. The path-loss exponent is denoted with α and the transmit powers of the D2D transmitter and the i–th CUE are given by P_D and P_{C_i}, respectively. Based on Eq. (4), the transmit power of the D2D transmitter can be derived by setting a SIR target ζ_0:

$$P_{DTX} = \frac{\zeta_0 \sum\limits_{i=1}^{N} |h_{DC_i}|^2 P_{C_i} d_{DC_i}^{-\alpha}}{|h_{D2D}|^2 d_{D2D}^{-\alpha}}. \tag{5}$$

As mentioned beforehand, we are only using location information to determine the interference. The knowledge of instantaneous channel coefficients h_{D2D} and h_{DC_i} is not available to the power control mechanism. To simplify, we assume that the mean value of both coefficients (h_{D2D} and h_{DC_i}) is equal to 1. Taking this assumption into account, and setting the upper limit on transmit power P_{max}, we obtain:

$$P_D = \min\left(P_{max}, \zeta_0 \cdot d_{D2D}^{\alpha} \sum_{i=1}^{N} P_{C_i} d_{DC_i}^{-\alpha}\right). \tag{6}$$

5. Simulations and Results

5.1. Scenarios and Parameters

The performance of the proposed LTSIPC power control solution is investigated via system level simulations performed with the use of a multi-cell OFDMA-based frequency reuse-1 network. The tool used in the simulations was co-created

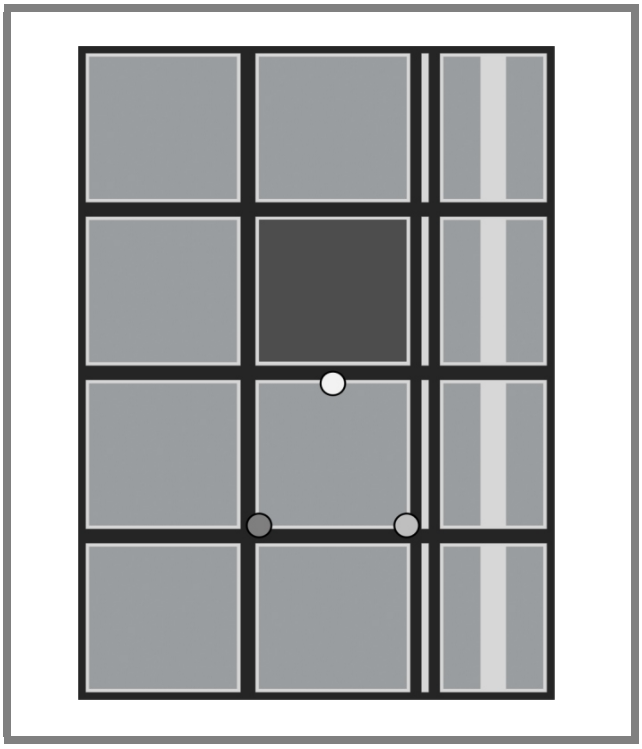

Fig. 2. In the Madrid grid model, locations of base station antennas are marked with circles.

by the author and it follows the guidelines established in the METIS project [14]. More details on the tool can be found in [15].

Channel models defined by METIS [16] are used for the cellular users. These models use, contrary to the most commonly used models, 3D map-based real-time methods for evaluating sight conditions between the individual nodes. For D2D users, a modified version of the D2D model defined by ITU-R [17] is used. The modification relies on a map-based approach for evaluating line of sight conditions, instead of the statistical approach that was defined in ITU-R documentation.

The solution under consideration is deployed with the help of the Madrid grid model [14] (Fig. 2) and consists of a macro base station operating in the frequency division duplex (FDD) mode and 3 sectors (each sector operates in the same frequency band). In the evaluation scenario, 400 users are uniformly placed outside the buildings, either on pavements (120 CUEs) or in cars (200 CUEs). Among these 400 users, 40 D2D pairs are deployed (80 DUEs) with the distance between each DUE and D2D pair ranging uniformly from 0 to 100 m. Additionally, 15 of the D2D pairs are pedestrian users, and the remaining 25 D2D pairs are deployed in cars (the distance between the users in cars is limited by the assumed dimensions of the vehicle). The mobility of the users, including cars, is also modelled in accordance with METIS guidelines. The process of allocating resources to cellular users is based on round robin mechanism. In the case of D2D users, resource blocks to be shared for communication are selected randomly. Cellular users are using the OLPC mechanism for determining the transmit power, whereas D2D users use the proposed LTSIPC mechanism with an SIR target of 20 dB. Benchmark scenarios in which D2D users used OLPC and in which no D2D communication was enabled, were considered as well.

