

Czech Technical University in Prague
Faculty of Electrical Engineering

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MASTER'S THESIS

Efficient Radio Resource Allocation for Device-to-Device Communication

Study program: Electronics and Communications

Branch of study: Communication System and Network

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I hereby declare that I have developed and written the enclosed Master's Thesis titled: *Efficiency Radio Resource Allocation for Device-to-Device Communication* completely by myself and have not used sources or means without declaration in the text. Any thoughts from others or literal quotations are clearly marked and list of references is enclosed.

In Prague

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II. Master's thesis details

Master's thesis title in English:

Efficient radio resource allocation for Device-to-Device communication

Master's thesis title in Czech:

Efektivní přidělování rádiových prostředků pro Device-to-Device (D2D) komunikaci

Guidelines:

The thesis is focused on radio resource allocation for Device-to-Device communication (D2D) underlying cellular communication. The main objective of the thesis is to propose a method/algorithm for allocation of radio resources to D2D users. The method/algorithm itself will select for each D2D user whether downlink or uplink frequency band should be utilized in order to minimize interference between cellular and D2D users and, thus, to maximize overall system capacity. The efficiency of the proposed method, for example, in terms of overall system capacity or spectral efficiency, will be validated and compared with existing scheme(s) using MATLAB simulation tool.

Bibliography / sources:

[1] Mach, P.; Bečvář, Z.; Vaněk, T.: In-Band Device-to-Device Communication in OFDMA Cellular Networks: A Survey and Challenges. IEEE Communications Surveys & Tutorials, vol. 17, no. 4, pp. 1-38, 2015.

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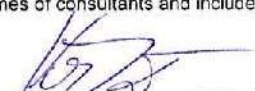

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Abstract

Device-to-Device communication in the cellular networks allows direct transmission between devices in each other's proximity that reuse the cellular spectrum intended for conventional cellular users to increase the network capacity and spectrum efficiency.

The use of Device-to-Device communication leads to certain challenges such as interference of Device-to-Device users with the conventional users. The resource management, network mode selection and power allocation technique in a cellular network with Device-to-Device can improve performance of the system in terms of throughput. To this end, this thesis proposes a technique maximizing the total throughput of cellular users in wireless networks under given quality-of-service and interference constraints. These conditions lead to the complexity that increases with the number of users and Device-to-Device pairs. The proposed methods of spectrum allocation give the close-to-optimal solution with reasonable time computation complexity.

Keywords: Spectral efficiency, Device-to-Device, channel allocation

Abstrakt

Využití Device-to-Device komunikace v bezdrátových sítích umožňuje přímou komunikaci mezi dvěma zařízeními, které se nachází v blízkosti sebe a využívají spektrum určené primárně pro běžné mobilní uživatele k navýšení kapacity sítě a k lepšímu využití spektra.

Použití Device-to-Device komunikace v mobilní síti vede k určitým výzvám jako je například rušení běžných mobilních uživatelů s uživateli využívající komunikaci Device-to-Device. Správné využívání radiových zdrojů, výběr dostupných modů pro Device-to-Device komunikaci a alokování výkonu pro Device-to-Device zařízení v síti vede ke zvýšení celkové propustnosti systému. Navrhované metody maximalizují celkovou propustnost sítě pro běžné mobilní uživatele za garantovaných služeb a omezení rušení od Device-to-Device uživatelů. Tyto podmínky vedou ke zvyšující se komplexitě výpočtu s rostoucím počtem uživatelů. Navrhované metody alokování spektra jsou blízké k optimálním při užití přiměřené výpočetní komplexity.

Klíčová slova: alokování kanálů, Device-to-Device komunikace, spektrální účinnost

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List of Acronyms

Acronym	Meaning
BTS	Base Transceiver Station
CM	Cellular Mode
CR	Cognitive Radio
CUE	Cellular User Equipment
DL	Downlink
DM	Dedicated Mode
DUE	Device-to-Device user equipment
D2D	Device-to-Device
eNB	evolved Node B
FDD	Frequency Domain Duplex
MaxiM	Maximum in Matrix
PL	Path Loss
QoS	Quality of Service
RSS	Received Signal Strength
SINR	Signal to Noise and Interference Ratio
SM	Shared Mode
TDD	Time Domain Duplex
UL	Uplink

1 Introduction

The increasing number of users, their requests and demands in wireless network is what leads us to increase network capacity and spectrum efficiency. In order to meet the user's requirements several approaches can be used. One of them is to reuse the existing spectrum in the network. First of the option how to do it is a deployment of the new cells or densification of the existing ones. This method is highly ineffective considering that whole new site must be built. Other option how to fulfill the requirements is to deploy small cells underlying the conventional cellular network. This method is commonly used inside building where is no signal from macro cell. To connect small cells to the network and meet the requirements for nowadays LTE network, high speed internet connection needs to be in the location, which is a problem in the rural areas. Another option is to use a Cognitive Radio (CR) approach and spectrum sharing [2] or direct communication between devices known as Device-to-Device (D2D) communication without using base transceiver station (BTS) or any other component of the core network. While the CR is fully autonomous system exploiting cognitive sensing, D2D communication could be managed by the network. As a result, CR may not be able to guarantee Quality of Service (QoS) to primary users. Thus, this thesis focuses on enhancement of system capacity by means of D2D communication.

In D2D communication two kinds of users can be distinguished: the primary users (conventional users of network) and secondary users which can access the spectrum through reuse of the radio resources by means of D2D communication. Primary user is called in this thesis as cellular user and secondary user is called D2D user.

The spectrum that can be used for D2D communication can be in licensed spectrum of the mobile operators. This type is called in-band D2D communication. If D2D communication is allocated in unlicensed spectrum we can talk about out-band D2D communication. For out-band D2D communication are used highly frequencies where other wireless technologies can communicate like Bluetooth or Wi-Fi direct.

The thesis is structured as follows. The second chapter gives basic introduction to allocation of resources to D2D communication and discusses related work in this area. In addition, the thesis of contribution is summarized. The next section gives the simulation parameters and how the capacity is calculated for purposes of this thesis. Fourth part is dedicated to used algorithms for channel allocation. In this part the proposed method of allocation can be found. In chapter five are simulation results as

the comparison of existing methods and proposed method. In last part is conclusion and possible future work.

2 Classification of D2D communication

In this chapter of the thesis is how the D2D user can access the network. Which frequencies can be allocated to D2D communication. Also, the main difference between the approach to these questions of existing works and this thesis.

