<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper presented at *IEEE International Conference on Communications (ICC), 8-12 June, London, UK*.

Citation for the original published paper:

Della Penda, D., Fu, L., Johansson, M. (2015)

Mode Selection for Energy Efficient D2D Communications in Dynamic TDD Systems.

In: IEEE conference proceedings

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-164966>

Mode Selection for Energy Efficient D2D Communications in Dynamic TDD Systems

Demia Della Penda, Liqun Fu and Mikael Johansson

Department of Automatic Control

Royal Institute of Technology (KTH), Sweden.

E-mails: {demiadp, liqun, mikaelj}@kth.se

Abstract—Network-assisted Device-to-Device (D2D) communication is a promising technology for improving the performance of proximity-based services. This paper demonstrates how D2D communication can be used to improve the energy-efficiency of cellular networks, leading to a greener system operation and a prolonged battery life of the mobile devices. Assuming a flexible TDD system, we develop optimal mode selection policies for minimizing the energy cost (either from the system or from the device perspective) while guaranteeing a certain rate requirement. The jointly optimal transmit power and time allocation, as well as the optimal mode selection, is found by solving a small convex optimization problem. Special attention is given to the geometrical interpretation of the obtained results. We show that when network energy is the primary concern, D2D mode is preferable in a large portion of the cell. When the device energy consumption is most important, on the other hand, the area where D2D mode is preferable shrinks and becomes close to circular. Finally, we investigate how network parameters affect the range where direct communication is preferred.

Index Terms—Network-assisted Device-to-Device, Mode Selection, TDD-LTE, Energy Efficient Communications

I. INTRODUCTION

During the last decade, the number of mobile subscribers and their traffic demand has increased tremendously, resulting in a larger energy consumption for cellular networks. Furthermore, the battery lifetime of mobile devices has been reduced considerably. Network-assisted Device-to-Device (D2D) communication is a promising technology to improve energy efficiency in future wireless networks: when mobile users in proximity to each other need to exchange data at high rate (e.g. media sharing, gaming, and other proximity-based services [1,2]), direct communication can potentially offload the BS and improve throughput, delay and energy consumption [3,4].

A natural question in the context of D2D communication is under which condition two users should communicate through a direct link rather than via the BS. We call this problem the *mode selection problem*. The optimal mode selection naturally depends on the performance measure that we would like to optimize. For example, the authors in [5] select the transmission mode to maximize user rate in both single-cell and multiple-cell scenarios, while satisfying SINR constraints on active cellular links. In [6] and [7], the authors focus on maximizing the power-efficiency of the network. A joint mode selection and resource allocation problem in a multi-cell scenario is presented in [8] and shown to be NP-Hard. In [9], the authors address the mode selection problem of

a single pair of mobile users with two dual performance objectives: to maximize the quality-of-service (QoS) for a given transmit power, and to minimize the power for a given QoS. The latter formulation has later been extended to the multiple link case in OFDMA-based networks [10], but the multi-link formulation has high computational complexity and was solved using heuristic approaches.

In this paper, we consider the joint mode selection and resource allocation problem to minimize the energy consumption of a single D2D communication pair. From Shannon's capacity formula, it can be seen that the transmission energy per bit can be reduced exponentially by increasing its transmission time [11]. In dynamic Time-Division Duplex (TDD) systems the base station can adjust the time allocated to uplink and downlink traffic dynamically [12,13]. Traditionally, this feature has been used to compensate for the asymmetry in uplink and downlink traffic demand. In contrast, we use this degree of freedom to minimize the energy consumption of D2D communication, from the perspective of both the mobile user and the network as a whole. We show that in both cases, the joint resource allocation and mode selection problem can be formulated as a convex optimization problem. The optimal time allocation and transmission mode can thus be efficiently found. We demonstrate that D2D communication is to prefer when the direct path is "sufficiently strong", and characterize how the mode selection threshold depends on the traffic rate requirement and the channel gains to the base station. A special attention is given to developing a geometrical interpretation of energy-optimal mode selection policy. Somewhat surprisingly, we find that D2D mode is preferable in a large area of the cell and that even cell-edge users can benefit from D2D communication, achieving the required rate with much lower energy cost. Last but not least, we discuss how our techniques can be extended to a more general network with bidirectional traffic and multiple pairs of mobile users.