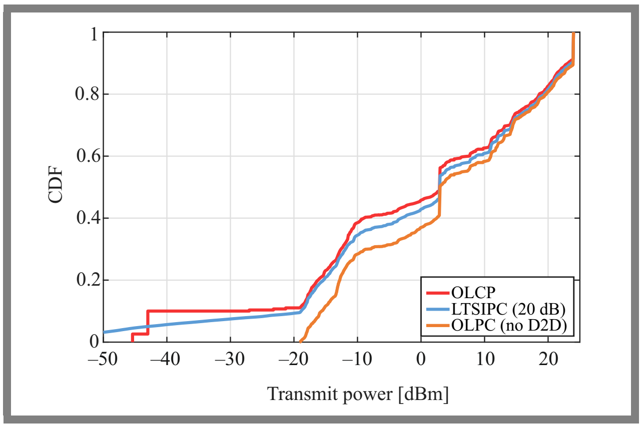

Fig. 3. CDFs of UE transmit power (for both CUEs and DUEs).

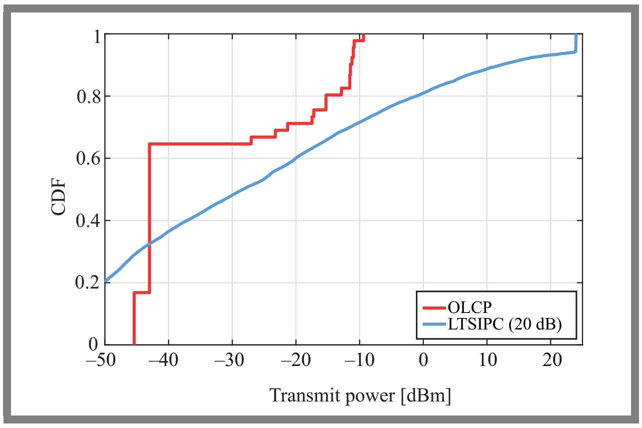

Fig. 4. CDFs of DUE transmit power.

Various system performance statistics are collected in the simulation tests, with the most important of them being:

- cumulative distribution function (CDF) of the transmit power of all users and active D2D users,
- spectral efficiency of the system (expressed in bits/s/Hz) for downlink (DL) and uplink (UL) transmissions and for active D2D users.

5.2. Results

The first set of results presented in Figs. 3 and 4 shows the CDFs of transmit powers for all UEs in the system and for D2D users, respectively. The introduction of D2D communication allows to reduce the transmit power of the UEs, regardless of the power control mechanism deployed. This is of course due to the assumption that the distance between devices communicating directly is lower than the distance between the individual devices and the base station.

Another observation is that the OLPC method achieves grater reduction in the transmit power than the proposed LTSIPC approach. This is due to the fact that LTSIPC aims at achieving the SIR target at the receiver, which in some cases may lead to an increased transmit power requirement in order to mitigate interference generated by cellular transmissions. Looking at the transmit power curves for D2D devices only (Fig. 4), we can observe that the LTSIPC performs slightly worse

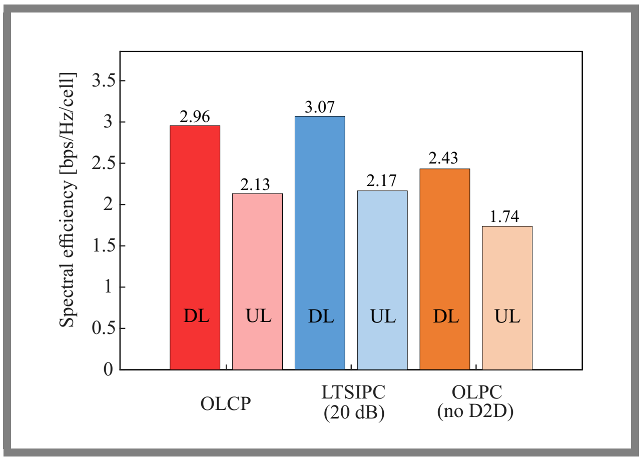

Fig. 5. Spectral efficiency of the system.