2.1 Allocation of radio resource to D2D communication

From the point of reuse the radio resources in cellular network can D2D users access the resources either in time domain duplex (TDD) or frequency domain duplex (FDD) duplexing mode. Channels for D2D communication can be allocated in downlink (DL), uplink (UL) or both simultaneously. Nowadays the most common approach is to use the UL resources [3],[4]. The biggest advantage of selecting UL instead of DL is that the UL resources is not so used as the DL resources because most of the cellular users are downloading data from the network instead of uploading them to the servers. In addition, the interference situation in the UL is much easier to resolve with respect to cellular transmission because the victim of D2D interference is solely the evolved Node B (eNB).

Cellular mode (CM) – this mode corresponds to conventional cellular communication because Device-to-Device user equipment (DUE) communicate through the eNB and no direct communication is involved between DUEs. This mode is used when DUEs are too far from each other (more than 500 meters [5]) or simply if communication would not pay off. The biggest advantage of using cellular mode is that radio resources are managed by eNB and no other equipment or software are implemented in network. Due to use of spectrum primary intended for cellular users this method has low spectral efficiency.

Dedicated mode (DM) – this allocation mode is also known as an orthogonal mode or an overlay mode. Compare to CM in this mode DUEs can transmit data directly between each other without eNB retransmitting data between DUEs. But cooperation between DUEs and eNB must be established because eNB dedicate the radio resources to D2D communication. The advantages of DM are that DUEs do not interfere with Cellular User Equipment (CUE) as in communication in CM but with higher spectral efficiency than CM because the communication between DUEs is strictly in DL or in UL in one period of time.

Shared mode (SM) – in SM, also known as a non-orthogonal or an underlay mode, are used for D2D communication the same radio resources as for the primary

communication between CUEs. Same as in DM for communication between DUEs can be used the radio resources either from DL or from UL or both as shown in Figure 2.1. This method of allocation has higher spectral efficiency because the same resources can be used for communication between CUEs and for communication between DUEs. Radio resources are shared between these two modes of communication. The biggest disadvantage is that the communication between DUEs interfere with primary communication between CUEs. For minimizing the interference new methods and techniques must be implemented into network. As a result, the complexity of whole system is increasing with increasing number of cellular users or D2D pairs.



Figure 2.1: a) Cellular mode, b) Dedicated mode (uplink), c) Dedicated mode (downlink), d) Shared mode

2.2 Related work

Most of the work has been proposed on mode selection and power control on static system model, in literature can be found selection schemes based on minimum distance of D2D transmitter and D2D receiver [6], biased D2D link quality and the quality of the cellular uplink [7] or guard zones protecting D2D users [8]. All these works considering primarily the overall throughput of D2D users.

Once the mode selection has been done power control and channel allocation methods are used to manage transmit power and the interference. In [9] power optimization for one D2D transmitter and one cellular user was studied in uplink spectrum. Power allocation for maximizing sum rate of overall system was also studied in [10]. This work is focused on binary power decision. The transmitters have two states, power operates on maximum or minimum to guarantee the SINR for any user. This work also showed that the binary power control is optimal for two users but not for more users in system.

2.3 Thesis contribution

The biggest benefit of this thesis is that most of the work [11]-[13] considering overall capacity of the system, both conventional communication and D2D communication combined. This thesis maximizes the overall capacity of cellular users.

To have guaranteed the QoS for cellular users use of power control is necessary. Instead of defined the transmitting power given by equation like in [14], where big signaling overhead is used this thesis proposed use of power control function where the transmitted power of D2D transmitter is determined using the recursive algorithm. In terms of reuse the spectrum exists in the literature works which either use UL [9], [15], [16] or DL [17], [18], but only few which consider both like [19], [20]. The reuse of both has highest spectral efficiency that's why it is used in this thesis. In this thesis the CUEs are considered as moving mobile station which change activity over the time. No other paper listed in this chapter use the mobility model with changing the activity of cellular users.

3 System model

To compute overall capacity of the system, parameters for the simulation itself need to be define in the first place. In this thesis, the model considering square area with size of 400 m. There is only one BTS situated in the middle of the area. For purposes of the simulation, positions of the CUEs and the DUEs are randomly generated. System model can be seen in Figure 3.1.

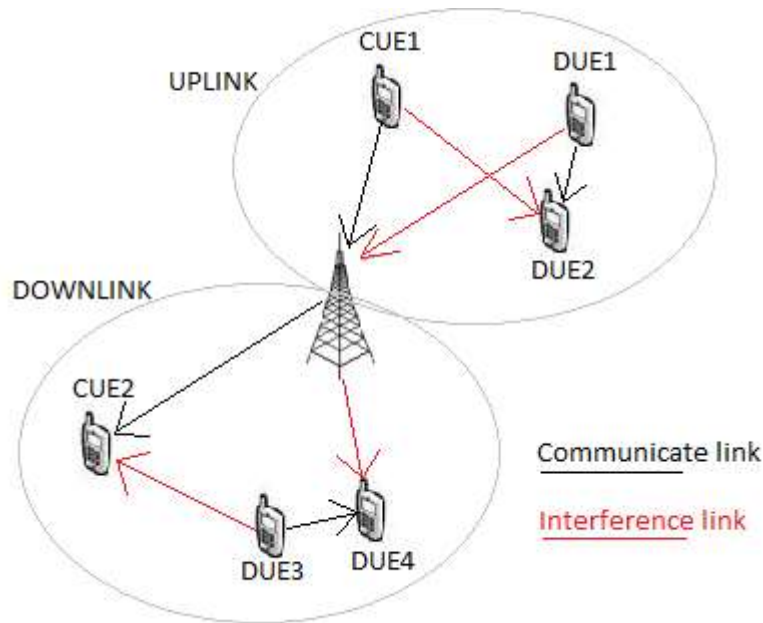


Figure 3.1: System model

In each simulation second all CUEs change the position based on the random waypoint mobility model [21]. This model is commonly used in mobile network and specifies the mobility pattern of each mobile user, change its velocity and acceleration over time. The movement of the CUEs is governed in the following manner. Each node begins by pausing for a fixed number of seconds (in the thesis this time is defined as 0 second). The CUE then selects a random destination in the simulation area and a random speed (see Tab. 3-1). The CUE moves to this destination and again pauses for a fixed period (1 second in this thesis) before it moves to another random location with define speed. Furthermore, the number of active CUEs during the simulation is changing over time. More specifically, the number of active CUEs is distributed normally according to Gaussian distribution. The probability of how many active cellular users are active in each second of the simulation is shown in figure below (see Fig. 3.2). This behavior is repeated for the whole length of the simulation which is one minute. Notice that unlike the CUEs, the DUEs do not change the position and the

activity over the time. Consequently, all D2D pairs are assumed to active for the duration of the whole simulation.

