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Device–to-Device Association Algorithm for Optimal Neighbour Selection and Channel Sharing in 5G Cellular Networks

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Abstract

The integration of device-to-device (D2D) communication in 5G cellular networks has generated the possibility of multiple transmission modes in a single cell. This has motivated scholars to investigate different mode selection and D2D association algorithms that guarantee the selection of proper transmission mode. However, the complexity of algorithms and tractability of devices in the cell are still remarkably challenging. This paper, therefore, presents a utility based D2D association algorithm that ensures optimal neighbour selection by using numerical linear algebra to minimize computational complexity. Simulation results show that the minimum utility based D2D association increases the expected values of attached devices by 6% and 10% compared to the relative distance and maximum utility based D2D associations, respectively. Alternatively, the throughput expectation increases by 2.5% and 4% compared to the relative distance and maximum utility based D2D associations, respectively.

Keywords: Cooperative Communication, D2D, Mode Selection, Relay-assisted, Traffic Overload.

Introduction

Device-to-Device (D2D) communication constitutes an architectural enhancement that copes with data transmission limitations experienced by current cellular networks as it enables direct communications among devices without involving the base station or predefined network infrastructures (Wang 2014, Tang et al. 2015, Jiang et al. 2016). It has been envisioned by the third generation partnership project (3GPP) as a mechanism to allow proximity communication in LTE release 12, to reduce the overhead at the base station and traffic overloading in the core network (Kaleem et al. 2018, Ni et al. 2018, Zuo and Yang 2018, Kumar et al. 2019). Also, D2D communication provides advantages in allowing relay assistance and frequency reuse to systems that work under constrained power and limited wireless resources (Sreedevi and Rao 2017, Gui and Deng 2018, Zhang et al. 2018). The optimization is done such that wireless resources are reused between D2D and regular cellular users while cancelling the interference generated by users (Zhang et al. 2018, Lee and Lee 2019). These aspects made the D2D communication a favourite candidate for 5G cellular networks (Jiang et al. 2016, Omri and Hasna 2018).

However, the integration of D2D communication certainly poses additional challenge to cellular networks: the transmission mode selection or the problem of deciding whether devices should communicate via a dedicated or shared base station channel, dedicated or shared D2D channel (Kim et al 2016, Hussein and Sherine 2017). The mode selection is of great importance to ensure proper transmission mode is used and communication channels are shared appropriately to maximize the system capacity (Li et al. 2018).

Researchers were consequently motivated to address this challenge, and have therefore, developed different mode selection schemes and algorithms (Kim and Lee 2014, Jiang et al. 2016, Hussein and Sherine 2017, Christophe et al. 2019, Lin et al. 2019) . In Kim and Lee (2014), the relative distance between devices was used to perform the selection between group D2D communication and cellular communication. Jiang et al. (2016) proposed a mode selection scheme such that two devices use either a dedicated or a shared channel based on the potential interference conditions. Kim et al. (2016), Li et al. (2018) and Putjaika et al. (2018) designed different mode selection algorithms based on end to end delay, revolutionary game approach and coalition game approach, respectively. In Christophe et al. (2019), a mixed mode device-to-device communication scheme was proposed whereby devices with a higher attachment utility were prioritized to participate in the mixed mode communication.

Despite the outperformance of this mixed mode communication scheme as compared to the normal cellular communication, the work did not evaluate the scheme for multiple D2D association metrics, such as the relative distance as in (Kim and Lee 2014) and the lower attachment utility values. Therefore, this paper evaluates the mixed mode communication scheme presented in Christophe et al. (2019) under multiple conditions (or D2D association metrics) to get a general agreement on the matter concerning use cases and performances of the scheme. Indeed, the paper presents a D2D association algorithm that ensures optimal neighbour selection for consistent channel sharing.

