Performance Analysis of Network-Assisted Two-Hop D2D Communications

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***Abstract*—Network-assisted single-hop device-to-device (D2D) communication can increase the spectral and energy efficiency of cellular networks by taking advantage of the proximity, reuse, and hop gains. In this paper we argue that D2D technology can be used to further increase the spectral and energy efficiency if the key D2D radio resource management algorithms are suitably extended to support network assisted *multi-hop* D2D communications. Specifically we propose a novel, distributed utility maximizing D2D power control (PC) scheme that is able to balance spectral and energy efficiency while taking into account mode selection and resource allocation constraints that are important in the integrated cellular-D2D environment. Our analysis and numerical results indicate that multi-hop D2D communications combined with the proposed PC scheme can be useful not only for harvesting the potential gains previously identified in the literature, but also for extending the coverage of cellular networks.**

I. Introduction

Although the ideas of integrating ad hoc relaying systems into cellular networks are not new [1], [2], the advantages of Device-to-Device (D2D) communications in cellular spectrum have been identified and analyzed only recently [3], [4]. Specifically, it has been found that D2D communications can increase the spectral and energy efficiency by taking advantage of the proximity, reuse and hop gains when radio resources are properly allocated to the cellular and D2D layers [5].

Another line of research suggests that relay-assisted multi-hop (MH) communications, including mobile relays and relay-assisted D2D communications can not only enhance the achievable transmission capacity, but can also improve the coverage of cellular networks [4], [6]–[8].

Recognizing the potential of combining D2D and relay technologies, the standardization and research communities have initiated studies on the achievable gains and enabling technology components to support network-assisted MH D2D communications in operator licensed spectrum. For example, the 3rd Generation Partnership Project (3GPP) is investigating the use of D2D communication both in commercial and National Security and Public Safety (NSPS) scenarios [9]. Integrating MH D2D communications can also help to meet the evolving requirements of next generation wireless networks [10]. In all these cases, both spectral and energy efficiency requirements must be met due to the limited spectrum resources and the requirement on providing broadband services.

However, extending the key enabling technology components of single-hop network-assisted D2D communications to

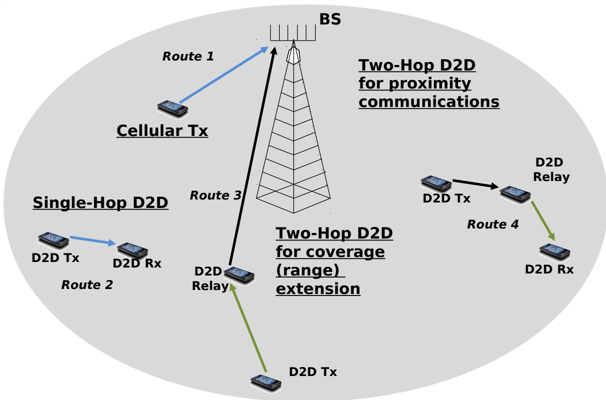

Figure 1. An example of a cellular network supporting single- and multi-hop D2D communications in cellular spectrum. Between each source-destination (S-D) pair, a *route* must be defined and resources need to be allocated to each *link* along the route. We use different colors to indicate different time-frequency resources, while the same color for different links indicate the possibility for intracell resource reuse. In this paper we assume that in the multi-hop case, the incoming and outgoing links of a relay node must use orthogonal resources. Notice that a given S-D pair may have the possibility to communicate in *cellular* mode through the base station or using single- or multi-hop D2D communications.

MH D2D communication is non-trivial, because (Figure 1):

1) Existing single-hop *mode selection* (MS) algorithms must be extended to select between the single-hop D2D link, MH D2D paths and cellular communications.
2) Existing single-hop *resource allocation* algorithms must be further developed to be able not only to manage spectrum resources between cellular and D2D layers, but also to comply with resource constraints along MH paths.
3) Available D2D power control (PC) algorithms must be made capable of taking into account the rate constraints of MH paths. Specifically, it must be taken into account that along the multiple links of a given path, only a single rate can be sustained without requiring large buffers or facing buffer underflow situations at intermediate nodes.