The paper is organized as follows. In Section II, we present the system model. In §III we present convex optimization formulations and optimal threshold conditions for energy-efficient mode selection. In §IV we give a geometrical interpretation of the derived conditions, supported by simulations. Finally, in §V and §VI we discuss the practical implementation together with possible extensions. We conclude with Section VII.

II. ASSUMPTIONS AND PROBLEM FORMULATION

We consider a single cell network where Device-to-Device (D2D) communication is enabled with the assistance of the base station (BS). Two users within the cell can communicate using one of two possible modes, as illustrated in Figure 1(a):

- 1) in *cellular mode*, users use conventional cellular transmission and communicate via the BS, *i.e.* user-1 first sends data to the BS (uplink) which, in turns, forwards the data to user-2 (downlink);
- 2) in *D2D mode*, a dedicated D2D link is set up and used for communication between the two devices.

Fig. 1. System model for D2D communication underlying a cellular network with dynamic TDD scheme. User-1 communicates to user-2 either via the BS (*cellular mode*) or through a direct link (*D2D mode*).

Our objective is to develop algorithms that jointly determine the communication mode and allocate transmission resources so as to minimize the energy consumption of the user devices and of the system as a whole.

We assume that there is a single communication pair in the cell and the traffic flows from user-1 to user-2 (extensions to this scenario are discussed in Section VI). We enumerate the transceivers by 0, 1 and 2, corresponding to the BS, user-1 and user-2, respectively. Time is divided into frames with a duration of T seconds. Let t_{ij} denote the time allocated to communication between transceivers i and j . The *cellular mode* is based on a flexible TDD system, such as LTE-TDD, where the uplink and downlink transmissions operate in the same bandwidth but alternate in time. The portion of time allocated to the uplink and downlink transmissions can be adjusted dynamically. D2D communication, on the other hand, can use the full frame for its transmission, see Fig. 1(b).

We further assume *in-band D2D communication*, which means that both D2D and cellular links use the cellular (*i.e.*, licensed) spectrum. The instantaneous rate r_{ij} between transceivers i and j follows Shannon's capacity formula:

$$r_{ij}(p_{ij}, G_{ij}) = W \log \left(1 + \frac{p_{ij} G_{ij}}{\sigma^2} \right), \quad (1)$$

where W is the allocated bandwidth, G_{ij} is the channel gain between the transmitter- i and the receiver- j , p_{ij} is the transmit power level used by transmitter- i to communicate to receiver- j and σ^2 is the noise power. We assume maximum transmission power levels $p_{ij}^{\max}$, and denote the corresponding instantaneous rate in (1) by $r_{ij}^{\max}(G_{ij})$.

We assume that b^{tgt} bits must be transmitted in each time frame, which translates into a session rate requirement of $r^{\text{tgt}} = b^{\text{tgt}}/T$ bps. When the instantaneous rate exceeds r^{tgt} , the session rate requirement can be satisfied by transmitting only a fraction of the full frame. Specifically, the fraction of time t_{ij} during which transmitter- i is active is such that

$$r_{ij} t_{ij} = b^{\text{tgt}}. \quad (2)$$

Clearly, the maximum achievable transmission rate sets a lower bound for the required transmission interval, *i.e.* $t_{ij} \geq b^{\text{tgt}}/r_{ij}^{\max}$. Lower values of t_{ij} would require p_{ij} to exceed $p_{ij}^{\max}$, leading to a power-infeasible time allocation.

By inverting the power-rate relationship (1), we find that the energy cost for meeting the session rate requirement is

$$E_{ij}(t_{ij}) = p_{ij} t_{ij} = \left(\exp \left(\frac{b^{\text{tgt}}}{W t_{ij}} \right) - 1 \right) \frac{\sigma^2}{G_{ij}} t_{ij}. \quad (3)$$

It has been shown in [11] that E_{ij} is a convex and monotonically decreasing function of the transmission duration t_{ij} .

III. MINIMUM-ENERGY MODE SELECTION

The system objective is to exploit the possibility of direct communication between two devices to reduce the transmission energy consumption. Since in some cases prolonging the mobile user's battery life can be more important than reducing the total network energy consumption, we develop an optimal mode selection policy for each of the two following scenarios:

- The overall network energy consumed by both the mobile user and the BS is minimized;
- The energy consumption of the mobile transmitter is minimized.