Materials and Methods

System model

Consider a busy-state mobile communication system with new connections rejected when the number of devices is greater than the available communication channels. When, the network environment is characterized by different levels of channel utilization or target data rates with some devices or applications partly utilizing the allocated channels, the rejected connections can be enabled through content aggregation and channel sharing (Christophe et al. 2019). This implies that two nearby devices communicate using D2D links to aggregate their content at one point and use a single channel to reach the base station when one device does not fully utilize the allocated channel as shown in Figure 1.

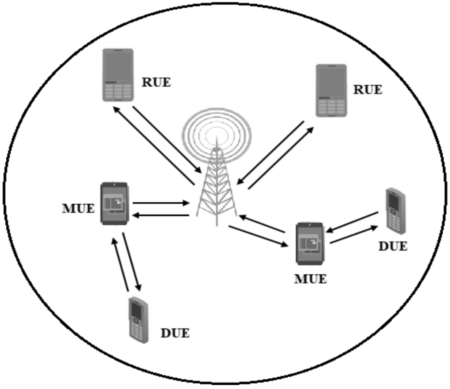

Figure 1: D2D system architecture with shared channel.

Data from the D2D user equipment (DUE) and the mixed mode user equipment (MUE) will share the same device to base station (D2B) link when the channel capacity is not exceeded and their target data rates can still be achieved, as assumed in Christophe et al. (2019). A DUE represents a user equipment that has been rejected due to insufficient communication channels. The MUE is a regular user equipment (RUE) that does not fully utilize the allocated channel and has, therefore, been associated with a DUE to share the channel. In this case, a RUE is considered as a user equipment that has been granted a communication channel.

Device-to-device association

It is assumed that the device position and target data rate are known in priori and the association of two devices as in Figure 1 should be enabled when devices are in each other's D2D coverage area and the sum of their target data rates does not exceed the maximum channel capacity. Considering that the cell embeds M RUEs and N DUEs, two $M \times N$ matrices, $\boldsymbol{P}$ and $\mathbf{\Omega}$, were constructed with respect to the D2D communication range and channel capacity constraints, respectively.

The matrix $\boldsymbol{P}$, termed as the falling matrix, is constructed such that RUEs and DUEs fall randomly in each other's D2D coverage area. The element in $\boldsymbol{P}$ is either one, when a specific RUE falls into a DUE D2D coverage area or zero, otherwise, as in equation (1). Similarly, an element in $\mathbf{\Omega}$, known as matching matrix, is one when the sum of m^{th} RUE and n^{th} DUE devices' target data rates does not exceed the maximum channel capacity, otherwise it is zero, as in equation (2).

$$\boldsymbol{P} = \begin{bmatrix} P_{1,1} & \cdots & P_{1,N} \\ \vdots & \ddots & \vdots \\ P_{M,1} & \cdots & P_{M,N} \end{bmatrix}, \qquad (1)$$

$$P_{m,n} = \begin{cases} 1, \sqrt{(x_m^{\text{RUE}} - x_n^{\text{DUE}})^2 + (y_m^{\text{RUE}} - y_n^{\text{DUE}})^2} \\ \qquad \leq R \\ 0, \qquad\qquad otherwise \end{cases}$$

where the coordinates $(x_m^{\text{RUE}}, y_m^{\text{RUE}})$ and $(x_n^{\text{DUE}}, y_n^{\text{DUE}})$ represent the Cartesian coordinates of the m^{th} RUE and n^{th} DUE, respectively. The variable R is the D2D communication range.

$$\mathbf{\Omega} = \begin{bmatrix} \Omega_{1,1} & \cdots & \Omega_{1,N} \\ \vdots & \ddots & \vdots \\ \Omega_{M,1} & \cdots & \Omega_{M,N} \end{bmatrix}, \qquad (2)$$

$$\Omega_{m,n} = \begin{cases} 1, & TR_m + TD_n \leq C \\ 0, & otherwise. \end{cases}$$

where TR_m and TD_n represent the m^{th} RUE and n^{th} DUE devices' target data rates, respectively, and C represents the maximum channel capacity.