In this paper we (1) propose and analyze heuristic mode selection and resource allocation strategies that are applicable in cellular networks integrating MH D2D communications and (2) develop a utility optimal distributed PC scheme that takes into account both the achievable rates along MH paths and the overall energy consumption. The PC scheme can operate in concert with both the PC schemes available in cellular networks and the mode selection and resource allocation algorithms, taking into account that a relaying device cannot receive and transmit data on the same frequency resource at the same time. Therefore, our main contribution is the MH power control scheme that is analyzed by means of a realistic system simulator when performing practically feasible mode selection and resource allocation.

II. System Model

The system model consists of two parts. First, the *routing matrix* describes the network topology and associates links with resources. Secondly, the *utility function* associated with an S-D pair characterizes the utility of supporting some communication rate between the end nodes of the pair.

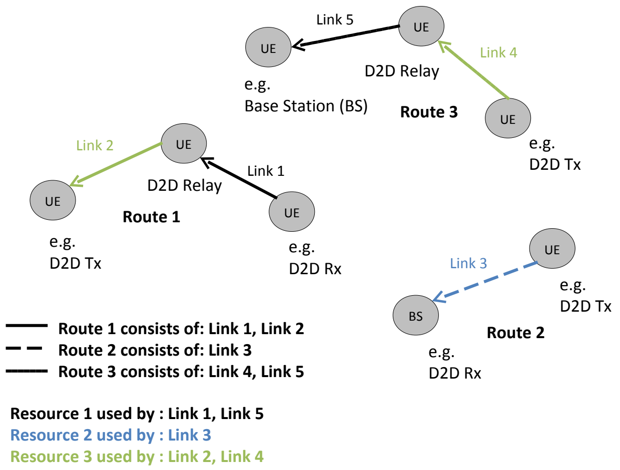

Figure 2. An example of a network with 3 routes, where Route 1 and Route 3 are two-hop routes, and Route 2 consists of a single-hop route. In the specific case of Figure 1, Route 1, 2 and 3 can model the two-hop D2D route for coverage extension, the single-hop D2D link and the two-hop D2D route for proximity communication. Note that the resources allocated to the incoming and outgoing links of a relay node must be orthogonal, as indicated in this Figure. A node can represent a User Equipment (UE) or a Base Station (BS).

A. Network Topology

We model the integrated cellular-D2D network as a set of L transmitter-receiver (Tx-Rx) pairs. A Tx-Rx pair can be a cellular User Equipment (UE) transmitting to its serving Base Station (BS), a D2D Tx node transmitting to a D2D Rx node in single-hop D2D mode, a D2D Tx node transmitting to a D2D relay node or a D2D relay node transmitting to a D2D Rx node. A *link* refers to a single-hop transmission between a Tx-Rx pair, while a *route* is a concatenation of one or more links between a S-D pair. For example, a two-hop route consists of two Tx-Rx pairs, in which case the middle node must be a D2D-capable relay node (Figure 2). The links and routes are labelled as $l = 1, \dots, L$ and $i = 1, \dots, I$ respectively. Next, we define the 3-dimensional *routing matrix* that associates links with routes and resources and thereby describes both the network topology in terms of links and routes and the resources assigned to links. The routing matrix is defined as $\mathbf{R} = [r_{liq}] \in \{0,1\}^{L \times I \times Q}$, where the entry r_{liq} is 1 if data between the S-D pair i is routed across link l and resource q, and zero otherwise. With this definition, the routing matrix can be seen as a set of Q single-resource matrices, $\mathbf{R}_q \in \{0,1\}^{L \times I}$, such that the $r_{l,i}$ element of $\mathbf{R}_q$ indicates whether link l is part of route i on resource q. For the example of Figure 2, the $Q = 3$ routing matrices are the following:

$$\mathbf{R}_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \mathbf{R}_2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \mathbf{R}_3 = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

For example, $\mathbf{R}_1$ corresponds to resource $q = 1$ and describes that it is (re-)used by link $l = 1$ (first hop of route $i = 1$) and link $l = 5$ (second hop of route $i = 3$). We will find it useful to define the 2-dimensional equivalent routing matrix, given by $\tilde{\mathbf{R}} = \sum_{q=1}^{Q} \mathbf{R}_q$ and entries $\tilde{r}_{li}$. We assume the data to be routed along a single fixed link, i.e., we do not allow the data flow between a Tx-Rx pair to be spread between 2 or more resources.

