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Mixed Mode Device-to-Device Communication Scheme for Congestion Reduction and Channel Usage Optimization in 5G Cellular Networks

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Abstract

Device-to-Device (D2D) communication schemes have gained more attention in cellular networks particularly in normalization process of the upcoming 5G networks. They have been investigated in core network offloading, congestion reduction and channel usage optimization. The two last cases are among the major constraints in current cellular networks and are the main concerns of this paper. The paper presents a mixed mode D2D communication scheme to decentralize data collection between devices and the base station in order to reduce the number of direct connections at the base station of ultra-dense cells characterized by different levels of channel utilizations or target data rates, as expected for 5G networks. The attachment utility is derived as the overall gain of a device for a target data rate and is used as a metric for D2D association's decision. Results show that the attachment utility and D2D pairs increase by either increasing the D2D communication range or decreasing devices' target data rates. A further important consideration is that the proposed mixed mode D2D communication scheme improves the throughput expectation in the cell by 14.2% compared to the regular cellular communication.

Keywords: 5G Networks, Channel Usage Optimisation, Congestion Reduction, D2D Communication Scheme, Target Data Rate.

Introduction

Current mobile communication infrastructures are expected to experience overloading due to overgrowing data traffic which demands extremely high data rates (Hu et al. 2019). Therefore, mobile communication pioneers have been subjected to an urgent need of developing enhanced mechanisms and features to cope with the current and the expected future mobile traffic overloading. The upcoming 5G networks will provide meaningful advantages to mobile network operators (MNOs). The 5G networks are expected not only to support the very high data transmission demand wanted by current users, but also bring an assurance in investigating and creating additional services and applications (Singh and Chawla 2017). Compared to classic infrastructure based cellular communications, 5G networks will carry different modes of communications in a single cell and enhance network slicing allowing on demand and flexible radio resource allocation (Lee et al. 2019, Sattar and Matrawy 2019). Multiple communication modes lead to a high network throughput and overhead reduction at the access point or base station (Sheybani et al. 2018, Lee and Lee 2019). With multiple modes of communications, devices operate either in regular, D2D or both modes based on their locations and required quality of service (Lee and Lee 2019).

The Device-to-Device (D2D) communication is viewed as a potential component of the upcoming 5G network infrastructures because it enables devices which are closer to initiate direct communication rather than interacting via the base station or remote radio head (Kar and Sanyal 2017, Li et al. 2019). It was introduced by the 3GPP to support proximity services (ProSe) in enhancing network performance or enabling communications in circumstances where network infrastructures may not be operational to support information and alerts exchange; circumstances such as terror situations, tsunami and earthquakes (Kunz et al. 2013, Jung and Kim 2016). In addition, the emergence of multimedia services has triggered the integration of D2D communication in LTE Release 12 networks to enable content sharing when subscribers or devices that are closer to each other request for the same content (Liu et al. 2012, Gupta et al. 2018, Seth and Sharma 2018).

With the promising consideration of D2D communication, cooperative D2D communication and relay assisted D2D communication have indeed gained more attention (Lee and Lee 2019). These two concepts are used to extend the cell coverage, to improve the transmission reliability, to reduce congestions, to reduce the power consumption, and to upgrade either the throughput or load balancing in the core network (Jung and Kim 2016, Li and Cai 2018, Gao et al. 2019). In cooperative D2D communication, devices interactively collect their contents at one point and use a single link to reach the base in order to reduce congestions and the feedback load at the base station (Gui and Deng 2018, Li and Cai 2018, Lee and Lee 2019). In relay assisted D2D communication, a user equipment (UE) at the edge of a cell attaches at its serving base station by relaying its content through a UE to UE communication. This operation reduces the power consumption while improving the transmission efficiency (Qiao et al. 2010, Jung and Kim 2016, Lee and Lee 2019). Due to the challenge of the first nearest relay unavailability, the research done by Rajabi and Ghorashi (2018) has studied the impact of connecting to the n^{th} nearest device rather than connecting to the first nearest device. Indeed, D2D load balancing, resource allocation and routing algorithms have been provided by Zhang et al. (2018) such that a device at the edge of a congested small cell attaches to the closest uncongested small cell by using devices in the same path as relays.