In order to perform the association between the falling and matching matrices, the attachment matrix (Λ) is generated through Hadamard product, given by equation (3).

$$\Lambda = \boldsymbol{P} \odot \boldsymbol{\Omega} \qquad (3)$$

A DUE can match with multiple RUEs at the same time. The utility of the n^{th} DUE is equal to the sum of the gains from each RUE, whereby, a high utility shows that a DUE matches with a large number of RUEs and has more chances to get associated, as expressed in equation (4).

$$U_n^{DUE} = \sum_m G(m,n) = \sum_m \frac{\Lambda(m,n)}{\sum_{u=1}^{N} \Lambda(m,u)}, \qquad (4)$$

where $G(m,n)$ represents the gain of n^{th} DUE from the m^{th} RUE in the cell. The variable m captures the nonzero row of attachment matrix.

To perform associations between devices, one can use the relative distance between devices as in Kim and Lee (2014), where closest devices are associated or grouped. This is called distance based D2D association because the awareness of the distance between a device and the base station is required. With the consideration of devices' utilities, two scenarios: higher and lower utility DUEs can be prioritized. If the higher or lower utility DUE is prioritized, the association method is called maximum utility D2D association as used in Christophe et al. (2019), or minimum utility D2D association as presented in this paper, respectively. The algorithm that computes these D2D associations is summarized as follows:

Algorithm 1: D2D association process.

```
1. Start
2. Get the attachment matrix (Λ) and D2D association method.
3. Generate the association matrix;
   (a) If the D2D association method is distance based D2D association,
       calculate the D2B distance for each DUE and multiply each column of Λ
       by its DUE's D2B distance to obtain the association matrix A, then → (4).
   (b) If the D2D association method was minimum utility based D2D
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association or maximum utility based D2D association, then calculate the attachment utility U_n^{DUE} for each DUE and multiply each column of Λ by its corresponding U_n^{DUE} to obtain the association matrix $\boldsymbol{A}$, then → (4).

4. Drop all zero rows in $\boldsymbol{A}$.
5. Perform row by row association in $\boldsymbol{A}$ based on the specified D2D association method.

Case 1: D2D association method is distance based D2D association:

Find nonzero minimum distance, if minimum distance occurs in one entry, associate the corresponding RUE and DUE, else, consider the first positioned entry and associate the corresponding RUE and DUE.

Case 2: D2D association method is minimum utility based D2D association:

Find nonzero minimum attachment utility, if the minimum attachment utility occurs in one entry, associate the corresponding RUE and DUE, else, consider the first positioned entry and associate the corresponding RUE and DUE.

Case 3: D2D association method is maximum utility based D2D association:

Find maximum attachment utility, if the maximum attachment utility occurs in one entry, associate the corresponding RUE and DUE, else, consider the first positioned entry and associate the corresponding RUE and DUE.

6. Update the association matrix by dropping the associated RUE's row and DUE's column.
7. If all rows or columns have been dropped, → (8), else → (5).
8. Output D2D associations.
9. End.

Referring to these three association methods, the mode selection flow chart is given in Figure 2. The D2D association process is triggered when the number of devices in the cell is greater than the available communication channels.

The flowchart is mainly concerned with the identification of regular devices which do not fully utilize the allocated channel in order to be associated with other devices which can utilize the remaining channel capacity. A device works in D2D mode if it is directly attached to a cell user and it works in regular mode if it is directly attached to the base station. Indeed, a device works in mixed mode when it has been granted a communication channel and another device is associated to it via D2D links.

System throughput

The achievement of the expected throughput in a cell is often compelled by noises and co-channel interferences from active links or users. Concerning the transmission scheme under investigation, the expected throughput which is sum of devices' target data rates is expressed in equation (5).

$$E[\mathcal{R}(\tau)_{MX}] = \sum_{m(\tau)} X_{m(\tau)} + \sum_{n(\tau-\upsilon)} Y_{n(\tau-\upsilon)}, \qquad (5)$$

where $X_{m(\tau)}$ is the target data rate of the m^{th} RUE in the cell coverage area transmitting in the time frame τ and $Y_{n(\tau-\upsilon)}$ is the target data rate of the n^{th} DUE associated with a specific MUE, and that data was collected in a previous time frame $(\tau - \upsilon)$. The variable $\upsilon > 0$ represents an advance of data collection process.