To describe the association of links with resources, we define the following two functions. Let $f : I \to \{1, 2\}$ denote the number of hops in the route i; $\mathbf{t} : I \times \{1, \dots, f(i)\} \to L \times Q$ denote the link and resource used in route i and hop h respectively. In addition, we denote by $t_1(i,h)$ and $t_2(i,h)$ the first and second outputs of $\mathbf{t}$, which represent the link and resource respectively. Table I gives an example of how these functions help to describe the relationship between routes, links and resource usage.

Table I
An example of how the network in Figure 2 can be described using the three functions defined above.

Function	Description	Example in the Network of Figure 2
$f(i)$	Number of hops in route i	$f(1) = f(3) = 2$
$\mathbf{t}(i,h)$	Link and resource indexes in route i and hop h	$\mathbf{t}(3,2) = (5,1)$
$t_1(i,h)$	Link index l in route i and hop h	$t_1(3,2) = 5$
$t_2(i,h)$	Resource index q in route i and hop h	$t_2(3,2) = 1$

B. Assigning a Utility to an S-D Pair

We let s_i denote the end-to-end *rate* for communication between the S-D pair i, which is in correspondence with the Signal to Interference-Plus-Noise-Ratio (SINR) *targets* for hop h of route i denoted by $\gamma^{tgt}_{t_1(i,h)}$. In a multi-hop communication, the SINR targets of each link in a specific route must be the same, in line with the so-called *solidarity property* [11]. Thus, $\gamma^{tgt}_{t_1(i,h)}$ needs to be indexed with the single index $t_1(i,h)$.

Associated with each S-D pair i is a function $u_i(.)$, which describes the utility of the S-D pair communicating at rate s_i. We assume that u_i is *increasing* and *strictly concave*, with $u_i \to -\infty$ as $s_i \to 0^+$. In this paper we use $u_i(x) \triangleq \ln(x), \forall i$.

The matrix of link capacities is denoted by $\mathbf{C} = [\mathbf{c}_1 \cdots \mathbf{c}_q] \in \mathbb{R}^{L \times Q}$, which depends on the communication bandwidth W of one resource and the *achieved* actual SINR along route i and hop h, $\gamma_{\mathbf{t}(i,h)}$. Notice that the achieved SINR $\gamma_{\mathbf{t}(i,h)}$ is indexed by $\mathbf{t}(i,h)$, because the SINRs are generally different at different resources.

The vector of total traffic across the links of a route is given by $\tilde{\mathbf{R}}\mathbf{s}$ and the network flow imposes the following set of constraints on the source-destination rate vector $\mathbf{s}$:

$$\tilde{\mathbf{R}}\mathbf{s} \preceq \sum_{q=1}^{Q} \mathbf{c}_q \qquad \mathbf{s} \succeq 0.$$

In this formulation, it is convenient to think of the $\mathbf{s}$ vector as the vector of rates while the $\mathbf{c}_q$ vectors represent the Shannon capacity that can be achieved by the particular power vector $\mathbf{p}_q = [P_{1q}, \ldots, P_{Lq}] \in \mathbb{R}^L$ on resource q.

Let $G_{\mathbf{t}(i,h)}$ denote the desired link gain on route i and hop h, which includes both large- and small-scale fading gains. The thermal noise power at the receiver on route i and hop h is denoted by $\sigma_{\mathbf{t}(i,h)}$, and the transmission power on route i and hop h is $P_{\mathbf{t}(i,h)}$. The SINR on route i and hop h is given by

$$\gamma_{\mathbf{t}(i,h)}(\mathbf{P}) = \frac{G_{\mathbf{t}(i,h)} P_{\mathbf{t}(i,h)}}{\sigma_{\mathbf{t}(i,h)} + (P^{tot}_{\mathbf{t}(i,h)} - G_{\mathbf{t}(i,h)} P_{\mathbf{t}(i,h)})},$$

where $P^{tot}_{\mathbf{t}(i,h)}$ represent the total received power measured by the receiver on route i and hop h and $\mathbf{P} = [\mathbf{p}_1, \ldots, \mathbf{p}_Q] \in \mathbb{R}^{L \times Q}$ is the power allocation matrix.