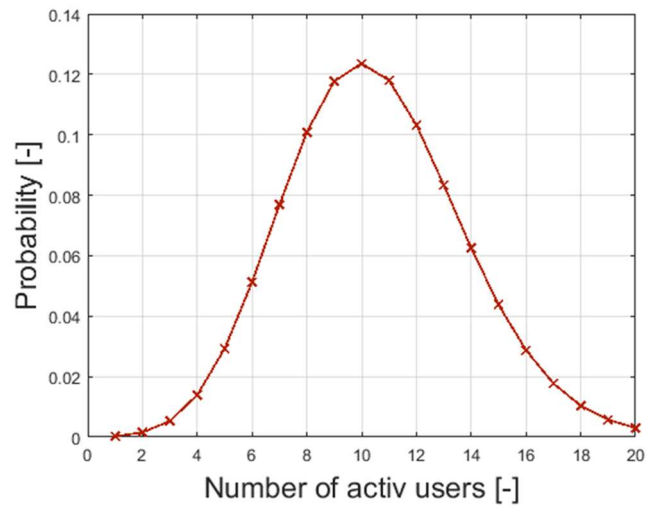


Figure 3.2: Distribution of number of active users

In the simulation area, 20 CUEs and 20 D2D pairs are randomly generated. Each D2D pair is composed of transmitting and receiving DUE. The first DUE in each pair is generated randomly in simulation area. In this thesis the first DUE in D2D pair is supposed to be a transmitting data to the second DUE in pair. The second DUE in each pair is then generated with a restriction. To be more specific, the position of the receiving DUE cannot be further than 50 m from the transmitting DUE (i.e., the maximum distance between transmitting and receiving D2D pair is set to 50 m). Used parameters for the simulation are in Table 3-1.

Length of the simulation	60 s
Number of DUEs	40
Average number of CUEs	20
Number of BTS	1
Area size	400 m
Capacity loss α	5 %
Minimum speed of CUE	0,2 ms ⁻¹
Maximum speed of CUE	10 ms ⁻¹
Maximum distance between DUEs in pair	50 m
Transmission power of an eNB	43 dBm
Transmission power of mobile station	20 dBm
System bandwidth	20 MHz
Frequency	2 GHz
Standard deviation of fading	6 dB

Table 3-1: Simulation parameters

For each simulated second in the scenario is computed a distance, the path loss (PL), the received signal strength (RSS), signal to noise and interference ratio (SINR) and capacity. In order to calculate path loss between the nodes given below:

- CUE and BTS in the center of the simulation area,
- DUE and BTS in the center of the simulation area,
- DUEs in all D2D pairs,
- all CUEs and DUEs.

The following equation for PL is used [22]:

$$PL = 35,2 + 35 * \log_{10}(d) + 26 * \log_{10}\left(\frac{f}{2}\right) + \text{randn}(\sigma) \quad [\text{dB}], \quad (3.1)$$

where d is a distance between positions in meters, f is a frequency in GHz, σ stands for a standard deviation caused by various obstacles between nodes positions. Slow fading is derived from the Gaussian distribution.

For the simulation frequency 2 GHz and standard deviation of fading 6 dB has been chosen.

After PL is calculated according to 3.1, RSS is computed as:

$$RSS = P_t - PL \quad [\text{dBm}], \quad (3.2)$$

where P_t is transmission power of the signal and PL represents path loss from (3.1).

The transmission power of the BTS is set to 43 dBm while transmission power of each CUE is for the purposes of the simulation 20 dBm (these are common values used for transmission power of both the BTS and mobile stations). For DUEs the maximal transmission power is set similarly as for the CUEs to 20 dBm and subsequently adjusted according to power control function in chapter 4.1.4, to meet the requirements for capacity loss of CUEs (equation 3.5).

SINR is computed according to

$$SINR = RSS - NI \quad [\text{dB}], \quad (3.3)$$

where NI is sum of white noise and interference in dBm.

The system capacity is computed according to Shannon theorem for maximum theoretical capacity of channel [23]

$$C = BW * \log_2(1 + SINR) \quad [\text{bps}], \quad (3.4)$$

where **BW** is bandwidth in Hz.

For the simulation purposes, the whole bandwidth is divided equally between the CUEs. Then each channel can be accessed by one D2D pair as well. Note that in the simulation the BTS has at its disposal channel bandwidth of 20 MHz.

From capacity matrix NxM (see Tab. 3-2), where N is twice the number of active CUEs and M is the number of D2D pairs. First half of N are channels in DL for n cellular users and the second half are channels in UL for n cellular users. If the j-th D2D pair is selected to share the channel with i-th CUE than CUEs capacity is in matrix as C_{ij} .

In first part of this thesis (Scenario A) was fixed the maximum capacity loss α , which is the percentage difference between capacity of the CUE without any interference from DUE ($C_{without}$) and capacity of the CUE with interference from DUE (C_{with}). Capacity loss can be obtained from equation 3.5.

$$\alpha = 100 - \left(\frac{C_{with}}{C_{without}} * 100 \right) \quad [\%], \quad (3.5)$$

After the use of power control function (chapter 4.1.4) to transmit power of DUEs, capacity for all the CUEs is computed with maximum capacity loss. These capacities are in Table 3-2.

		D2D 1	D2D 2	.....	D2D M
DL	CUE 1	C_{11}	C_{12}	.....	C_{1M}
	CUE 2	C_{21}	C_{22}	.....	C_{2M}
	⋮	⋮	⋮		⋮
	CUE n	C_{n1}	C_{n2}	.....	C_{nM}
UL	CUE 1	$C_{(n+1)1}$	$C_{(n+1)2}$	.....	$C_{(n+1)M}$
	CUE 2	$C_{(n+2)1}$	$C_{(n+2)2}$	.....	$C_{(n+2)M}$
	⋮	⋮	⋮		⋮
	CUE n	C_{N1}	C_{N2}	.....	C_{NM}

Table 3-2: Capacity matrix

4 Algorithms for resource allocation

In this chapter used methods of channel allocation techniques are described. Hungarian algorithm and method of minimal interference are existing ones and Maximum in Matrix (MaxiM) method is proposed. Also, recursive power control function is described in this chapter.

4.1 Hungarian algorithm (existing method)

Hungarian algorithm, also known as Munkres algorithm, was developed in year 1955 by Harold Kuhn. The reason why it's called Hungarian algorithm is that Kuhns work was based on two Hungarians: Dénes König and Jenő Egerváry.

In 1957 James Munkres observed that Kuhns algorithm is polynomial with time complexity $O(n^4)$. Jack R. Edmonds and Richard M. Karp modified Hungarian algorithm and it this modified algorithm has time complexity $O(n^3)$. In this simulation is used this modified Hungarian algorithm.