To solve these two mode selection problems we compare the minimum energy costs in the *D2D mode* and the *cellular mode*. We show that, in both cases, the energy minimization problem can be formulated as a convex optimization problem, and can thus be efficiently solved.

A. Cellular mode

To set up a cellular communication, the entire time frame must be divided into two intervals, t_{10} for the uplink and t_{02} for the downlink. In a dynamic TDD system, the time allocation can be adjusted according to different system objectives, here we are interested in the following two:

1) *Minimizing total energy of the network*: The minimum amount of energy that the overall network needs to communicate in *cellular mode* can be determined by solving the following convex optimization problem

$$\underset{t_{10}, t_{02}}{\text{minimize}} \quad E_{10}(t_{10}) + E_{02}(t_{02}) \quad (4a)$$

$$\text{subject to} \quad t_{10} + t_{02} \leq T, \quad (4b)$$

$$t_{10} \geq \frac{b^{\text{tgt}}}{r_{10}^{\max}}, \quad t_{02} \geq \frac{b^{\text{tgt}}}{r_{02}^{\max}}. \quad (4c)$$

Constraint (4b) ensures that the duration of the communication does not exceed the frame length, while constraints (4c)

ensure *power feasibility*. To guarantee that the constraint set of Problem (4) is non-empty, b^{tgt} must satisfy

$$b^{\text{tgt}} \leq T \cdot \frac{r_{10}^{\max} r_{02}^{\max}}{r_{10}^{\max} + r_{02}^{\max}}. \quad (5)$$

Since the objective function in Problem (4) is monotonically decreasing in (t_{10}, t_{02}) , the optimal solution is attained when $t_{10} + t_{02} = T$. Therefore, Problem (4) is equivalent to the following single-variable optimization problem:

$$\underset{t_{02}}{\text{minimize}} \quad E_{10}(T - t_{02}) + E_{02}(t_{02}) \quad (6a)$$

$$\text{subject to} \quad \frac{b^{\text{tgt}}}{r_{02}^{\max}} \leq t_{02} \leq T - \frac{b^{\text{tgt}}}{r_{10}^{\max}}. \quad (6b)$$

Problem (6) is a convex optimization problem in a single variable that can be solved very quickly using a wide variety of methods, including a simple bisection search [14].

2) *Minimizing device energy*: The energy used for data transmission is one of the main contributors to mobile device battery consumption, see [15]. When we focus only on minimizing the energy cost of the devices (and disregard the energy spent by the base station), the optimal resource allocation problem has the same constraints as in (6) while the objective is reduced to $E_{10}(T - t_{02})$. Since $E_{10}(T - t_{02})$ is monotonically increasing in t_{02} , the objective is minimized by setting t_{02} to its minimum admissible value $b^{\text{tgt}}/r_{02}^{\max}$, which corresponds to letting the BS transmit at its maximal power. The time interval left for the uplink transmission is then

$$t_{10}^* = T - t_{02} = T - \frac{b^{\text{tgt}}}{r_{02}^{\max}}, \quad (7)$$

with the corresponding energy cost

$$E_{10}(t_{10}^*) = \left(\exp\left(\frac{b^{\text{tgt}}}{W t_{10}^*}\right) - 1 \right) \frac{\sigma^2}{G_{10}} t_{10}^*.$$

B. D2D mode

The minimum energy needed to establish a direct communication between two users can be determined by solving the following simple optimization problem

$$\underset{t_{12}}{\text{minimize}} \quad E_{12}(t_{12}) \quad (8a)$$

$$\text{subject to} \quad \frac{b^{\text{tgt}}}{r_{12}^{\max}} \leq t_{12} \leq T. \quad (8b)$$

Here, constraint (8b) ensures that the communication is power feasible and that its duration does not exceed the frame length. We assume that b^{tgt} is selected such that the feasible set of problem (8) is not empty. Since the objective function in (8) is monotone decreasing in t_{12} , the D2D link should exploit the entire frame length T in order to be energy efficient. The energy cost in *D2D mode* is then

$$E_{\text{D2D}} = E_{12}(T) = \left(\exp\left(\frac{b^{\text{tgt}}}{WT}\right) - 1 \right) \frac{\sigma^2}{G_{12}} T. \quad (9)$$