Finally, it will be useful to view each link on route i and hop h as a single Gaussian channel with Shannon capacity

$$c_{\mathbf{t}(i,h)}(\mathbf{P}) = W_{t_2(i,h)} \log_2 \left(1 + \gamma_{\mathbf{t}(i,h)}(\mathbf{P})\right),$$

which represents the maximum rate that can be achieved on route i and hop h.

III. Mode Selection and Resource Allocation

A. Multi-Hop D2D Scenarios: Proximity Communication and Coverage (Range) Extension

Recall from Figure 1 that MH D2D communications can be advantageously used in two distinct scenarios. In the *proximity communication* scenario, a D2D relay node helps a D2D pair to communicate [9, Section 5.2.9], while in the *coverage* or *range extension* scenario a D2D relay node assists a coverage limited D2D Tx node to boost its link budget to a base station. In the proximity communication scenario, the mode selection problem consists of deciding whether the D2D Tx node should communicate with the D2D Rx node (1) via a direct D2D (single-hop) link, (2) via a 2-hop path through the D2D relay node or (3) through the cellular BS. In contrast, in the range extension scenario, the mode selection problem consists of deciding whether the D2D Tx node should communicate via a direct transmission with its serving BS or via the D2D relay node. We consider mode selection alternatives in the next subsection.

B. Mode Selection Schemes

For the proximity communication scenario, we use the notion of the equivalent channel from D2D Tx to D2D Rx through D2D relay based on the harmonic mean of the channels from D2D Tx to D2D relay (G_{TxRe}) and from D2D relay to D2D Rx (G_{ReRx}):

$$\frac{1}{G_{eq}} = \frac{1}{G_{TxRe}} + \frac{1}{G_{ReRx}}. \tag{1}$$

The intuition of defining the equivalent channel according to (1) is that the equivalent channel gain tends to be high only when both composite channels are high and therefore it is an appropriate single measure for mode selection purposes. A pseudo code of a heuristic mode selection algorithm based on the equivalent channel is given in Algorithm 1, where we need the channels from the D2D Tx to the BS (G_{TxBS}) and to the D2D Rx (G_{TxRx}).

Algorithm 1 Harmonic Mode Selection (HMS) for Proximity Communication

```
1: if G_eq ≥ max{G_TxRx, G_TxBS} then
2:     Choose D2D two-hop communications
3: else if G_TxRx ≥ G_TxBS then
4:     Choose D2D single-hop communications
5: else
6:     Choose cellular mode, that is D2D Tx and Rx communication through
       the BS.
7: end if
```

Recall from Section III-A that in the range extension scenario, there are only two possible communication modes (direct or relay-assisted) between the D2D Tx device and the BS. Therefore, in this scenario, we modify the definition of the equivalent channel such that it includes the path gain between the relay device and the BS (G_{ReBS}):

$$\frac{1}{G_{eq}} = \frac{1}{G_{TxRe}} + \frac{1}{G_{ReBS}},$$

and use a modified version of the Harmonic Mode Selection (HMS) algorithm (Algorithm 2).

Algorithm 2 Harmonic Mode Selection (HMS) for Range Extension

```
1: if G_eq ≥ G_TxBS then
2:     Choose D2D relay assisted communication
3: else
4:     Choose cellular mode that is D2D Tx transmits directly to the BS.
5: end if
```

C. Resource Allocation Scheme

First, we recognize that for two-hop communications with multiple resources the following resource allocation constraints must be met:

- A transmitter, either D2D Tx ($h = 1$) or D2D relay ($h = 2$), cannot have multiple receivers: $\sum_i \tilde{r}_{t_1(i,h),i} = 1$.
- A D2D relay cannot receive and transmit on the same resource: $r_{t_1(i,1),i,t_2(i,1)} + r_{t_1(i,2),i,t_2(i,2)} \leq 1$.