The purpose of Hungarian algorithm is to minimize the overall cost from matrix $n \times n$, where value can be chosen only once from each column and each row (one-to-one matching). To set the minimum cost it is recommended to follow strictly the next four steps [24].

First step: row reduction

Find the minimum of each row, after that the minimum of each row is subtract from every value in that row. It means that each row now contains at least one 0 as it can be seen in the example below (see Fig. 4.1).

80	40	50	46	-40		40	0	10	6
40	70	20	25	-20		20	50	0	5
30	10	20	30	-10		20	0	10	20
35	20	25	30	-20		15	0	5	10




Figure 4.1: First step of Hungarian method

Second step: column reduction

After first step of this method repetition of the subtraction must be done but now for each column. That leads to at least one 0 in each column (see Fig. 4.2).

40	0	10	6
20	50	0	5
20	0	10	20
15	0	5	10
-15	0	0	-5

25	0	10	1
5	50	0	0
5	0	10	15
0	0	5	5

Figure 4.2: Second step of Hungarian method

Third step: optimal assignment

In third step it must be found the minimum number of straight lines to cross all the zeros in matrix (see Fig. 4.3). If the number of lines is the same as the number of columns or rows in matrix the minimum cost for the assignment is found. In this example are only three straight lines so it needs to continue with step number four.

25	0	10	1
5	50	0	0
5	0	10	15
0	0	5	5

Figure 4.3: Third step of Hungarian method

Fourth step: shift zeros

In this step it must be shifted at least one zero to an uncovered position in order to increase the minimum number of lines require to cover all zeros. To do that it is find the smallest uncovered value. In this case number 1 in right upper corner. Then it is subtracted this number from each uncovered value and added this number to all the intersection of two lines (see Fig. 4.4). After that it continues back to follow the step number three.

25	0	10	1
5	50	0	0
5	0	10	15
0	0	5	5

1

24	0	9	0
5	51	0	0
4	0	9	14
0	1	5	5

Figure 4.4: Fourth step of Hungarian method

Evaluation of the minimum cost

If there is the same number of lines as the number of columns. It is selected from all the columns and all the rows only one zero. In this case it is selected firstly the zero in fourth and third row, where is only one zero. Then it is chosen from first row, where only last two columns remain and just one has zero - fourth column. The last

step is to choose from second row and third column. The final minimum cost of 111 in this case, as shown below on Figure 4.5.

24	0	9	0
5	51	0	0
4	0	9	14
0	1	5	5

80	40	50	46
40	70	20	25
30	10	20	30
35	20	25	30

Figure 4.5: Evaluation of Hungarian method

Hungarian algorithm applied for the maximization purpose

In this thesis the Hungarian algorithm is used for the maximization of capacity of CUEs. In order to use this method for maximization of capacity, the algorithm itself needs to be modified. To be more specific, before individual above-mentioned steps are used, the capacity matrix is firstly updated in the following way. At the beginning the maximum value in the matrix is found. Then every value in matrix is subtracted from the maximum (see Fig. 4.6). This makes the position of highest value equal to zero and the problem can be solved as for the minimal cost.

80	40	50	46
40	70	20	25
30	10	20	30
35	20	25	30

0	40	30	34
40	10	60	55
50	70	60	50
45	60	55	50

Figure 4.6: Updated cost matrix

If the matrix is not square and $N > M$ than highest possible value from vector of capacities of CUEs without interference is selected (C_n) and the n -th row from capacity matrix is deleted. This step is used repeatedly until the matrix is square.

If the matrix has more column than rows, then rows with zeros are added to form square matrix $M \times M$.

For matrix from example the maximum cost is $80 + 70 + 25 + 30 = 205$.

4.2 Method of minimal interference (existing method)

This method is based on Hungarian algorithm. It minimizes the total cost of the input matrix alpha. It consists of two simple steps. In the first step the matrix alpha is found, where each element of the matrix represents the capacity loss α .

Complexity of this method is the same as the complexity of Hungarian algorithm. In other words, the complexity of method of minimum interference is $O(n^3)$. The basic idea is to spend less time with power control function of DUE transmitting power.

The minimization of the interference is one of the possible ways how to increase the spectral efficiency of the network. This algorithm with respect to capacity of D2D communication can be seen in [25].

First step: generate the matrix alpha

For this method is used matrix alpha \mathbf{D} $N \times M$, where $N/2$ is the number of CUE and M is the number of D2D pairs. Firstly, is compute a vector \mathbf{A} of length N , where each element of this vector is the capacity of n -th CUE without any interference from DUEs in the system. It can be done without interference, because all CUEs are using different channel, so they don't interfere with each other. Second part is to compute matrix of interference \mathbf{B} of size $N \times M$, where each element B_{nm} of the matrix represent the capacity of n -th CUE with interference originated from m -th D2D pair. Third and the last part to generate the matrix alpha \mathbf{D} is to make the capacity loss between the vector \mathbf{A} and the matrix \mathbf{B} . For each element from matrix alpha applies that D_{nm} is the capacity loss between n -th element from vector \mathbf{A} and B_{nm} element from matrix \mathbf{B} .

Second step: minimum cost

For second step is used Hungarian algorithm which minimize the total cost of the matrix alpha. Than the total capacity is sum of all C_{nm} from capacity matrix on the same positions as the chosen ones D_{nm} from matrix alpha.

4.3 Proposed MaxiM method

In this method is chosen the maximum value from square capacity matrix $N \times M$ or maximum value from vector of CUEs capacities without interference if $N > M$. After the selection of maximum, it is needed to erase n -th row and m -th column for square matrix or n -th row in case of second option. That makes the matrix for the second iteration $(N-1) \times (M-1)$, if $N=M$, or $(N-1) \times M$, if $N > M$. And so on until one element of each row of the matrix is selected.

The complexity of this method is $O(n)$.

Pseudocode:

```
for i = 1:N
    while M < N
        capacity of N-th CUE = maximum value of  $C_n$  without interference
        erase row number n
        N = N - 1
    end
    capacity of N-th CUE = maximum value of  $C_{nm}$ 
    erase row number n and column number m
end
```

Matrix interpretation of proposed MaxiM method

80	40	50	46
40	70	20	25
30	10	20	30
35	20	25	30

Figure 4.7: Cost matrix

Find the maximum C_{nm} of the capacity matrix $N \times M$. In this case the maximum value for first iteration is on position $n=1; m=1; C_{nm} = 80$. Erase n-th row and m-th column.

In second iteration the maximum value is on position $n=1; m=1; C_{nm}=70$. Erase n-th row and m-th column.