C. Mode selection policy

With the characterization of the minimum energy costs for *D2D mode* and *cellular mode* above, the optimal mode selection policy is simply to use the communication mode that requires the smallest energy. The resulting policy has the intuitive form that *D2D mode* is preferred when the direct link is strong enough, *i.e.* when

$$G_{12} \geq \Theta(G_{10}, G_{02}).$$

The threshold $\Theta(G_{10}, G_{02})$ depends on the uplink and downlink gains, and whether we want to minimize the total system energy, or only the energy consumption of mobile devices.

From the overall network perspective, a direct communication should be established if E_{D2D} in (9) is smaller than the minimum amount of energy needed for the *cellular mode*, derived from the solution to problem (4). Let (t_{10}^*, t_{02}^*) denote the optimal time allocation in problem (4). Thus, the threshold when *D2D mode* is more energy efficient is

$$\Theta(G_{10}, G_{02}) = \frac{\left(\exp\left(\frac{b^{\text{tgt}}}{WT}\right) - 1 \right) T}{\left(\exp\left(\frac{b^{\text{tgt}}}{W t_{10}^*}\right) - 1 \right) \frac{t_{10}^*}{G_{10}} + \left(\exp\left(\frac{b^{\text{tgt}}}{W t_{02}^*}\right) - 1 \right) \frac{t_{02}^*}{G_{02}}}. \quad (10)$$

When we only care about the energy consumption by user-1, the threshold condition for when *D2D mode* is more energy-efficient becomes

$$\Theta(G_{10}, G_{02}) = g(G_{02}) G_{10}, \quad (11)$$

where

$$g(G_{02}) = \frac{\left(\exp\left(\frac{b^{\text{tgt}}}{WT}\right) - 1 \right) T}{\left(\exp\left(\frac{b^{\text{tgt}}}{W \left(T - \frac{b^{\text{tgt}}}{r_{02}^{\max}(G_{02})} \right)} \right) - 1 \right) \left(T - \frac{b^{\text{tgt}}}{r_{02}^{\max}(G_{02})} \right)}. \quad (12)$$

Note that even though we neglect the energy cost for the downlink, G_{02} still plays a role in the mode selection decision.

IV. ANALYSIS AND GEOMETRICAL INTERPRETATION

To gain geometrical insight into the optimal mode selection policy, we assume that channel gains follow a conventional path-loss model $G_{ij} = G_0 D_{ij}^{-\alpha}$, where D_{ij} is the distance between user- i and user- j , G_0 is the path gain at a reference distance of 1m, and α is the path-loss exponent, normally in the range of 2 to 6. For simplicity we focus on mode selection for device energy saving, and re-write (11) in terms of distances as

$$D_{12} \leq \bar{g}(D_{02}) D_{10}, \quad (13)$$

where $\bar{g}(D_{02}) \triangleq \left[g(G_0 D_{02}^{-\alpha})^{-1/\alpha} \right]$. To characterize the region where *D2D mode* is preferable, we fix the position of user-1 (and hence D_{10}). We then vary the position of user-2 along a circle centered at the base station, hence keeping D_{02} and $\bar{g}(D_{02})$ constant. Condition (13) then states that *D2D mode* is preferable when user-2 is located at the intersection of this circle and a disc centered at the position of user-1 (and with radius $\bar{g}(D_{02}) D_{10}$). The area where the *D2D mode* is optimal can be constructed by tracing out these arcs for various

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Carrier Frequency	1 GHz
Cell Radius (R_{cell})	500 m
Channel Bandwidth (W)	5 MHz
Noise Power	-174 dBm/Hz
PathLoss coeff. (α)	4
Path gain at reference distance of 1m (G_0)	$5.7 \cdot 10^{-4}$
Max Tx Power for BS ($p_{02}^{\max}$)	40 W
Max Tx Power for User-1 ($p_{10}^{\max} = p_{12}^{\max}$)	0.25 W
Time Frame duration (T)	1 time unit

distances between user-2 and the base station, see Fig. 2. Note that, as user-2 gets closer to the BS, G_{02} increases, $g(G_{02})$ decreases and the radius of the circle around user-1 becomes smaller.