Secondly, the set of nodes transmitting to a BS must use orthogonal resources. That is, cellular transmissions maintain intracell orthogonality. Apart from these constraints, in this paper we assume that resources are allocated randomly to communication links and leave the study of efficient resource allocation algorithms for future studies.

IV. Distributed Power Control Optimization

A. SINR Target Setting and Power Control Problem - Utility Maximization

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

$$\begin{array}{ll} \underset{\mathbf{P},\mathbf{s}}{\text{maximize}} & \sum_i u_i(s_i) - \omega \sum_{i=1}^{I} \sum_{h=1}^{f(i)} P_{\mathbf{t}(i,h)} \\ \text{subject to} & \tilde{\mathbf{R}}\mathbf{s} \preceq \sum_{q=1}^{Q} \mathbf{c}_q(\mathbf{P}), \quad \forall i,h, \\ & \mathbf{P},\mathbf{s} \succeq 0 \end{array} \tag{2}$$

which aims at maximizing the utility while taking into account the transmit powers (through a predefined weight $\omega \in (0, +\infty)$ [12]), so as to increase spectrum efficiency while reducing the sum power consumption.

Unfortunately, Problem (2) is not convex. However, exploiting the results presented in [12], we can transform it into the following equivalent form:

$$\begin{array}{ll} \underset{\tilde{\mathbf{s}},\tilde{\mathbf{P}}}{\text{maximize}} & \sum_i u_i(e^{\tilde{s}_i}) - \omega \sum_{i=1}^{I} \sum_{h=1}^{f(i)} e^{\tilde{P}_{\mathbf{t}(i,h)}} \\ \text{subject to} & \log(\tilde{\mathbf{R}}\mathbf{e}^{\tilde{\mathbf{s}}}) \leq \log\left(\sum_{q=1}^{Q} \mathbf{c}_q(e^{\tilde{\mathbf{P}}})\right) \quad \forall i,h, \end{array} \tag{3}$$

where $s_i \leftarrow e^{\tilde{s}_i}$ and $P_{\mathbf{t}(i,h)} \leftarrow e^{\tilde{P}_{\mathbf{t}(i,h)}}$. The transformed Problem (3) is proved to be convex (now in the $\tilde{s}_i$-s and $\tilde{P}_{\mathbf{t}(i,h)}$-s), for the utility functions $u_i(\cdot)$ are selected to be $(\log, x)$-concave over their domains [12].

Under the utility's condition, we can solve Problem (3) to optimality by means of decomposing the problem into separate subproblems in $\tilde{\mathbf{s}}$ and $\tilde{\mathbf{p}}$. Problem-I [13, eq. 5] can be solved by gradient iterations and using Lagrangian duality to obtain the SINR targets, while Problem-II [13, eq. 8] can be solved by an iterative SINR target following inner loop (set by a Zander type iterative SINR target [14]). The relationship between Problem-I and Problem-II can be exploited such that the necessary Lagrange multipliers in the iterations of Problem-I are provided by solving Problem-II. The details are omitted here due to space limitations.

V. Numerical Results and Discussion

A. Simulation Setup and Parameters

In this section, we consider a seven cell system with a cell radius of 500 m supporting 18 uplink physical RBs in each cell. The D2D communication uses uplink RBs in both the proximity communication and the range extension scenarios. For simplicity and to gain insights, we assume that each UE and D2D pair uses a single uplink RB. The most important system parameters are summarized in Table II.

To collect statistics on the measured SINR and transmit power levels, we perform Monte Carlo simulations, such that in each Monte Carlo experiment we randomly drop 6 *cellular* UEs and 6 D2D *triplets* per cell for the proximity communication scenario and 18 D2D *triplets* per cell for the range extension scenario. A cellular UE refers to a UE that transmits to its serving BS, while a triplet is a set consisting of a D2D transmitter, a D2D relay and a D2D receiver node. Recall that in the proximity communication scenario a D2D transmitter transmits to a D2D receiver node (possibly via a D2D relay), while in the range extension scenario, a D2D transmitter node transmits to its serving BS (possibly via a D2D relay). In the range extension scenario, the D2D receiver node is not used.