For third iteration the maximum value is on position $n=1; m=2; C_{nm}=30$. If there are two or more same values in matrix than the method selects the one with higher n respectively higher m if n is the same. Erase n-th row and m-th column.

Fourth iteration the maximum value is on position $n=1; m=1; C_{nm}=20$. Erase n-th row and m-th column.

The whole process of the one-to-one matching with respect to MaxiM method is shown in Figure 4.8.

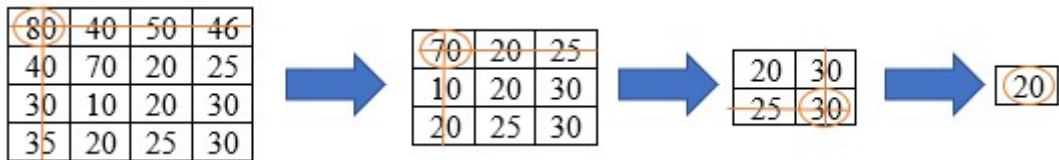


Figure 4.8: MaxiM method

Evaluation of the method $80 + 70 + 20 + 30 = 200$. For comparison same matrix was used for Hungarian method and MaxiM. The highest cost by Hungarian method is 205 for given cost matrix.

4.4 Power control function

The idea of this thesis is to maximize the capacity of each CUE. To do that it has to be control the maximum transmitting power of the D2D pairs which are interfering. For each method of how to choose the maximum capacity of the system, the methods are: Hungarian algorithm, MaxiM method and minimal interference method, the level of interference for each CUE is different. It depends on selected channel that is used by D2D pair.

This function uses the recursive iteration. In each iteration it reduces the transmitting power of D2D pair, started on 20 dB, which was selected for CUE channel. Also, in each iteration it calculates the capacity with interference with reduced transmitting power of D2D pair and the capacity loss α . If the α meets the requirements of maximum capacity loss, the power control function stops. Otherwise it reduces the transmitting power again.

Pseudocode:

```

C_without                                % capacity without interference
while alpha >= requirements
    Ptr = Ptr - step
    C_with (Ptr, RSS, SINR, BW)           % capacity with interference
    alpha = difference (C_without, C_with) [%]
end,
where Ptr is the transmitting power of D2D pair, which interfere.

```


5 Simulation results

In this thesis was simulated two scenarios. For both scenarios was used Hungarian method of channel allocation and MaxiM method of channel allocation. For the scenario B was also used method of minimal interference. For both scenarios was the transmission power of DUEs modified by proposed power control function.

The main problem of the power control function is to find the best value for step reduction in each iteration. If the step is small it takes many iterations to alpha meets the requirements, but the variance of the final alpha and the requirements is minimal (see Fig. 5.1).

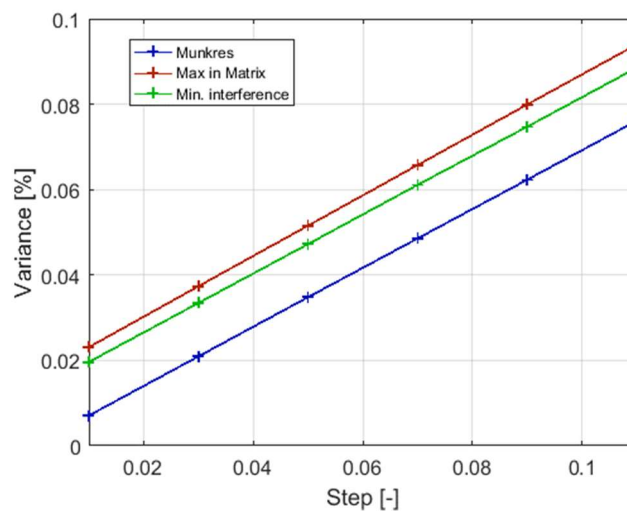


Figure 5.1: Variance of power control function

If the step of the reduction is bigger, the variance of the final capacity loss and the requirements can be up to tenth of percent but the number of iteration is much lower (see Fig. 5.2). For Figures 5.1 and 5.2 the capacity loss α was set to 5 %.

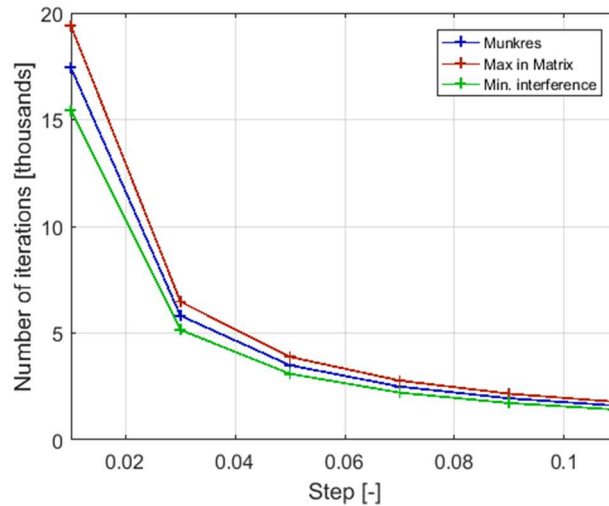


Figure 5.2: Number of iterations in PC function

In the simulation the step of reduction of the power control function was chosen 0,07. This parameter gives us the best compromise between the number of the iterations in power control function and the variance of the capacity loss.

5.1 Scenario A

In scenario A was power control function used for all capacities C_{nm} in capacity matrix (chapter 3). The methods than choose the best channel for D2D with respect to maximize the overall capacity of CUEs.

5.1.1 Capacity over Alpha

Firstly, it was used fixed area size for the simulation. The area size was set to 400 meters and the overall capacity was compute for different capacity loss.

The overall capacities for this scenario are shown in figures below. The overall capacity of CUEs is in Figure 5.3, DUEs is in Figure 5.4 and overall system capacity is shown in Figure 5.5.

