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Clustering Concept using Device-to-Device Communication in Cellular System

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***Abstract*—We study how direct communication within a group of devices, cluster, can improve the performance of a conventional cellular system. The clusters are formed from devices that are close and communicating with each other, for example, sharing data. The clusters share the radio resources among other devices in the system thus creating a mixed network system comprising directly communicating devices and devices having radio links to and from the base stations. In this kind of a system the additional challenge is to decide when clusters shall use direct communication and when conventional cellular radio links to communicate with each other. Here, in addition to clustering concept description we provide new means to analyse achievable system performance when clustering communication is integrated into a cellular network and especially into an interference limited system.**

I. Introduction

Although techniques to allow clustering of devices, such as 802.11b, have been around for quite a while and are available for mobile devices the real service development has not been very active to really utilize possibilities of the current techniques. Today, clustering the devices usually requires manual setup and is carried out in non-licensed spectrum without any network control. Device-to-Device (D2D) clustering concept considered in this paper offers features which can enable new, different kind of services to be deployed in the cellular network.

Key motivator for utilizing direct communication in a cellular network is to keep local communication local. For example, in Frequency Division Duplex (FDD) system a device pair having an intra-cell communication occupies two uplink-downlink resource pairs in cellular communication mode. In addition, the traffic between communicating devices is routed via core network thus increasing the network load, data delay and base station resource utilization. In D2D cluster concept devices can be assigned to direct communication mode utilizing cellular network resources. Direct communication mode excludes the unnecessary core network involvement and enhances the base station resource utilization. Direct communication can also bring its own flavour to the current mobile applications and services. Also today's "hot" social networking applications like Facebook, Youtube or Myspace are approaching mobile world and can possibly benefit from direct communication, especially when combined with mobility and location awareness. Other possible services that could benefit from direct communication and clustering are e.g. mobile multiplayer gaming, file sharing, mobile advertising, streaming services [1] and co-operative download [2].

Previously CDMA type network with direct communication is analysed e.g. in [3]. A few references about utilizing cellular bands for direct communication can be found e.g. in [4], [5]. Direct communication with clustering is analysed in [6] using teletraffic approach to calculate blocking probabilities. In that study the devices were able communicate directly while being members of different clusters. Capacity enhancements in UMTS system with direct mobile to mobile communications was studied in [7].

As licensed spectrum is assumed the network controls the utilization of radio resources. Thus the network controls resource allocation of user devices in the system whether devices are in conventional cellular or D2D cluster communication mode. However the devices in D2D cluster mode may themselves decide how they use the allocated radio resources within the constraints set by the network. D2D pair or cluster of devices can determine e.g. used modulation and coding scheme (MCS), transmit/receive slot allocation (TDD specific), link adaptation etc, thus allowing distributed resource allocation methods to be applied in the cellular network. Further, the network may assign a cluster head (CH) for the device group which is responsible for dividing the allocated resources between cluster members (different metrics for CH selection can be found e.g. in [8]). The network is able to control cluster members via control link to CH.

Major benefit of the D2D clustering concept when it is integrated into cellular system is that the setup and operation can be made transparent for the end user. A D2D capable device can be connected simultaneously to multiple similar terminals that are located relatively close to it and at the same time be connected to network and having e.g. a phone call. The mode switching between cellular and direct communication mode can be made flexible and utilizing cellular communication mode as backbone the service continuity can be guaranteed in case of mobility. Thus, the most challenging problem in the network is to decide whether communicating devices should use cellular or direct communication mode.

In this study we extend the system equations used to

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analyse D2D operation in cellular network [9] to cover also D2D clustering. Similarily, here D2D clusters operate in Time Division Duplex (TDD) on cellular uplink (UL) band.