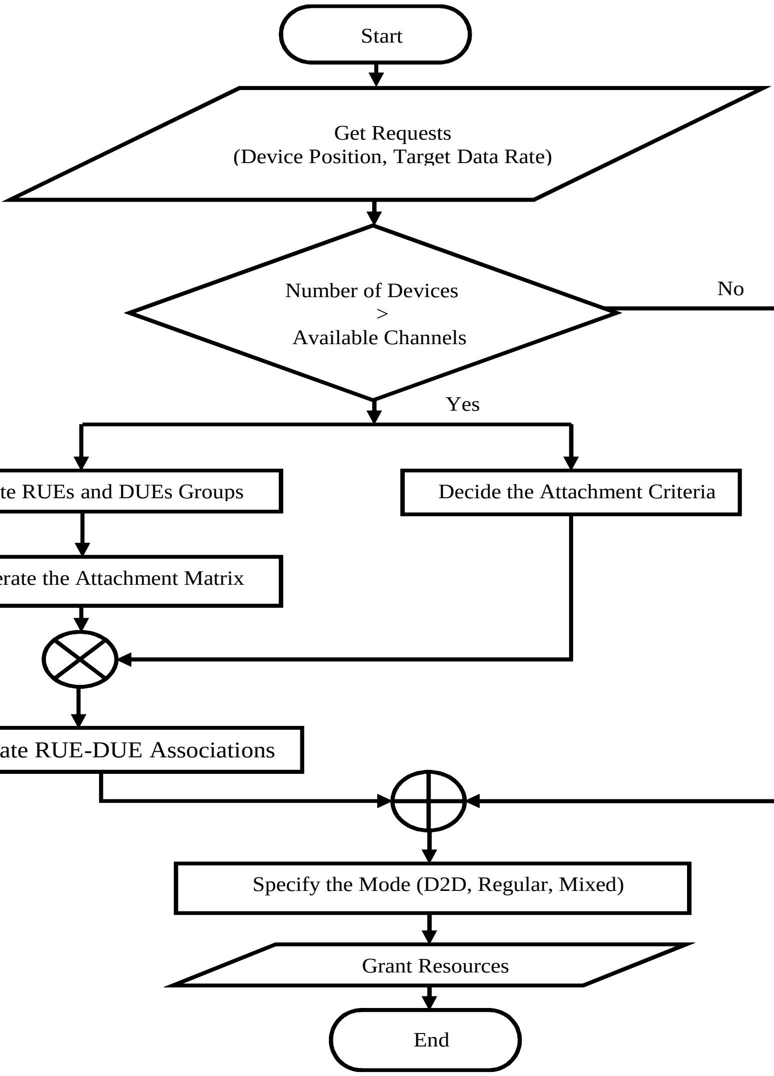

Figure 2: Flow chart of the proposed mode selection algorithm.

When the interference condition is assumed, the instantaneous throughput at the base station up-link is expressed as a sum rate; a sum of individual devices' data rates estimated with Shannon capacity as in equation (6).

$$\mathcal{R}(\tau)_{MX} = \sum_{m(\tau)} \omega_{m(\tau)} \log_2\left(1+\gamma^I_{m(\tau)}\right), \qquad (6)$$

where

$$\gamma^I_{m(\tau)} = \frac{P_{m(\tau)} G_{m(\tau)} G_r \dfrac{\lambda^2}{16\pi^2 d^{\alpha}_{m(\tau)}}}{I_{m(\tau)} + N},$$

and

$$I_{m(\tau)} = \sum_{k(\tau)} P_{k(\tau)} G_{k(\tau)} G_r \frac{\lambda^2}{16\pi^2 d^{\alpha}_{k(\tau)}}.$$

The element $\omega_{m(\tau)}$ is the channel bandwidth, $P_{m(\tau)}$ and $G_{m(\tau)}$ are respectively the transmission power and the antenna gain of the m^{th} active RUE or D2B link, and $\gamma^I_{m(\tau)}$ its signal to interference plus noise ratio (SINR) at the base station. The element $I_{m(\tau)}$ represents the power of the interference generated by active DUEs or D2D links reusing the same frequency with the m^{th} active RUE. Here $P_{k(\tau)}$ and $G_{k(\tau)}$

respectively represent the transmission power and the antenna gain of the k^{th} active DUE transmitting at time frame τ. Also, $d_{m(\tau)}$ represents the distance between the base station and m^{th} active RUE, and $d_{k(\tau)}$ represents the distance between the base station and k^{th} active D2D transmitter.

Furthermore, when the experimental throughput is gathered for multiple instants or Monte Carlo trials, the root mean square error (RMSE) between the expected throughput and the observed throughput is used as measure of performance and is given in equation (7).

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T}(E[\mathcal{R}(t)_{MX}] - \mathcal{R}(t)_{MX})^2}{T}}. \qquad (7)$$

where, T represents the number of Monte Carlo trials.

Results and Discussions

To implement the developed D2D association algorithm, MATLAB software was used. The base station was positioned at the centre of the cell, RUEs and DUEs were randomly distributed in a circular cell by following a Poisson distribution. It was assumed that RUEs and DUEs utilize the communication channels independently. System level simulations were, therefore, performed by varying number of DUEs in the cell and other parameters as presented in Table 1.

Table 1: Simulation settings

S/N	Parameter	Assumption/Value
1	Micro cell radius	$1000\ m$
2	D2D communication range	$100\ m$
3	Number of RUEs	200 devices
4	Number of DUEs	Up to 100 devices
5	Carrier frequency	$28\ GHz$
6	Maximum channel capacity	$1\ Gbps$
7	Channel bandwidth	Adjustable based on target data rate
8	RUE and MUE transmission power	$25\ dBm$
9	DUE transmission power	$20\ dBm$
10	Noise power	$-175\ dBm/Hz$
11	Path loss exponent	2
12	Monte Carlo trials	1000 trials
13	Number frequency reuse	5
14	Target data rate distribution	10 elements linearly distributed set
15	Distribution of devices	Poisson distribution