Table II
Simulation parameters

Parameter	Value
Number of BSs	7
Cell radius	$500\,\mathrm{m}$
Minimum distance BS-UE	$50\,\mathrm{m}$ (Scen. 1)/$400\,\mathrm{m}$ (Scen. 2)
Minimum distance UE-UE	$10\,\mathrm{m}$
Mean distance D2D Tx-D2D Rx	$100\,\mathrm{m}$
Number of cellular UEs per cell	6
Number of D2D triplets per cell	6 (Scen. 1)/18 (Scen. 2)
Monte Carlo iterations	100
Central carrier frequency	$2\,\mathrm{GHz}$
System bandwidth	$5\,\mathrm{MHz}$
Number of RBs	18 RBs
Gain at $1\,\mathrm{m}$ distance	$-37\,\mathrm{dB}$
Thermal Noise power per RB	$-116.4\,\mathrm{dBm}$
Path Loss coefficient	3.5
Shadowing standard deviation	$8\,\mathrm{dB}$
BS transmit power	$40\,\mathrm{dBm}$
UE min/max transmit power	$-23\,\mathrm{dBm}/23\,\mathrm{dBm}$
Fixed Power for LTE PC	$-10\,\mathrm{dBm}$
Path loss compensation factor (α)	0.8
SNR/SINR target	$15\,\mathrm{dB}$
Number of outer-loop iterations	70
Number of inner-loop iterations	10
ϵ for the outer-loop	0.05
Initial power for the inner-loop	$10\,\mathrm{dBm}$
Initial γ^{tgt} for the outer-loop	$0\,\mathrm{dB}$
ω of Eq. (2)	[0.1 1 10 100]

Table III
Mode selection algorithms

Name	Proximity Communications Scenario	Range Extension Scenario
Cellular mode (**Cmode**)	Forced cellular mode (no D2D communications)	Forced cellular mode (no D2D communications)
D2D mode (**DMS**)	Mode selection between single-hop D2D mode and cellular mode	Forced relaying (two hop) D2D mode, that is transmission through the D2D relay node
Adaptive mode selection with the HMS algorithms (**HMS**)	Mode selection by **Algorithm 1**	Mode selection by **Algorithm 2**

To gain insight into the performance impacts of mode selection algorithms, we evaluate the mode selection (MS) alternatives listed in Table III.

Table IV
Power control algorithms

Name	Cellular UE power control	D2D power control
Fix	LTE Open Loop	Fixed Power
Fix SNR	LTE Open Loop	Fixed SNR target
Open Loop **(OL)**	LTE Open Loop	LTE Open Loop
Closed Loop **(CL)**	LTE Open Loop	LTE Closed Loop
Utility Maxim. **(UM-ω)**	Utility maximizing PC with parameter ω	Utility maximizing PC with parameter ω

To evaluate and benchmark the performance of the utility maximizing power control scheme, we compare its SINR and power consumption statistics with those based on the well known LTE power control schemes [15], as listed in Table IV.

B. Impact of Mode Selection Algorithms

Figures 3-5 compare the performance of the forced cellular mode, D2D mode (mode selection between single hop and cellular communications) and HMS (see Table III).

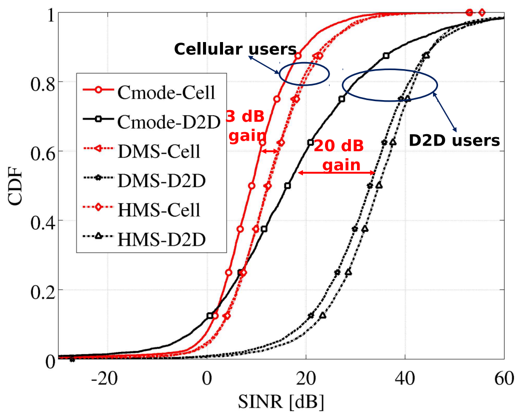

Figure 3. **Proximity communication scenario:** CDF of the SINR for both cellular UEs and D2D candidates with Cmode, DMS and HMS (see Table III). HMS is superior for both the cellular UEs (denoted '-Cell') and the D2D candidates and considering all the modes. The cellular UEs benefit somewhat ($\approx$ 3 dB) from D2D communications. For the D2D candidates, the mode selection gain is much more pronounced ($\approx$ 22 dB) with the HMS.