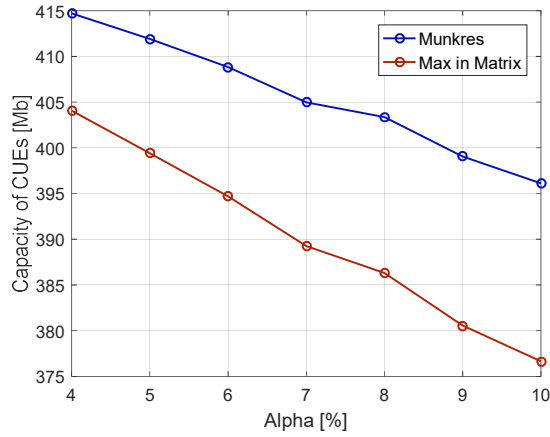


Figure 5.3: CUEs capacity over alpha - Scenario A

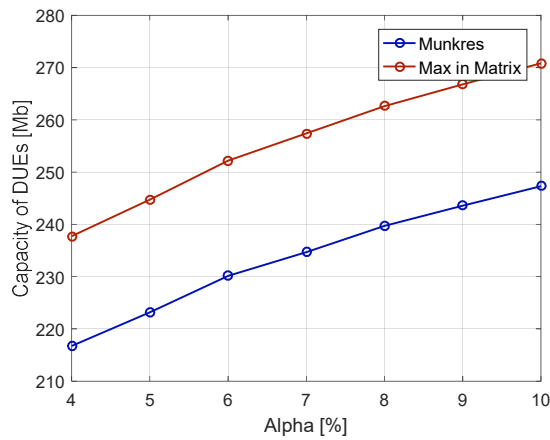


Figure 5.4: DUEs capacity over alpha - Scenario A

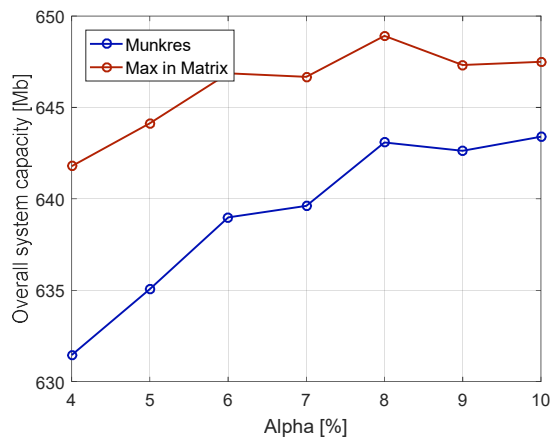


Figure 5.5: System capacity over alpha - Scenario A

The difference between Hungarian algorithm and MaxiM method is in Table 5-1 and was compute from the values shown in figures above. The CUEs capacity difference between Hungarian channel allocation and allocation by MaxiM method is

less than 5% for all simulated values of α . As the effect of MaxiM method channel allocation, the DUEs capacity is higher about 10% for all simulated values of α , also overall system capacity is higher about 1% for MaxiM method than the Hungarian algorithm. The DUEs capacity is higher because the distances between DUEs in D2D pairs is much lower than distances between CUEs and DUEs in Hungarian algorithm.

Table 5-1: Capacity difference over alpha – Scenario A

Capacity difference (Hungarian - MaxiM)							
α [%]	4	5	6	7	8	9	10
CUE [%]	-2,57	-3,03	-3,46	-3,88	-4,23	-4,64	-4,92
DUE [%]	9,68	9,67	9,58	9,70	9,55	9,53	9,53
System [%]	1,64	1,43	1,23	1,10	0,91	0,73	0,64

5.1.2 Capacity over Area

In the second part of the simulation the overall capacity is computed for fixed capacity loss. It was chosen the $\alpha = 5\%$. The overall capacity was compute for different area size.

Capacities are shown in figures below. The CUEs capacity (see Fig. 5.6), the DUEs capacity (see Fig. 5.7) and overall system capacity (see Fig. 5.8).

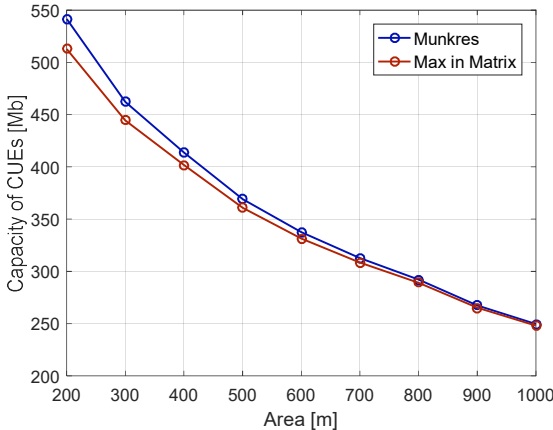


Figure 5.6: CUEs capacity over area - Scenario A

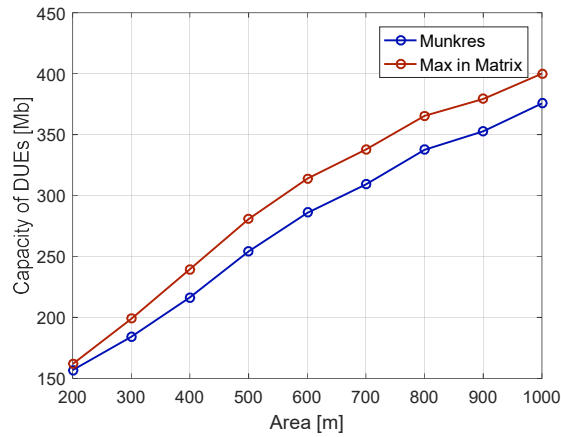


Figure 5.7: DUEs capacity over area - Scenario A

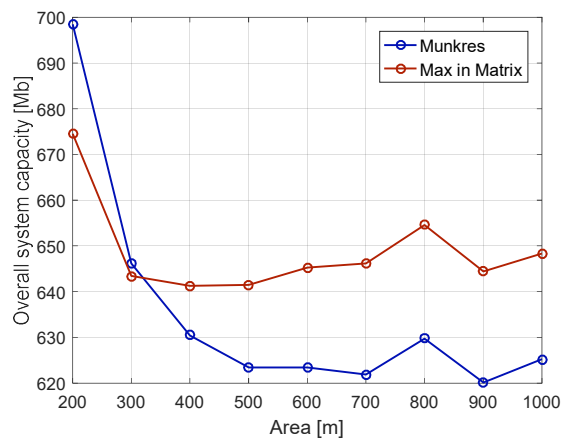


Figure 5.8: System capacity over area - Scenario A

The differences between Hungarian algorithm and MaxiM method are computed from values shown in figures in this chapter and the differences are shown in Table 5-2. The CUEs capacity chosen by MaxiM method is lower maximally about 5 % for smallest simulated area and 0,6 % for biggest simulated area. As in the previous chapter DUEs capacity and overall capacity of the system is higher for MaxiM method of channel allocation.

Capacity difference (Hungarian - MaxiM)									
Area [m]	200	300	400	500	600	700	800	900	1000
CUE [%]	-5,32	-3,83	-2,94	-2,26	-1,83	-1,42	-1,02	-0,84	-0,60
DUE [%]	3,10	8,11	10,62	10,41	9,81	9,30	8,23	7,53	6,55
System [%]	-3,43	-0,43	1,72	2,90	3,51	3,91	3,94	3,92	3,70

Table 5-2: Capacity difference over area – Scenario A

5.2 Scenario B

The simulation parameters for this scenario is the same as in the previous one. Positions of cellular users, D2D users and BTS are the same. The simulation area has same dimensions for simulation “Capacity over Alpha” and same capacity loss for simulation “Capacity over Area” is 5 %.