than OLPC in almost the entire transmit power range under consideration. However, the proposed LTSIPC approach offers better granularity of transmit power settings and allows for lower transmit power settings for D2D devices that are very close to each other, for instance in cars.

The second set of results presents the spectral efficiency of the simulated scenario. Figure 5 presents the spectral efficiency for downlink and uplink transmissions within the system. We can notice that the introduction of D2D may lead to an increase in spectral efficiency in both directions, regardless of the power control mechanism deployed. Taking into account the previous results related to the transmit power, this means that energy efficiency has increased as well. Better spectral efficiency has been achieved thanks to the spectrum sharing aspect of the D2D underlay. By allowing some devices to communicate directly and to share the spectrum with cellular users, we reduce the number of devices that have to be served by the base station and thus extend the network reuse factor above one.

Another observation that may be made based on spectral efficiency plots is that the proposed LTSIPC mechanism outperforms the OLPC approach, but as mentioned previously, at the cost of slightly increased transmit power demands. This can also be noticed from the spectral efficiency plot for the D2D devices only, as shown in Fig. 6.

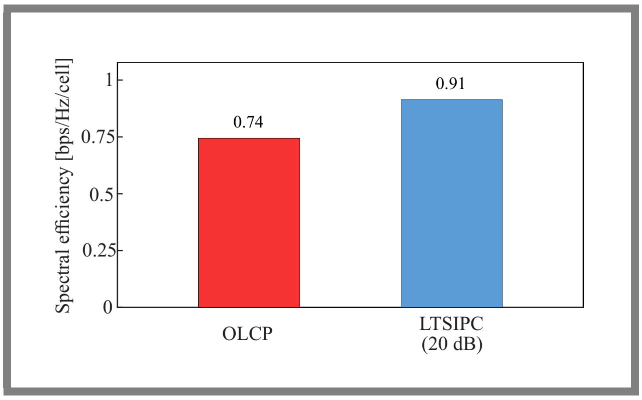

Fig. 6. D2D communication spectral efficiency.

6. Conclusion

The results show that the introduction of D2D communications, exploiting the proposed location-based power control method that shares UL resources with CUEs, may bring about benefits in terms of decreased transmit power levels, increased spectral efficiency and better energy efficiency. However, when comparing LTSIPC with OLPC, one may notice that the former offers slightly higher transmit power outputs almost in the entire transmit power range under consideration. However, the proposed LTSIPC approach allows for better granularity of transmit power settings and enables lower transmit power levels for D2D devices that are very close to each other, for instance in cars. Moreover, the LTSIPC approach achieves better spectral efficiency than the OLPC mechanism, both for the entire network and for D2D users only. It is also worth mentioning that the location-based approach does not require additional reports and channel measurements, needing to track the user's location only.

References

[1] P. Janis *et al.*, "Device-to-Device Communication Underlaying Cellular Communications Systems", *International Journal of Communications, Network and System Sciences*, vol. 2, no. 3, 2009 (`https://doi.org/10.4236/ijcns.2009.23019`).

[2] J. Seppala, T. Koskela, T. Chen, and S. Hakola, "Network controlled Device-to-Device (D2D) and cluster multicast concept for LTE and LTE-A networks", in: *2011 IEEE Wireless Communications and Networking Conference (WCNC)*, Cancun, Mexico, pp. 986–991, 2011 (`https://doi.org/10.1109/WCNC.2011.5779270`).

[3] K. Doppler, M. Rinne, C. Wijting, C. Riberio, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks", *IEEE Communications Magazine*, vol. 47, no. 12, pp. 42–49, 2009 (`https://doi.org/10.1109/MCOM.2009.5350367`).