II. System Model

A. Background

In [9] authors derive system equations to assign optimal communication mode for devices in a cellular network where direct D2D communication mode is an option along with conventional cellular communication. The optimal communication mode selection is taking into account all the devices in the system and the state of the network. In that study as well as here direct communication will occur on uplink resources. In this study, we extend those system equations and approach to cover the clustering operation in the cellular system. In addition to [9] where the derived system equations considered only uplink here we utilize both uplink and downlink because the applied application, a file sharing, using a cellular communication mode requires both uplink and downlink operation. Here the devices in the system may have three different communication modes: 1) continuous transmission and reception to/from the BS, 2) cellular communication mode multicast transmission where one of the devices (the source) transmits to the BS and then the other devices in the cluster receive a multicast transmission from the BS, and 3) D2D cluster communication mode multicast transmission where one of the devices transmit and other devices in the cluster receive. The first group comprises of devices that are not locally communicating and the latter two groups comprise locally communicating devices for which we try to find the optimal communication mode.

Let's assume that we have a cluster of devices and one cluster member wants to share e.g. a file with other cluster members. To simplify the analysis all the receiving cluster members within a cluster are combined to be one receiver to which the source device sends its data. The approach when the cluster is operating in cellular communication mode is depicted in left part of Fig. 1. Similarly the approach for the D2D clustering operation is presented in right part of Fig. 1.

After presented simplification we can consider that the source device in both cellular communication mode and D2D cluster communication mode shares its data to only one destination and thus we can apply the similar system equations proposed in [9] to study optimal communication mode selection. The extensions to those system equations are described in the next subsection.

B. System equations for the clustering

Let's assume that we have altogether L devices in the system. Further, we define a local communication probability as p_{local} and cluster size N_c in terms of number of devices per cluster. Then there are $floor\left(p_{local}L\right)$ locally communicating devices and $cl_{num} = ceil\left(floor\left(p_{local}L\right)/N_c\right)$ clusters with the constraint that each cluster has at least two devices. Next we do the simplification explained above and form clusters having a transmitter and a combined receiver and end up having two devices in each cluster for the further analysis.

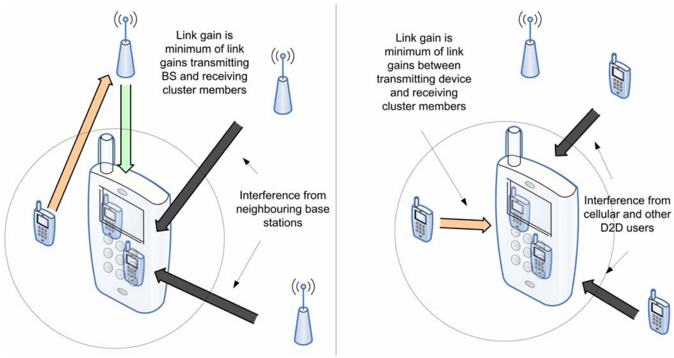

Fig. 1. Forming a combined cluster member from receiving cluster members in cellular communication mode.

Also we now consider number of devices in the system to be $L_{virt} = L - \left(floor\left(p_{local}L\right) - 2cl_{num}\right)$ for which the following system equations are generated.