Fig. 2. Dashed circles centred at the position of user-1 have radius $\bar{g}(D_{02})D_{10}$ and represent, for each position of user-2, the area within which *D2D mode* is selected.

We now present the simulation results obtained with the practical system parameters summarized in Table I. We consider a single circular cell of radius R_{cell} , with the BS placed in the center and equipped with omnidirectional antenna. In each simulation, the position of user-1 is fixed, while we vary the location of user-2 within the cell. The traffic requirement b^{tgt} is set to guarantee power feasibility for the *cellular mode*. Specifically, we set $b^{\text{tgt}} = kT \frac{r_{10}^{\max} r_{02}^{\max}}{r_{10}^{\max} + r_{02}^{\max}}$, where $k \in (0, 1]$, and the maximum rates are computed as $r_{10}^{\max}(G_0 D_{10}^{-\alpha})$ and $r_{02}^{\max}(G_0 R_{\text{cell}}^{-\alpha})$ to ensure that power feasibility holds for any position of user-2 within the cell.

In the presented figures, the red area represents the *D2D optimality area* in which *D2D mode* is more energy efficient than the *cellular mode*. The blue disk, instead, represents *D2D power feasibility area* within which transmitter-1 can fulfil the rate requirement in *D2D mode* with $p_{12} \leq p_{12}^{\max}$. Hence, the intersection of the two areas represents the locations of user-2 where *D2D mode* is both power feasible and energy-optimal.

Figure 3 shows the D2D optimality area when the mobile user energy is the primary concern. We consider $k = 1$ and two different locations of user-1. In both cases D2D optimality area is close to circular. We can understand this shape by the following argument: In the simulation set-up, $p_{02}^{\max}$ is much higher than $p_{10}^{\max}$, which leads to $r_{10}^{\max} \ll r_{02}^{\max}$ with consequent $b^{\text{tgt}} \sim Tr_{10}^{\max}$, especially for small G_{10} (when

user-1 moves towards the cell-edge). As a result, $\bar{g}(D_{02}) \rightarrow 1$ (because $b^{\text{tgt}}/r_{02}^{\max} \rightarrow 0$), which leads to the circular-like D2D optimality area. The same result happens if the time allocation is fixed regardless of the network parameters. A similar circular-like mode selection approach is used in [9], where the time frame is equally divided between the uplink and the downlink transmissions and the power consumption is minimized.

(a) D2D optimality area for $D_{10} = 250\text{m}$.

(b) D2D optimality area for $D_{10} = 450\text{m}$.

Fig. 3. D2D optimality area when minimizing the mobile user energy consumption.

Figure 4(a) and Figure 5(a) represent the D2D optimality area when the overall network energy is the primary concern. Interestingly, D2D communication is preferable in a large portion of the cell, almost close to half cell. Figure 4(b) and Figure 5(b) show the reduction of the energy cost in the D2D mode compared with the cellular mode. When the two users are very close to each other, the energy saving is significant. The high gains are due to both better channel conditions and the larger time duration available for the D2D communication. It is worth noting that even cell-edge users can benefit from the D2D communication, achieving the required session rate with much lower energy cost.

Figure 6 shows the impact of rate requirement on the D2D optimality area for the network energy saving problem. User-1 is located at a distance of 250m from the BS. We consider three different values of the target rate by choosing $k = 0.1$, $k = 0.5$ and $k = 1$. First of all, Figure 6 shows as b^{tgt} increases, the D2D power feasibility area clearly reduces. An interesting observation from Figure 6 is that, as D_{02} increases, the corresponding D2D optimality area enlarges. The reason is as follows. When user-2 moves towards the cell edge, the feasible set of Problem (6) reduces. The feasible set actually

(a) D2D optimality area and D2D power feasibility area.

(b) Percentage of energy saved in *D2D mode* compared with *cellular mode*.

Fig. 4. D2D optimality area when minimizing the network energy consumption, $D_{10} = 250\text{m}$, D_{02} ranges from 50m to 500m , and $k = 0.5$.

(a) D2D optimality area and D2D power feasibility area.

(b) Percentage of energy saved in *D2D mode* compared with *cellular mode*.

Fig. 5. D2D optimality area when minimizing the network energy consumption, $D_{10} = 450\text{m}$, D_{02} ranges from 50m to 500m , and $k = 0.5$.