Studies on relay assisted D2D communication have, however, investigated ideal environment devices which fully utilize the allocated channels (Qiao et al. 2010, Jung and Kim 2016, Rajabi and Ghorashi 2018). Therefore, with the ultrahigh 5G channel capacity that can accurately support multiple devices, a regular device can be allocated a full channel although its target data rate requires the portion of the channel capacity (Jian et al. 2015). Consequently, a device serving as a relay can attach data when the served device does not fully utilize the allocated channel, but the investigated relay assistance scenarios do not enable a relay to attach its content.

The main contribution of this paper is providing analysis of mixed mode D2D communication taking into account the target data rate in congestion reduction and channel usage optimisation. Different from previous works which considered that devices fully utilize the allocated channels and focused on the relay assistance aspect of devices, this paper presents the feasibility of data aggregation in ultra-dense cells characterized by different levels of channels utilization or target data rates. Both the D2D transmission and the regular transmission are considered, and generate a mixed mode D2D transmission. With this generated transmission mode, analysis is done such that two devices aggregate their data by using D2D mode and use a common regular cellular link to transmit the collected data to the base station based on their target data rates. This procedure is envisioned because a real environment device can partly utilize the allocated channel while its neighbours have missed channels.

Materials and Methods

Overview of the analysis

This paper presents the obtained simulation results in form of plots, and discussions in form of insights. The software material used for numerical implementation of equations is MATLAB simulator. Numerical simulations were run by varying various parameters, mainly the number of devices in the cell coverage area, the D2D communication range and the target data rates. Statistical probabilistic analysis is used as the method for modelling the randomized distribution and location of devices in the cell coverage area, as in Rajabi and Ghorashi (2018), Sheybani et al. (2018), Lee and Lee (2019). The channel utilization is done based on the target data rate and the rest of the channel capacity should be available for other devices. Hence, accessing the reserved channel is opportunistic and has to be modelled probabilistically.

The paper presents opportunistic attachment when devices in the same cell coverage area do not fully utilize the allocated channels. The scenario is mathematically modelled such that devices follow the Poisson Point Process (PPP) with different distribution densities, and independently utilize the allocated channels. The probability at which devices are located in each other D2D communication range is related to the probability at which Poisson points fall in a given area. This probability is called falling probability throughout this paper. Indeed, the probability at which two devices can share the same channel without exceeding the maximum channel capacity defines matching probability. These probabilities are combined to give the attachment utility that represents the overall gain of a device for a target data rate, and characterizes the chance at which the device can aggregate its content with a neighbour that does not fully utilize the allocated channel. In some cases, multiple devices are assumed nearby the same neighbour which does not fully utilize the allocated channel, these devices compete by tuning their target data rates in order to improve their attachment utilities. A high attachment utility means that a device is likely to get attached and trigger the data aggregation process. The target data rate denotes the portion of the maximum channel capacity which satisfies the device's need.

In the analysis, the base station is located at the centre of the cell and defines the cell coverage area in which devices are randomly distributed. The base station has less number of channels or wireless resources than required. Therefore, as illustrated in Figure 1, some devices will be granted the available communication channels (Type I devices) and others will miss (Type II devices). The variables M and N, respectively, represent the number of Type I and Type II devices in the cell coverage area. So, given a particular device with D2D communication range R, the D2D communication coverage is πR^2.

Assuming that a Type I device fully or partially utilize the allocated channel capacity, a Type II device can be attached to a near Type I device by using the D2D mode as long as the maximum channel capacity is not exceeded. Based on the competition and complexity aspects of this scenario, the analysis is carried out in different environments such as simple homogeneous, simple heterogeneous, and complex homogeneous.