We define i and j be an indices of a device having values $1, \ldots, L_{virt}$, m as a vector of transmission mode ($m_i = 1$ is cellular mode and $m_i = 0$ is D2D clustering mode), a_{c_ul} as an activity of devices in cellular communication and transmitting on uplink ($a_{c\_ul,i} = 1$ if device i is transmitting in cellular communication mode either locally or not locally communicating, otherwise 0), $a_{c\_dl,i}$ as an activity vector of devices in cellular communication mode and receiving on downlink ($a_{c\_dl,i} = 1$ if device i is receiving in cellular communication mode either locally or not locally, otherwise 0), a_{d2d} as an activity vector of devices in D2D clustering communication mode ($a_{d2d,i} = 1$ if device i is transmitting in D2D clustering mode locally communicating, otherwise 0). As we have two devices in a cluster, a transmitter and receiver, and in cellular communication mode the transmitter device of a cluster is transmitting on uplink and the receiver device of the cluster is receiving on downlink, $a_{c\_ul,i} = 0$ when $\mathrm{mod}\left(i,2\right) = 0$ and $i < \left(2cl_{num} + 1\right)$ and otherwise $a_{c\_ul,i} = 1$, and $a_{c\_dl,i} = 0$ when $\mathrm{mod}(i,2) = 1$ and $i < \left(2cl_{num}\right)$ and otherwise $a_{c\_dl,i} = 1$. Correspondingly $a_{d2d,i} = 0$ when $\mathrm{mod}\left(i,2\right) = 0$ and otherwise $a_{d2d,i} = 1$. In addition we define β_{c_ul} and β_{c_dl} as target signal-to-interference ratio (SINR) for cellular communication mode on uplink and downlink, respectively, β_{d2d} as target SINR for D2D cluster communication mode on uplink, G_{c_ul}, G_{c_dl} and G_{d2d} as processing gains for cellular communication mode on uplink, downlink and D2D clustering communication on uplink, respectively, $\alpha_{i,b(j)}$ as the link gain [1] between a device i and serving BS $b\left(j\right)$ of device j on uplink, $\varphi_{b(j),i}$ as the link gain between a serving BS of device j and device i on downlink, $\gamma_{i,j}$ as the link gain between device i and device j, N_b as noise power over the bandwidth at the BS receiver including both thermal noise and receiver's noise figure, N_u as noise power over the bandwidth at the receiver of the device, and b as a BS assignment vector devices, i.e. $b\left(i\right)$ indicates

[1]A link gain comprises a shadowed path loss attenuation, and transmitter and receiver antenna gains

the serving BS of device i.

Following [9] we can derive a transmission power of device i on uplink as follows:

$$\begin{aligned} P_{UL,i} &= a_{c\_ul,i} m_i \\ &\cdot \begin{pmatrix} \sum_{\substack{j=1 \\ j \neq i}}^{L_{virt}} a_{c\_ul,j} m_j \frac{\beta_c \alpha_{j,b(i)}}{G_c \alpha_{i,b(i)}} P_{UL,j} \\ + \sum_{\substack{j=1 \\ j \neq i}}^{L_{virt}} (1 - m_j) a_{d2d,j} \frac{\beta_c \alpha_{j,b(i)}}{G_c \alpha_{i,b(i)}} P_{UL,j} \\ + \frac{\beta_c}{G_c \alpha_{i,b(i)}} N_b \end{pmatrix} \\ &+ (1 - m_i) a_{d2d,j} \\ &\cdot \begin{pmatrix} \sum_{\substack{j=1 \\ j \neq i}}^{L_{virt}} a_{c\_ul,j} m_j \frac{\beta_d \gamma_{j,i+1}}{G_d \gamma_{i,i+1}} P_{UL,j} \\ + \sum_{\substack{j=1 \\ j \neq i}}^{L_{virt}} (1 - m_j) a_{d2d,j} \frac{\beta_d \gamma_{j,i+1}}{G_d \gamma_{i,i+1}} P_{UL,j} \\ + \frac{\beta_d}{G_d \gamma_{i,i+1}} N_u \end{pmatrix} \end{aligned} \tag{1}$$

and a transmission power of BS for device i on downlink [2] as follows :

$$P_{DL,i} = a_{c\_dl,i} m_i \begin{pmatrix} \sum_{\substack{j=1 \\ j \neq i}}^{L_{virt}} a_{c\_dl,j} m_j \frac{\beta_{c\_dl} \varphi_{b(j),i}}{G_{c\_dl} \varphi_{b(i),i}} P_{DL,j} \\ + \frac{\beta_{c\_dl}}{G_{c\_dl} \varphi_{b(i),i}} N_u \end{pmatrix} \tag{2}$$