(a) Rate target is equal to 10% of the maximal feasible rate.

(b) Rate target is equal to 50% of the maximal feasible rate.

(c) Rate target is equal to the maximal feasible rate.

Fig. 6. D2D optimality area with different target rate, $D_{10} = 250\text{m}$, D_{02} ranges from 50m to 500m .

reduces to a single point when $k = 1$ and $D_{02} = R_{\text{cell}}$, which corresponds to the case when both transmitters use their maximum power. In general, there is a certain distance D_{02} after which the optimal solution (t_{10}^*, t_{02}^*) to Problem (6) remains the same. As a result, the threshold (10) starts depending only on G_{02} . Since $\Theta(G_{10}, G_{02})$ decreases with D_{02} , *D2D mode* is more preferable in a larger area.

V. IMPLEMENTATION GUIDELINE

In the network-assisted D2D communication, each transmission is coordinated by the BS through signalling. We would like to specify the necessary signalling needed for the mode selection decision. The BS is responsible for gathering all the information of the channel gains. Gains between mobile users and BS are known at the BS in nowadays cellular systems. For example, in the LTE system the *Sounding Reference Signal*

(SRS) can be used [16]. There is not a standardized procedure to estimate the gain between two mobile users. However, we can assume that the BS assigns *D2D beacon resources* to the two devices after user-1 has sent a transmission request to the BS. Such request message can also contain the type/amount of data that user-1 wants to send to user-2, [3,17]. User-2 can estimate the channel gain of the D2D link by detecting the D2D beacon transmitted by user-1, and report this information to the BS. The BS then solves the *mode selection problem* (verifying conditions (10) or (11), depending on the desired energy consumption to minimize), and broadcasts the decision together with the allocated resources to the mobile users.

VI. EXTENSIONS AND FUTURE WORKS

1) *Bidirectional traffic*: In this paper we propose the mode selection method in the unidirectional traffic case from user-1 to user-2. However, the analysis can be easily extended to the bidirectional traffic case. For the network energy saving, mode selection threshold (10) is the same as in the bidirectional traffic case, under the assumption of channel reciprocity and the same rate requirement for the two directions of transmission. For the user energy saving, instead, to develop the mode selection policy, we first need to compute the optimal uplink time allocation for the two directions: t_{10}^* and t_{20}^* . The computation approach is the same as described in Section III-A2. Then, the transmission mode can be decided by comparing the sum of the corresponding energy costs to twice the energy for *D2D mode* given in (9).

2) *Multiple pairs*: The techniques proposed in this paper can be adapted to solve the joint mode selection and time allocation in certain dynamic TDD systems with multiple links. Let us consider *overlay D2D communications*, where D2D links are given dedicated frequency resources so to avoid mutual interference. The uplink/downlink time configuration can be adjusted dynamically, but should be the same for all pairs in *cellular mode*. In this scenario, the optimal solution that minimizes the energy consumption of all users can be found efficiently by exploiting the proprieties of the optimization problem. In particular, the objective function can be expressed as sum of piecewise non-increasing functions, corresponding to the energy of each pair- i : $E_i(t_{ul}) = \min\{E_{D2D}^{(i)}, E_{i0}(t_{ul})\}$, where $E_{D2D}^{(i)}$ is the energy for *D2D mode* and $E_{i0}(t_{ul})$ is the energy for *cellular mode*, depending on the uplink time t_{ul} . Hence, the objective function is also a piecewise non-increasing function of the uplink transmission time. This piecewise monotonicity allows us to find the optimal solution using very low complexity algorithms. Other interesting and challenging problems include considering the overall network energy consumption and/or *underlay D2D communications*, but we leave these topics for future studies.

VII. CONCLUSIONS

We investigated the problem of efficient mode selection in network-assisted D2D communication, considering a single-cell scenario and a flexible TDD system. The *mode selection problem* has been analysed with two objectives: minimizing

the energy consumption of the overall network (mobile user and BS), and saving the energy of the mobile user only. In both cases we derived the optimal policy based on the three involved channel gains. Simulation results show that the D2D optimality area is strongly affected by the network parameters. In some cases, D2D communication is preferable in large portion of the cell, which shape is, surprisingly, not always circular-like. Large gain in terms of saved energy can be achieved by properly exploiting the possibility of direct communication, especially for cell-edge users.