[4] C.-H. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen, "On the performance of device-to-device underlay communication with simple power control", in: *VTC Spring'09-IEEE 69th Vehicular Technology Conference*, Barcelona, Spain, 2009 (`https://doi.org/10.1109/VETECS.2009.5073734`).

[5] C.-H. Yu, K. Doppler, C. Ribeiro, and O. Tirkkonen, "Power optimization of device-to-device communication underlaying cellular communication systems", in: *IEEE International Conference on Communications*, Dresden, Germany, 2009 (`https://doi.org/10.1109/ICC.2009.5199353`).

[6] J. Gu, S.J. Bae, B.-G. Choi and M.Y. Chung, "Dynamic Power Control Mechanism for Interference Coordination of Device-to-Device Communication in Cellular Networks", in: *2011 Third International Conference on Ubiquitous and Future Networks (ICUFN'11)* , Dalian, China, pp. 71–75, 2011 (`https://doi.org/10.1109/ICUFN.2011.5949138`).

[7] P. Janis *et al.*, "Interference-aware resource allocation for device-to-device radio underlaying cellular networks", in: *VTC Spring'09-IEEE 69th Vehicular Technology Conference*, Barcelona, Spain, pp. 1–5, 2009 (`https://doi.org/10.1109/VETECS.2009.5073611`).

[8] M. Zulhasnine, C. Huang, and A. Srinivasan, "Efficient resource allocation for device-to-device communication underlaying LTE network", in: *IEEE 6th International Conference on Wireless and Mobile Computing, Networking and Communications*, Niagara Falls, Canada, 2011 (`https://doi.org/10.1109/WIMOB.2010.5645039`).

[9] N. Reider and G. Fodor, "A distributed power control and mode selection algorithm for D2D communications", *EURASIP Journal on Wireless Communication and Networking*, art. no. 266, 2012 (`https://doi.org/10.1186/1687-1499-2012-266`).

[10] P. Bao and G. Yu, "An interference management strategy for device-to-device underlaying cellular networks with partial location infor-

mation", in: *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC)*, Sydney, Australia, pp. 465–470, 2012 (`https://doi.org/10.1109/PIMRC.2012.6362830`).

[11] H. Min, J. Lee, S. Park, and D. Hong, "Capacity enhancement using an interference limited area for device-to-device uplink underlaying cellular networks", *IEEE Transactions on Wireless Communications*, vol. 10, no. 12, pp. 3995–4000, 2011 (`https://doi.org/10.1109/TWC.2011.100611.101684`).

[12] X. Chen, L. Chen, M. Zeng, X. Zhang, and D. Yang, "Downlink resource allocation for Device-to-Device communication underlaying cellular networks", in: *2012 IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC)*, Sydney, Australia, pp. 232–237, 2012 (`https://doi.org/10.1109/PIMRC.2012.6362746`).

[13] H. Wang and X. Chu, "Distance-constrained resource-sharing criteria for device-to-device communications underlaying cellular networks", *Electronics Letters*, vol. 48, no. 9, pp. 528–530, 2012 (`https://doi.org/10.1049/el.2012.0451`).

[14] P. Agyaponc *et al.*, "Simulation guidelines" METIS Deliverable D6.1 [Online]. Available: (`https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D6.1_v1.pdf`).

[15] K. Bakowski, K. Wesolowski and M. Rodziewicz, "Simulation Tools for the Evaluation of Radio Interface Technologies for IMT-Advanced and Beyond", in: *Simulation Technologies in Networking and Communications: Selecting the Best Tool for the Test*, CRC Press, pp. 365–391, 2014 (`https://doi.org/10.1201/b17650-17`).

[16] V. Nurmela *et al.*, "Initial channel models based on measurements", METIS deliverable D1.2, 2013. [Online]. Available: (`https://www.metis2020.com/wp-content/uploads/deliverables/METIS_D1.2_v1.pdf`).

[17] Recommendation ITU P.1411-7, "Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz", 2013. [Online]. Available: `https://www.itu.int/rec/R-REC-P.1411-7-201309-S/en`

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