If we define diagonal matrices, of size $L_{virt} \times L_{virt}$, $A_{c,ul}$ with diagonal elements of vector a_{c_ul}, $A_{c,dl}$ with diagonal elements of vector a_{c_dl}, A_{d2d} with diagonal elements of vector a_{d2d}, M with diagonal elements of vector m, C with diagonal elements $C_{ii} = \beta_{c\_ul} / \left(G_{c\_ul} \alpha_{i,b(j)} \right)$, D with diagonal elements $D_{ii} = \beta_{d2d} / \left(G_{d2d} \gamma_{i,i+1} \right)$ when i is odd, otherwise $D_{ii} = 0$, and J with diagonal elements $J_{ii} = \beta_{c\_dl} / \left(G_{c\_dl} \varphi_{b(j),i} \right)$. Further, if we define matrices, of size $L_{virt} \times L_{virt}$, Φ with elements

$$\Phi_{ij} = \begin{cases} 0 & i = j \\ \beta_c \alpha_{j,b(i)} / G_c \alpha_{i,b(i)} & i \neq j \end{cases} \tag{3}$$

Θ with elements

$$\Theta_{ij} = \begin{cases} 0 & i = j \\ \beta_d \gamma_{j,i+1} / G_d \gamma_{i,i+1} & i \neq j, i \text{ is odd} \\ 0 & i \neq j, i \text{ is even} \end{cases} \tag{4}$$

and Ξ with elements

$$\Xi_{ij} = \begin{cases} 0 & i = j \\ \beta_{c\_dl} \varphi_{b(j),i} / G_c \varphi_{b(i),i} & i \neq j \end{cases} \tag{5}$$

In addition, we define vectors, of size $L_{virt} \times 1$, $N_B = \begin{bmatrix} N_b & N_b & \cdots & N_b \end{bmatrix}^T$ of size $L_{virt} \times 1$ and $N_U = \begin{bmatrix} N_u & N_u & \cdots & N_u \end{bmatrix}^T$.

[2]Uplink and downlink are modeled in similar fashion to simplify analysis, i.e. devices both on uplink and downlink are separated by non-orthogonal codes.

Next we can formulate the system equations for the power vector of all devices in the system as a function of mode selection in uplink direction as follows:

$$\begin{aligned} P_{UL} = &\begin{pmatrix} A_{c,ul} M \\ \cdot \left(\Phi M A_{c,ul} + \Phi A_{d2d} - \Phi M A_{d2d} \right) \\ + A_{d2d} (I - M) \\ \cdot \left(\Theta M A_{c,ul} + \Theta A_{d2d} - \Theta M A_{d2d} \right) \end{pmatrix} P_{UL} \\ &+ A_{c,ul} M C N_B + A_{d2d} (I - M) D N_U \end{aligned} \tag{6}$$

and in downlink direction as follows:

$$P_{DL} = A_{c,dl} M \Xi P_{DL} + A_{c,dl} J M N_U \tag{7}$$

Both (6) and (7) can be simplified to have the following equations, respectively, as follows:

$$P_{UL} = \Im_{UL} P_{UL} + \aleph_{UL} \tag{8}$$

and

$$P_{DL} = \Im_{DL} P_{DL} + \aleph_{DL} \tag{9}$$

The following applies for both P_{UL} and P_{DL} and thus subscript has been omitted from P. The set of feasible power vectors under mode selection m is

$$P = \{ P \geq 0 \, | P \geq \Im P + \aleph \} \tag{10}$$

The set P describes a cone of feasible powers in that if $p \in P$ then $\alpha p \in P$ for all $\alpha \geq 1$. Each cone P is specified by an interference matrix $\Im$ and noise vector $\aleph$. The non-negative noise vector $\aleph$ displaces these cones from the origin [10]. Since $\Im$, in both uplink and downlink case, is non-negative, Perron-Frobenius theory guarantees the existence of a dominant, positive eigenvalue r [11]. Equation (11) has a positive solution if and only if $r < 1$. This is referred later as eigenvalue criteria. If $r < 1$ then there is a unique solution P individually done for uplink and downlink given by