Pairs of MUEs and DUEs were generated in the cell based on devices' target data rates. It is observed in Figure 3 that the minimum utility based D2D association (min utility based association) outperforms the maximum utility based D2D association (max utility based association) and the distance based D2D association (distance based association). This outperformance results from the aspect that the minimum utility based association starts associating lower utility DUEs under assumption that a higher utility DUE matches with a large number of RUEs and hence, it has more chances to get attached. Therefore, minimum utility based association associates some DUEs which should otherwise be rejected when the maximum utility or the distance based D2D associations are used. From the same Figure 3, it is observed that with a large number of RUEs and small number of DUEs, all the association methods present similar performances; this is because the smaller the number of DUEs, the lesser the conflict among DUEs and the higher is the chance to find a free RUE that partly utilizes the channel. In contrast, a large number of DUEs implies that more DUEs target the same RUEs and hence the prioritization effect is observed. The randomized distribution of device in the cell coverage area has resulted into random variation of the attached DUEs. Therefore, Monte Carlo simulation of 1000 trials was applied. The minimum utility based D2D association presents an outperformance of 3% by average and 6% at 100 DUEs compared to the distance based D2D association. Also, it is observed that the minimum utility based D2D association maintains an outperformance of 5% by average and 10% at 100 DUEs compared to the maximum utility based D2D association.

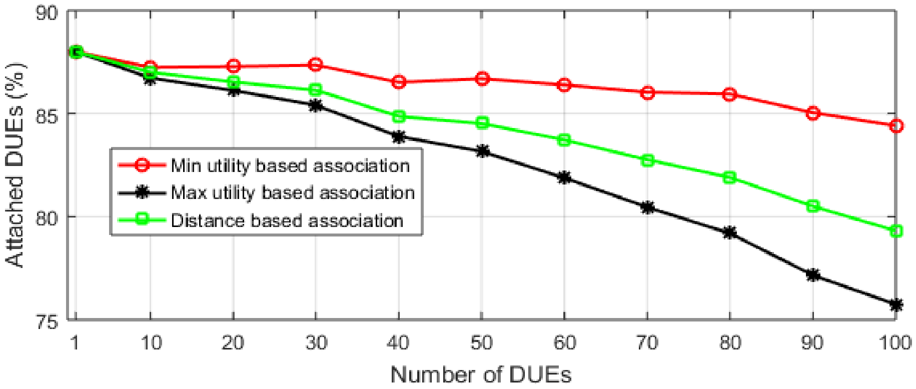

Figure 3: Variation of the number of attached DUEs.

Though, the D2D users or attached DUEs characterize the reduction of connections at the base station, the throughput is a major factor that characterizes profit improvement in a communication system. Therefore, Figure 4 describes the impact of the association under the three D2D association methods. It is observed that the minimum utility based association up bounds the maximum utility and the distance based association methods. The minimum utility based association outperforms the other methods because DUEs that have minimum utility are likely the ones targeting high channel capacity (Christophe et al. 2019), and hence, enabling their attachment results into high expectation of consistent channel utilization and throughput improvement.

Results from Monte Carlo simulation of 1000 trials shown in Figure 4 indicate that the minimum utility based association up bounds the other methods with an average difference of 2% and 4% at 100 DUEs as compared to the maximum utility based D2D association. Furthermore, the minimum utility based association outperforms the distance based association by an average difference of 1.6% and 2.5% when 100 DUEs are assumed. The throughput is a random variable which depends on the target data rates of the associated devices. Small number of DUEs results into similar or closer throughput expectation trends for all the three D2D association methods because all the DUEs in the cell are likely to get attached.

Analytically, the observed throughput performance is of an average difference of 1.5%, and 3.6% at 100 DUEs as compared to the maximum utility based association. Also, it is observed that minimum utility based D2D association ensures optimal neighbour selection as compared to the distance based D2D associations, and results into an analytical throughput improvement of 1% by average and 2.2% when 100 DUEs are assumed.