Figure 3 shows the SINR distributions of cellular UEs and D2D pairs when employing the mode selection schemes of Table III in the proximity communication scenario. This figure shows that cellular UEs (transmitting to their serving BS) benefit somewhat ($\approx$ 3 dB) from D2D communications, especially when adaptive mode selection (the HMS algorithm) is used for mode selection. For the D2D users the mode selection gain is much more pronounced ($\approx$ 20 dB). The intuitive explanation of this is that D2D communication with adaptive power control takes advantage of the proximity gain and reduces intercell interference. At the same time, D2D UEs benefit from an improved link budget due to the proximity, which allows for lower transmit power and higher SINR at the D2D receivers. HMS can adaptively take advantage of the two-hop path, which explains the additional gain of HMS over DMS ($\approx$ 2 dB).

Figure 4 is the scatter plot of the transmit power levels and achieved SINR levels of D2D candidates in the proximity communication scenario, which shows that Cmode results in lower SINR values with a higher power consumption than all the other modes. Also, HMS reaches higher SINR values than single-hop D2D mode with a lower power consumption, which suggests that in addition to the SINR gains, two-hop communications outperform single-hop D2D mode in terms of power efficiency.

Figure 5 shows the SINR distribution for the D2D nodes using the Cmode and the HMS mode selection algorithm in the range extension scenario. Figure 5 shows that the HMS outperforms Cmode with margin of 5 dB in the low SINR

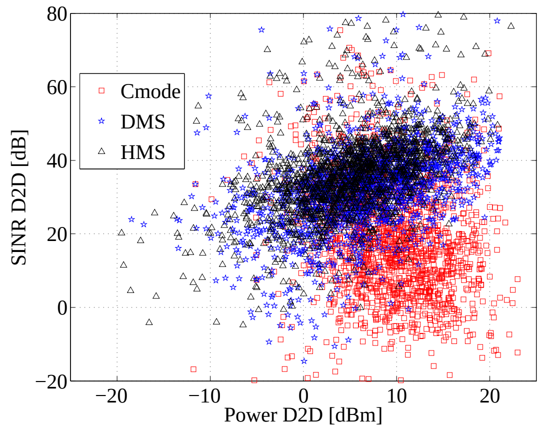

Figure 4. **Proximity communication scenario:** CDF of the SINR for both cellular UEs and D2D candidates when considering different communication modes. We notice that Cmode results in lower SINR values with a higher power consumption than all the other modes. In addition, HMS reaches higher SINR values than single hop D2D mode with a lower power consumption, which suggests that in addition to the SINR gains, two-hop communications outperform the single-hop D2D mode.

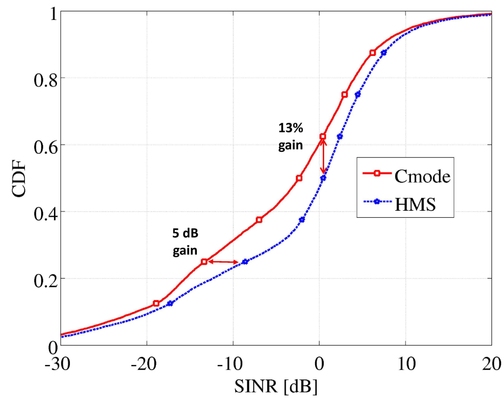

Figure 5. **Range extension scenario:** CDF of the SINR for D2D candidates when considering different communication modes. We notice that the HMS outperforms the Cmode in the low SINR regime. Moreover, HMS decreases the occurrence of SINR values below 0 dB.

regime. The UEs that experience low SINR values are the ones at the cell edge and benefit the most from the presence of D2D relay nodes. In addition, HMS reduces the probability of the SINR being below 0 dB from 60 % to 47 %. This is because the mode selection algorithm exploits the fact that the MH path is stronger than in the Cmode, and thus yields a proximity gain for cell edge users.