$$P = (I - \Im)^{-1} \aleph \tag{11}$$

C. Utilization of system equations

Using (11) for both uplink and downlink we can find the optimal mode selection vector m for example via minimizing the first norm of power vector of devices conditioned that eigenvalue criteria is fulfilled for both uplink and downlink system equations (8) and (9), respectively, as follows

$$\arg \min_{M} \|P\|_1 \tag{12}$$

subject to

$$\begin{aligned} &P = (I - \Im)^{-1} \aleph \\ &p_i = 0 : a_{d2d,i} = 0 \text{ OR } a_{c\_ul,i} = 0 \\ &p_i > 0 : m_i = 0, a_{d2d,i} = 1 \text{ OR } m_i = 1, a_{c\_ul,i} = 1 \end{aligned}$$

Further one can find a probability for fulfilling the eigenvalue criteria both in uplink and downlink, or individually either in uplink or downlink. This probability is considered here as a system outage. Then we can analyse system capacities as a function of system outage when D2D clustering is allowed using an optimal mode selection and compare those results to the pure cellular mode system and practical mode selection algorithms.

III. Simulations (Numerical Analysis)

System level simulations are carried out by utilizing the system equations described in section II. The results are then analysed to find out whether D2D clustering can improve the capacity of a CDMA type cellular network in file sharing scenario.

A. Simulation Setup and User Distribution

In the beginning of each simulation drop the number of locally communicating users (N_{local}) is obtained by multiplying the total number of users in the system (N_{tot}) with direct communication probability (p_{local}). Every locally communicating user is assumed to be part of a fixed size cluster thus number of clusters is determined by (N_{local}) divided by number of devices in the cluster (N_c). Users are distributed to the system in the following way; one device in the cluster is selected as a CH (acting also as a file sharer) and rest of the cluster members are placed randomly within the cluster radius (R_c) of the CH. The CH is acting as a file sharer while rest of the members are receiving. If a device is not communicating locally (with probability of 1-p_{local}) it is placed to random location within the range of the base station and is assigned to normal cellular mode.

From the resource utilization point of view it is assumed that cluster multicast transmission occupies one UL resource regardless of the number of devices participating in file sharing session. If the file sharing service is carried out with cellular multicast the total resource utilization is one UL resource and one DL resource.

B. Clustering Mode Selection

In D2D cluster mode the file is directly transmitted to cluster members with multicast transmission. The required service (data rate) determines the SINR target for the transmission and the required transmission power is therefor determined by weakest D2D link between the file sharer and receiving cluster members. In cellular mode the packets are first transmitted to base station by the file sharer and packets are then multicasted to the group on DL. Actual data flows, retransmissions, or feedback is not modelled in these simulations. The same service (on UL and DL) is assumed for all the devices regardless of the communication mode. Only one hop communication is considered in the cluster.

In the simulations four different mode selection criteria are evaluated:

CELLULAR: All devices are in cellular mode (CH multicasts via base station)

OPT D2D: Mode selection vector for all devices is searched in order to fulfil eigenvalue criteria

PL D2D: D2D cluster mode is selected if path loss between source device and its serving BS is greater than any of the path losses between a source device and a destination device within a cluster

FORCE D2D: D2D cluster mode is selected always for all the clusters

TABLE I
Simulation Parameters

Parameter	Value
Cellular layout	Isolated cell, 1-sector
System area	User devices are distributed within a range of 500 m from the BS
Shadow Map Resolution	1m
Path loss model for cellular link	128.1 + 37.6log10(d [km]) [12]
Path loss model for D2D link	148+40log10(d [km]) [12]
Shadow fading standard deviation	10 dB for cellular mode links and 12 dB for D2D mode links [12]
Noise spectral density	-174 dBm/Hz
System bandwidth	5 MHz
Noise figure	5 dB at BS / 9 dB at device
Minimum coupling loss	70 dB BS-Device / 40 dB Device-Device
Antenna gains and patterns (transmitter and receiver)	BS: 14 dBi Device: Omnidirectional 0 dBi
Cluster Radius R_c	5m, 25m
Cluster Size	3 (1 Cluster Head, 2 members)
Processing gain	Cellular 60, D2D: 60
Data Rate	128kbps both UL/DL
Probability of local communication per device	0.2, 0.4