To fulfill the goal of this thesis, reduce the time complexity of the computation, the capacity matrix was no longer computed after power control function. That means the capacity loss for each element C_{nm} in capacity matrix could acquire any value from 0% - 100%. The method of selection the shared channel was used on this matrix. After the channels was assigned to D2D pairs, power control function was used only for those capacities. This make the power control function to run only once for each D2D pair instead of running it for “number of active CUEs” times in DL and the same number of repetition in UL. Also, the minimal interference method of channel allocation can be simulated.

The difference for Hungarian method of channel allocation between running the power control for all pairs of CUE and interfering DUE and running it only for selected pair is not so significant. But for the method MaxiM is huge. This difference is because Hungarian algorithm almost never choose the highest possible value from the matrix, but MaxiM do even it means that the overall cost of the capacity matrix is lower. Simple example is in Table 5-3.

Highest capacity of CUE selected by method			
	Without interference	Selected (no Power control)	After power control ($\alpha=10\%$)
MaxiM method	250 Mb	212 Mb	225 Mb
Hungarian method	236 Mb	210 Mb	212,4 Mb

Table 5-3: Highest capacity of CUE

5.2.1 Capacity over Alpha

As the results for the scenario A, even with use of power control function after channel allocation method, the overall capacity of the system and DUEs capacity are higher with using the MaxiM method (see Fig. 5.10 respectively Fig. 5.11). From the cellular user point of view, the capacity calculated by MaxiM method is higher this time (see Fig. 5.9).

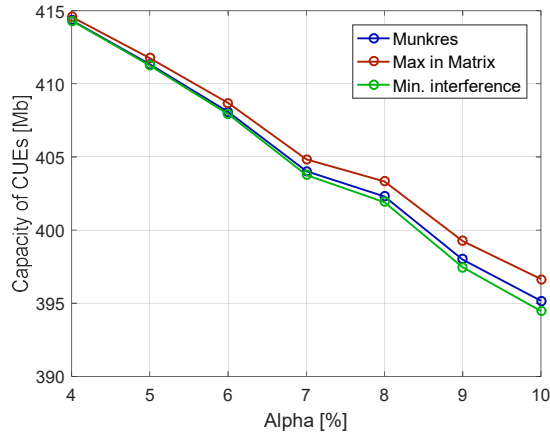


Figure 5.9: CUEs capacity over alpha - Scenario B

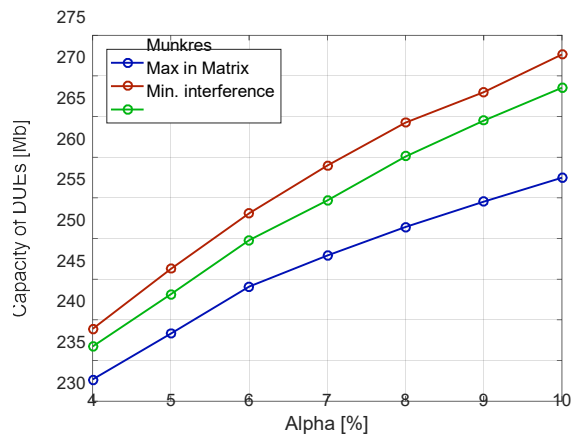


Figure 5.10: DUEs capacity over alpha - Scenario B

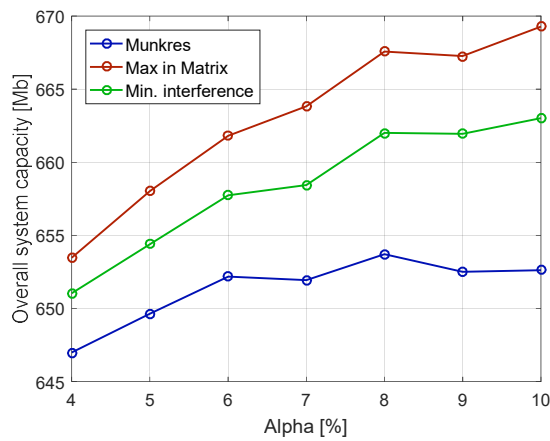


Figure 5.11: System capacity over alpha - Scenario B

The capacity of CUEs is higher maximally 0,5 % (see Table 5-4). MaxiM method is better than Hungarian method up to the capacity loss α is around 40 %. After this

limit the power control function is mostly not used because the interferences from DUEs satisfied the limit of capacity loss.

Capacity difference (Hungarian - MaxiM)							
α [%]	4	5	6	7	8	9	10
CUE [%]	0,06	0,10	0,15	0,20	0,26	0,32	0,37
DUE [%]	2,68	3,34	3,69	4,46	5,09	5,30	5,89
System [%]	1,00	1,29	1,48	1,82	2,12	2,26	2,55

Table 5-4: Capacity difference over alpha for MaxiM – Scenario B

In this part of simulation method of minimal interference of channel allocation can be used. Time complexity of this method is same as the Hungarian method but the time for computing transmitted power of each DUE is lower. This channel allocation is also used in [25]. The CUEs capacity is lower with using this method than using the Hungarian method. The capacity difference for CUEs is not higher than 0,2 % (see Table 5-5). The overall capacity of the system is higher from the same reason as in the MaxiM method of channel allocation.

Capacity difference (Hungarian - Minimal interference)							
α [%]	4	5	6	7	8	9	10
CUE [%]	-0,01	-0,02	-0,04	-0,06	-0,10	-0,14	-0,18
DUE [%]	1,75	2,03	2,34	2,73	3,45	3,92	4,31
System [%]	0,62	0,73	0,85	1,00	1,27	1,44	1,59

Table 5-5: Capacity difference over alpha for Min. interference– Scenario B

While the capacity difference α is increasing the capacity of CUEs is decreasing but overall capacity of the system getting higher due to increasing capacity of DUEs. The reason why DUEs capacity is increasing faster than CUEs capacity is decreasing is the smaller distance between DUEs in D2D pair than distance between CUE or BTS and DUE which interfere.

5.2.2 Capacity over Area

Power control function in this scenario is set to fulfill selected capacity loss 5 %. Shown in Table 5-6, MaxiM method of channel allocation for D2D communication perform better than Hungarian method and the channel allocation by method of minimal interference (see Tab. 5-7). Hungarian method is worse than both because if it selects the capacities before the power control function it is method close-to-optimal. These values are calculated from figures below.