REFERENCES

- [1] M. Corson, R. Laroia, J. Li, V. Park, T. Richardson, and G. Tsirtsis, "Toward proximity-aware internetworking," *Wireless Communications, IEEE*, vol. 17, no. 6, pp. 26–33, December 2010.
- [2] 3GPP, "3rd generation partnership project; technical specification group SA; feasibility study for proximity services (ProSe) (Release 12)," TR 22.803 V1.0.0, Tech. Rep., August 2012.
- [3] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Miklos, and Z. Turanyi, "Design aspects of network assisted device-to-device communications," *Communications Magazine, IEEE*, vol. 50, no. 3, pp. 170–177, March 2012.
- [4] K. Doppler, M. Rinne, C. Wijting, C. Ribeiro, and K. Hugl, "Device-to-device communication as an underlay to LTE-advanced networks," *Communications Magazine, IEEE*, vol. 47, no. 12, pp. 42–49, December 2009.
- [5] K. Doppler, C. Yu, C. Ribeiro, and P. Janis, "Mode selection for device-to-device communication underlaying an LTE-Advanced network," in *Wireless Communications and Networking Conference (WCNC), IEEE*, April 2010, pp. 1–6.
- [6] M. Jung, K. Hwang, and S. Choi, "Joint mode selection and power allocation scheme for power-efficient device-to-device (D2D) communication," in *Vehicular Technology Conference (VTC Spring), IEEE*, May 2012, pp. 1–5.
- [7] S. Hakola, T. Chen, J. Lehtomaki, and T. Koskela, "Device-to-device communication in cellular network - performance analysis of optimum and practical communication mode selection," in *Wireless Communications and Networking Conference (WCNC), IEEE*, April 2010, pp. 1–6.
- [8] M. Belleschi, G. Fodor, and A. Abrardo, "Performance analysis of a distributed resource allocation scheme for D2D communications," in *GLOBECOM Workshops (GC Wkshps), IEEE*, December 2011, pp. 358–362.
- [9] S. Shalmashi, E. Bjornson, S. Ben Slimane, and M. Debbah, "Closed-form optimality characterization of network-assisted device-to-device communications," in *Wireless Communications and Networking Conference (WCNC), IEEE*, April 2014, pp. 508–513.
- [10] C. Gao, X. Sheng, J. Tang, W. Zhang, S. Zou, and M. Guizani, "Joint mode selection, channel allocation and power assignment for green device-to-device communications," in *IEEE International Conference on Communications (ICC), 2014*, June 2014, pp. 178–183.
- [11] E. Uysal-Biyikoglu, B. Prabhakar, and A. El Gamal, "Energy-efficient packet transmission over a wireless link," *IEEE/ACM Transactions on Networking*, vol. 10, no. 4, pp. 487–499, August 2002.
- [12] P. Chan, E. Lo, R. Wang, E. Au, V. Lau, R. Cheng, W. Mow, R. Murch, and K. B. Letaief, "The evolution path of 4G networks: FDD or TDD?" *Communications Magazine, IEEE*, vol. 44, no. 12, pp. 42–50, December 2006.
- [13] J. Li, S. Farahvash, M. Kavehrad, and R. Valenzuela, "Dynamic TDD and fixed cellular networks," *Communications Letters, IEEE*, vol. 4, no. 7, pp. 218–220, July 2000.
- [14] S. Boyd and L. Vandenberghe, *Convex Optimization*. New York, NY, USA: Cambridge University Press, 2004.
- [15] A. Carroll and G. Heiser, "An analysis of power consumption in a smartphone," in *Proceedings of the 2010 USENIX Conference on USENIX Annual Technical Conference*, ser. USENIXATC'10. Berkeley, CA, USA: USENIX Association, 2010, pp. 21–21.
- [16] S. Sesia, I. Toufik, and M. Baker, *LTE - The UMTS Long Term Evolution: From Theory to Practice*. Wiley, 2011.
- [17] B. Lindoff, G. Fodor, L. Wilhelmsson, and M. Kazmi, "Beacon management for network assisted device-to-device (D2D) communication," 2013, wO Patent App. PCT/EP2013/059,598.