C. Simulation parameters

Simulation parameters are listed in Table I. Simulations are carried out in single cell system. Different path loss model and shadowing values are used for cellular to device and device to device links. Mobility is not considered in the simulations.

D. Results and analysis

Results are presented in the bar diagram form. In the figures, system capacity results are plotted for each mode selection criteria and are further arranged into two groups based on the local communication probability. System capacity is defined as total amount of users (both active and non-active, where non-active users are the recipients in file sharing session) the system can support with certain outage percent. Analysis is divided to two parts, for two different cluster radius values.

Fig. 2 presents the system capacity at 5% outage with cluster radius of 5m. When p_{local} is 0.2 the FORCE, OPT and PL give the exact same capacity as OPT criterion. CEL mode falls slightly behind the three previously mentioned criteria. Results indicate that all the clusters operate in D2D mode which is also beneficial for the system capacity point of view since transmitting devices use less power and thus cause less interference than in multicast transmission in cellular mode. With p_{local} 0.4 the number of clusters is increased and system capacity is further enhanced with all the selection methods (PL and FORCE are same as OPT) but the difference to the CEL method increases due the DL limitation.

For next, the system capacity results are analysed for 25m cluster radius. UL and DL are first considered separately and then combined to present the real capacity of the system. With 5m radius the PL and FORCE modes gave exactly the same performance as optimum one, leaving the CEL mode behind in capacity. However, with 25m the results differ greatly. On the uplink Fig. 3 PL and FORCE mode selections fall clearly behind CEL and OPT. UL Results indicate that as the cluster radius increases the CEL mode gives better performance but it is still lower than OPT.

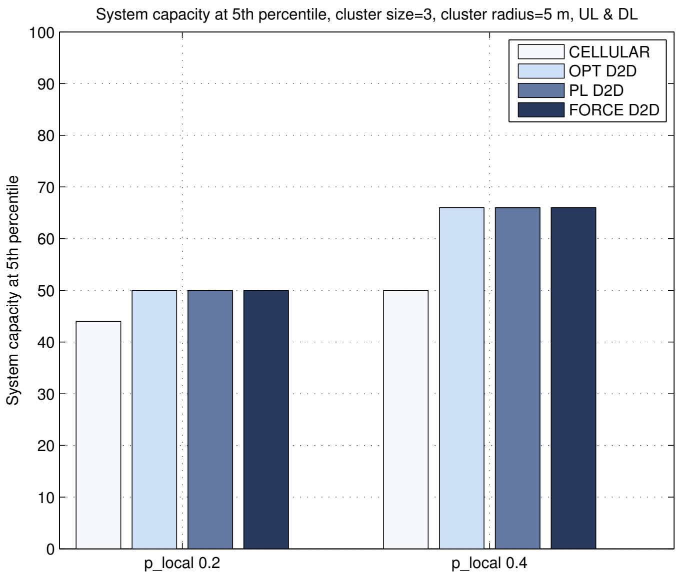

Fig. 2. System capacity at 5 percent outage with cluster radius of 5m.