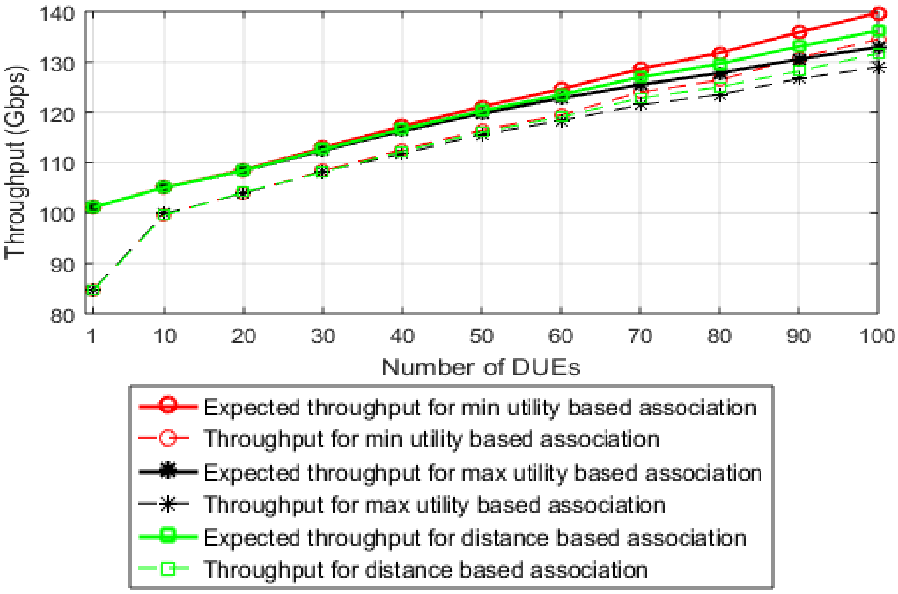

Figure 4: Throughput variation with the number of DUEs.

It is observed however, although the minimum utility based association method outperforms the maximum utility and the distance based association methods for both the expected and the observed throughputs, its drawback is that it presents a higher RMSE. Figure 5 illustrates this aspect such that the minimum utility based association presents a RMSE with an average difference of 0.5 $Gbps$ and 1.8 $Gbps$ for 100 DUEs as compared to maximum utility based association. The difference is of 2 $Gbps$ by average and 0.7 $Gbps$ with 100 DUEs as compared to the distance based association.

In summary, simulation results presented in this paper show that the minimum utility D2D based association is beneficial for the use of the D2D system architecture in Figure 1. It is used as compensating scheme to optimize the use of channels in busy-state wireless communication system. Thus, instead of rejecting a user equipment when the available channels have been granted to preceding devices as in a normal cellular communication system, the scheme in Figure 1 can enable the attachment of the rejected devices through content aggregation. This scheme presents high performance by using minimum utility D2D based association as compared to the maximum utility and distance based D2D association methods.

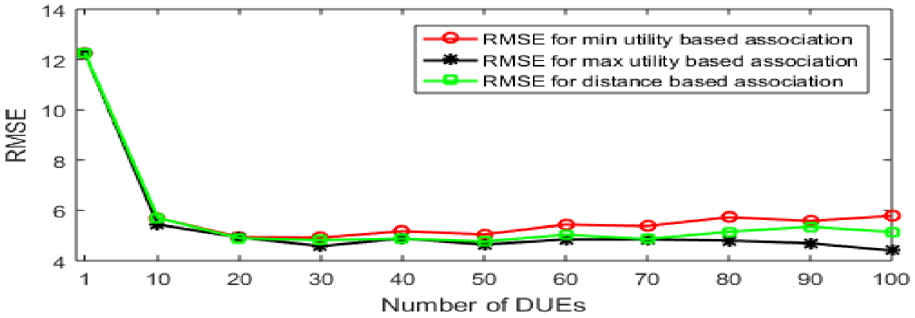

Figure 5: Root mean square error between the expected and the observed throughputs.

Conclusions

The consideration of D2D communication as a data plane technology to mitigate traffic overloading and base station overhead in mobile networks generated the possibility of multiple modes of communications. Thus, it raised the need of mode selection or D2D association mechanisms. This attracted scholars' attention and hence has led to the development of different mode selection and D2D association algorithms. This paper presents the utility based D2D association that ensures optimal neighbour is chosen for consistent channel sharing. Simulation results revealed the outperformance of the minimum utility based D2D association method as compared to the maximum utility and relative distance based D2D associations. In terms of throughput expectation for 100 DUEs, the outperformance was 4% with a RMSE of 1.8 $Gbps$ and 2.5% with a RMSE of 0.7 $Gbps$ as compared to the maximum utility and distance based associations, respectively. The average throughput improvement for the minimum utility based association was of 2% with a RMSE of 0.5 $Gbps$ and 1.6% with RMSE of 2 $Gbps$ compared to the maximum utility and distance based association, respectively. The minimum utility based D2D association is therefore, beneficial for the use of the mixed mode D2D communication system architecture in Figure 1 to optimize the use of channels in busy-state wireless communication system. Considerations of device mobility and availability of the generated D2D links were not taken into account and therefore they remain open problems for future studies.

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