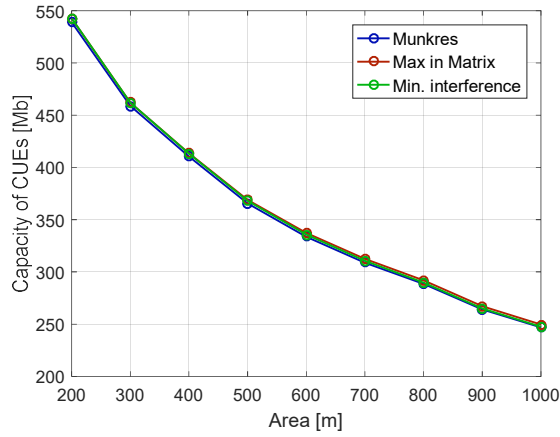


Figure 5.12: CUEs capacity over area - Scenario B

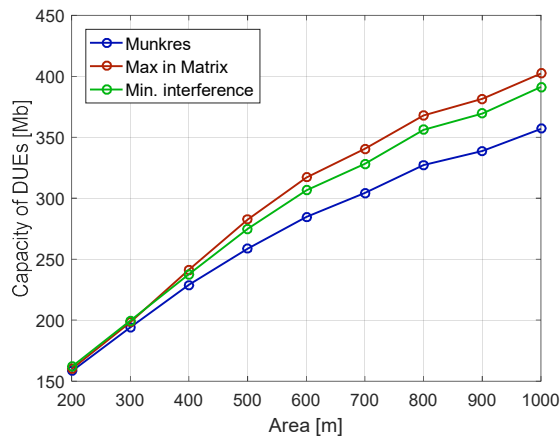


Figure 5.13: DUEs capacity over area - Scenario B

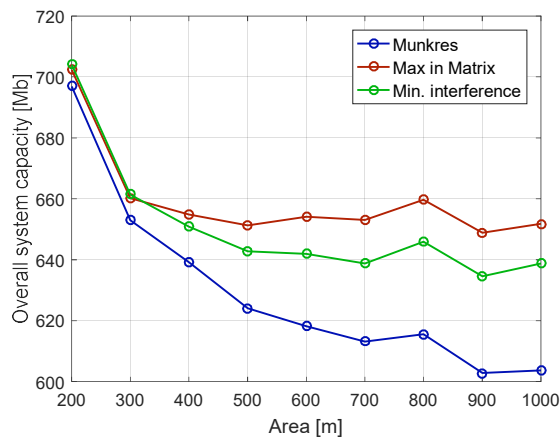


Figure 5.14: System capacity over area - Scenario B

If the distances between DUEs in D2D pairs were longer the method of minimal interference should perform the best for the overall system capacity.

Capacity difference (Hungarian - MaxiM)									
Area [m]	200	300	400	500	600	700	800	900	1000
CUE [%]	0,65	0,71	0,81	0,96	1,10	1,17	1,18	1,18	1,15
DUE [%]	1,23	2,09	5,41	9,15	11,36	11,95	12,46	12,66	12,70
System [%]	0,78	1,12	2,46	4,36	5,82	6,52	7,17	7,63	7,98

Table 5-6: Capacity difference over area for MaxiM– Scenario B

Capacity difference (Hungarian – Minimal interference)									
Area [m]	200	300	400	500	600	700	800	900	1000
CUE [%]	0,65	0,68	0,69	0,67	0,61	0,53	0,44	0,38	0,34
DUE [%]	2,28	2,76	3,86	6,28	7,63	7,88	8,87	9,07	9,59
System [%]	1,02	1,30	1,82	3,00	3,84	4,18	4,92	5,26	5,81

Table 5-7: Capacity difference over area for Min. interference– Scenario B

5.3 Comparison of the scenarios

From the first scenario CUEs capacities chosen by Hungarian method are shown in Table 5-8 for different values of alpha as well as the capacities selected by MaxiM method from the scenario B. As we can see the results for simulated values of capacity loss and area size (see Tab. 5-9) are almost the same. The differences can be obtained from the variance of the power control function that is about 0,07% for Hungarian method and 0,09% for MaxiM method of channel allocation. Hungarian method of channel allocation performs better only in case when the capacity loss is set to higher value where the power control function role is not so significant (see Fig. 5.15).

Capacity of CUEs [Mb]							
α [%]	4	5	6	7	8	9	10
Hungarian	414,7	411,9	408,8	404,9	403,3	399,1	396,1
MaxiM	414,5	411,7	408,6	404,8	403,3	399,2	396,6

Table 5-8: Capacity difference over alpha - comparison

Capacity of CUEs [Mb]									
Area [m]	200	300	400	500	600	700	800	900	1000
Hungarian	541,6	462,1	413,9	369,1	337,5	312,7	292,1	267,3	249,6
MaxiM	542,4	462,1	413,7	368,9	337,2	312,5	291,9	267,2	249,5

Table 5-9: Capacity difference over area - comparison

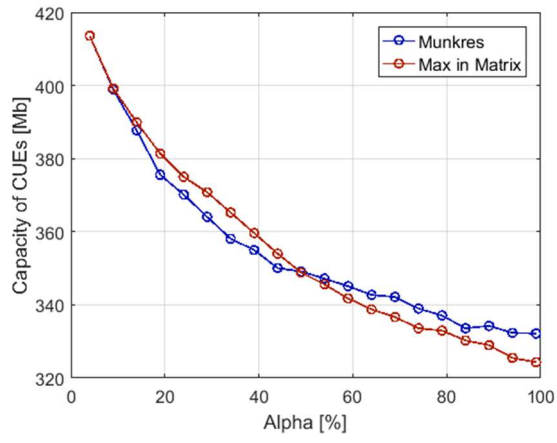


Figure 5.15: Comparison of methods

6 Conclusion

Three methods of channel allocation of D2D communication was compared. The existing one-to-one matching Hungarian algorithm has time complexity $O(n^3)$ with N times more iterations of proposed power control function than proposed MaxiM method of channel allocation. MaxiM has time complexity only $O(n)$. The results in simulated scenarios were the same for both methods. Method of minimal interference was simulated to compare with MaxiM method from the overall system capacity point of view. We can say that MaxiM method is the best compromise between time complexity of channel allocation and overall capacity of cellular users.

In continuation of this thesis lot of challenges can be answered. One of them can be comparison of efficiency of proposed power control function compare to existing ones where bigger signaling overhead is required. Next challenge which can be answered is use of channel allocation methods with respect to maximum distances between DUEs in D2D pairs. Possible system model with movement of DUEs can be also performed.

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