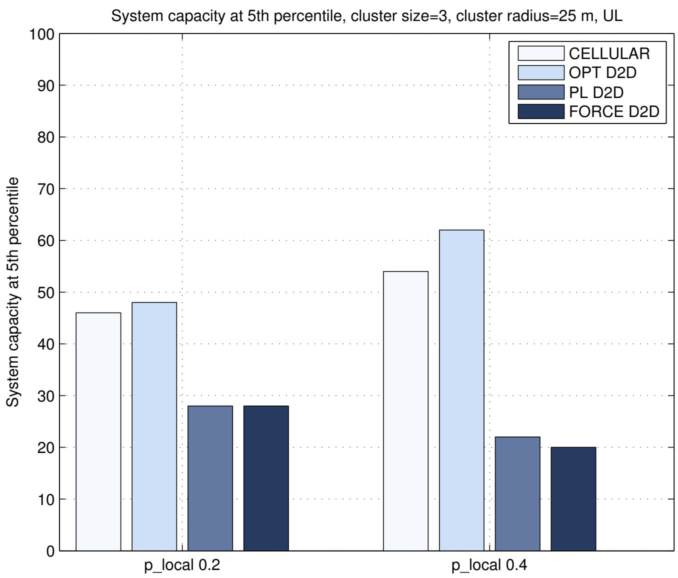

Fig. 3. System capacity at 5 percent outage with cluster radius of 25m (UL).

When looking at Fig. 4 (amount of realized D2D clusters with different p_{local} and number of users in the cell) an interesting observation can be made; the difference in system capacity between OPT and FORCE is large with p_{local} 0.4 but difference in the number of clusters in D2D mode is only two on average.

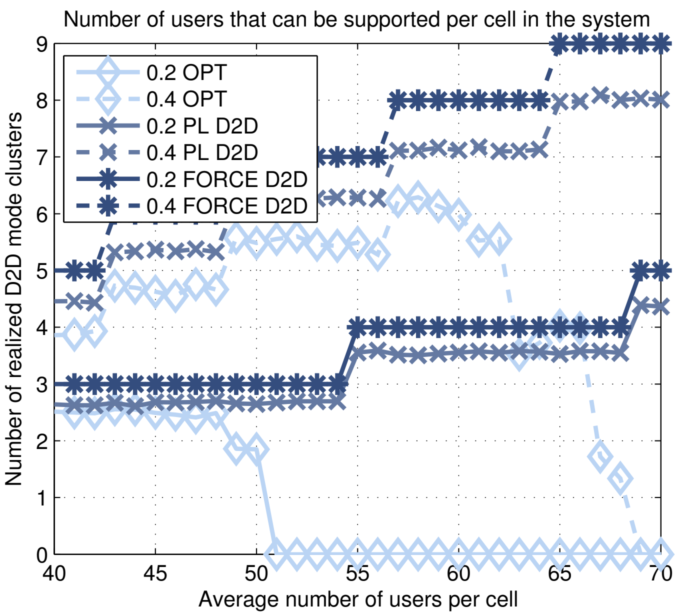

Fig. 4. Number of clusters in D2D mode with different mode selection schemes (Cluster Radius 25m, overall capacity).

Also, on the average, the PL mode has one more cluster compared to OPT but one less compared to FORCE at ~ 60 user capacity mark which indicates that having a small difference in the number of realised D2D clusters affects greatly to the system performance on UL. Having all clusters in CEL mode is giving good system capacity in UL but falling behind OPT indicates that with the help of direct communication, the UL capacity can be enhanced.

The UL results indicated that having all the clusters in direct communication mode is not very beneficial for the system with relatively large cluster radius. To get to the bottom of this lets look also the DL results at 5% outage Fig. 5. Its obvious that when looking at DL the FORCE gives the same capacity as OPT in since the traffic is offloaded from DL to UL with direct communication. PL based mode selection assigns less clusters to D2D mode than FORCE which reduces the DL capacity.