Our conclusion regarding mode selection algorithms is that both proximity communication and D2D range extension can benefit from MH communication in terms of spectral and energy efficiency when the communication mode is properly (that is adaptively) selected.

C. Impact of Power Control Algorithms

To gain insight into the impact of power control, we consider the power control algorithms of Table IV using HMS for both the proximity communication and range extension scenarios. For the utility maximization power control scheme, we employ four different values of ω, which controls the spectral and energy efficiency trade-off.

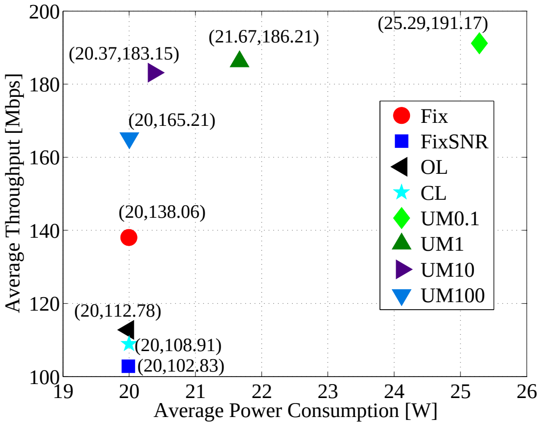

Figure 6. **Proximity communication scenario:** Scatter plot of the total power consumption and average throughput achieved by the examined power control algorithms. (x, y) near each symbol shows the x-axis (power consumption in W) and y-axis (throughput in Mbps) values. Note that UM10 can boost the average throughput with a small increase of the transmit power level.

Figure 6 is the scatter plot for the proximity communication scenario. With $\omega = 0.1$ the average throughput gain is approximately $39\,\%$ over the LTE PC with fixed power, but using approximately $26\,\%$ more power. However, with $\omega = 100$ the average throughput gain is approximately $20\,\%$ using similar transmit power levels as LTE PC. It is interesting to note that the utility maximizing PC can trade between different objectives while maintaining high values of average throughput compared with all the other PC algorithms.

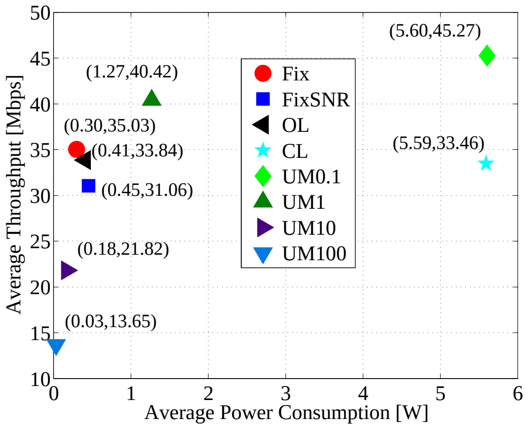

Figure 7. **Range extension scenario:** Scatter plot of the total power consumption and average throughput achieved by the examined power control algorithms. The utility maximizing PC can reach the highest throughput (with lower values of ω) or the lowest power consumption (with higher ω values). LTE OL provides a reasonable engineering trade-off.

Figure 7 is the scatter plot for the range extension scenario. Similarly to the previous figure, for $\omega = 0.1$ the utility maximization reaches the highest average throughput, with a gain of approximately $29\,\%$ over LTE PC with fixed power. However, with $\omega \geq 10$ the utility maximizing PC minimizes power consumption at the expense of reaching lower throughput values. Clearly, utility maximizing PC can reach high throughput when using low values of ω. However, if the power consumption has to be kept at low values with reasonable throughput values, utility maximization with higher ω values or using the LTE PC can be satisfactory.

VI. Conclusion

In this paper we developed radio resource management algorithms applicable in network-assisted MH D2D scenarios, including the proximity communication and the range extension scenarios. The proposed adaptive harmonic mode selection (HMS) scheme together with a utility maximizing PC scheme can improve the throughput and the energy efficiency of a system that does not support D2D communications or employs traditional mode selection and power control schemes. HMS can also decrease the outage probability and improve the average throughput using similar transmit power levels as users employing traditional PC techniques. LTE OL power control can also provide a reasonable trade-off between throughput and energy efficiency, especially in the range extension MH scenario.

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