The most interesting observation is what happens to the system capacity with CEL mode when DL is considered. On the UL it seemed that CEL can be close to OPT but now looking at DL the CEL falls notably behind (with p_{local} 0.2 it has the same capacity as PL and FORCE in UL). Although the UL capacity benefits from CEL mode with large cluster radius the DL starts to limit the system capacity. Fig. 6 presents the combined the UL and DL results at 5% outage [3]. Different mode selection schemes fall clearly behind OPT which then indicates that assigning devices always to CEL, using PL

[3]In separate results, only the link direction of interest is considered and outage in other direction is ignored. In combined results both link directions are considered at the same time thus they give better understanding of the system capacity.

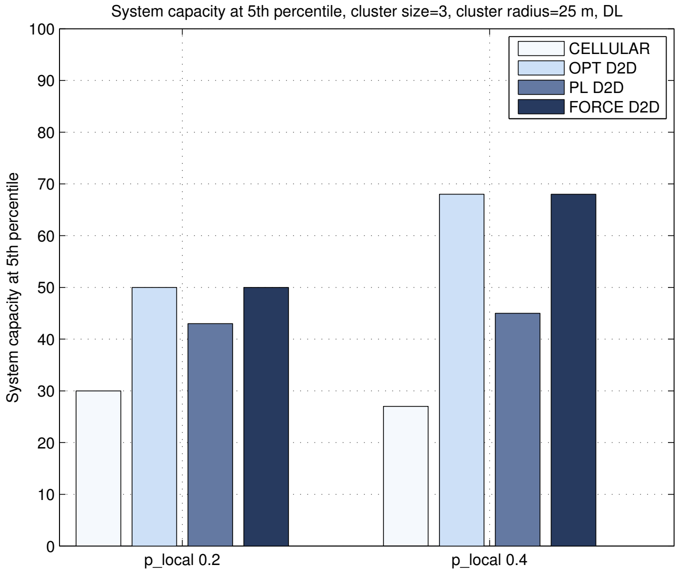

Fig. 5. System capacity at 5 percent outage with cluster radius of 25m (DL).

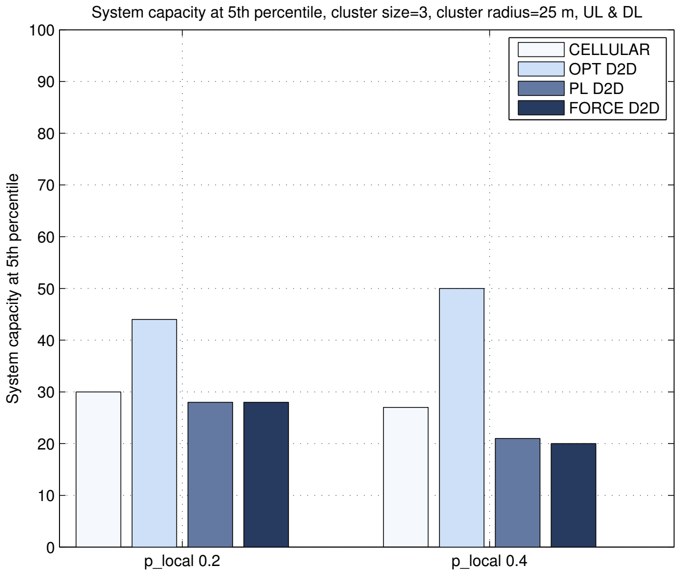

Fig. 6. System capacity at 5 percent outage with cluster radius of 25m (DL and UL).

metric or forcing the D2D connection are not good mode selection schemes in the interference limited systems when the cluster radius is relatively large.

IV. Conclusions

In this paper we gave the overview of D2D clustering concept in an FDD system and evaluated different mode selection schemes against optimal one in an interference limited system. The results indicated that it is possible to improve system capacity with direct communication. Considering the mode selection procedure the results indicated that with small separation of cluster members the D2D operation mode can be selected for the cluster by default and reach the optimum system performance. When the separation is relatively large the cluster members are subject to increased interference from other users in the system and the gain from the short path loss compared to cellular mode is diminished. In the future work to be able to reach the optimum system performance, more intelligent mode selection algorithm should be developed to close the gap to the optimum in system capacity.

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