Simple homogeneous environment

Consider a simple homogeneous environment (S.Ho.Env) to be a cell with M randomly distributed Type I devices and one Type II or a Particular device, as in Figure 1. Also a cell in which each Type I device falling in the Type II device's coverage area supports the attachment. The probability of having at least v points (transmitters) in a given subset (A) of the cell coverage area has been provided in Rajabi and Ghorashi (2018). This probability is given by p_v in equation 1.

$$p_v = P(V \geq v, A) = 1 - \sum_{b=0}^{v-1} \frac{(\lambda_B \times A)^b}{b!} e^{-\lambda_B \times A}. \quad (1)$$

The variables V and λ_B represent the number of points in the subset A and the distribution density of points in the cell coverage area, respectively. From equation 1, the probability of having at least one Type I device in a D2D communication area (A) under assumption that the cell coverage area contains M Type I devices, is expressed in equation 2.

$$p_1 = P(V \geq 1, A) = 1 - \frac{(\lambda_M \times A)^m}{m!} e^{-\lambda_M \times A} \Big|_{m=0} = \sum_{m=1}^{M} \frac{(\lambda_M \times A)^m}{m!} e^{-\lambda_M \times A}. \quad (2)$$

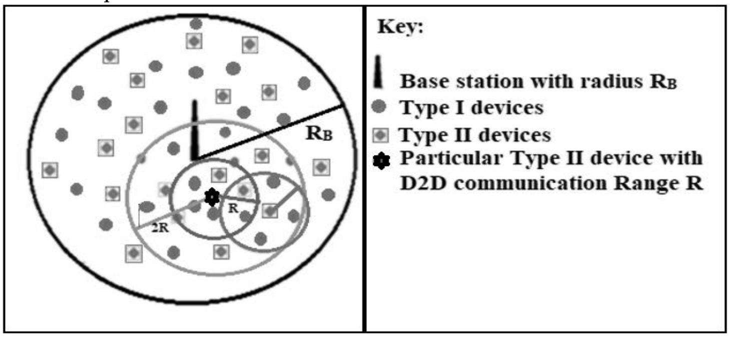

Figure 1: Distribution of devices in the cell coverage area.

In this case, λ_M represents the distribution density of Type I devices in the cell coverage area. For simplicity, let us denote p_1 in equation 2 to yield equation 3;

$$p_1 = \sum_{m=1}^{M} P_r[m|A], \quad (3)$$

where $P_r[m|A]$ represents the falling probability or the probability at which m Type I devices fall in a given coverage area A. To fit with the Poisson Point Process (PPP) used in Rajabi and Ghorashi (2018), $P_r\,[m|\,A]$ is constrained such that $m \in 0,1,2, \ldots . M$ and

$$0 < \sum_{m=0}^{M} P_r[m|A] \leq 1. \quad (4)$$

With this constraint in equation 4, $1 - P_r[0|\,A]$ holds the Choquet capacity of the PPP in Jeulin (2014).

Considering that in a S.Ho.Env each Type I device falling in A supports the attachment at 100%, the matching probability (W_j^{Ho}) between a Type II device and a j^{th} Type I device falling in A is equal to one. The sum of individual matching probabilities is m for m Type I devices in A. When a cell embeds M Type I devices and a part of them randomly falls in A, the matching and falling probabilities are multiplied to obtain the attachment utility U given by equation 5.

$$U = \sum_{m=1}^{M} \left(P_r[m|\,A] \sum_{j=1}^{m} W_j^{Ho} \right) = \sum_{m=1}^{M} m \times P_r[m|A]. \quad (5)$$

Equation 5 considers that each Type I device supports the attachment. However, in real environment different devices utilize the allocated channels independently. For instance, a device which needs to fully utilize the allocated channel cannot support the attachment, unless they cooperate to adjust their target data rates. The difference and independence in channel utilization generate a sort of heterogeneity. Hence, a simple heterogeneous environment is studied as in subsection below.

Simple heterogeneous environment

Consider a simple heterogeneous environment (S.He.Env) as a cell that contains M Type I devices and one Type II device. In this case, each device is supposed to utilize the allocated channel differently and independently. Based on this assumption, the attachment is conditioned by the probability of having m Type I devices in A and the probability at which the sum of target data rates do not exceed the maximum channel capacity. To analyze the impact of these two probabilities on the attachment utility, the notion of target data rate or the percentage of the maximum channel data rate which satisfies a device's needs is introduced. Thus, let $H = \{h_{1,} h_{2,} h_{3\,,\ldots\ldots,} h_k\}$ with $i = 1, 2, \ldots k$, represent a set of linearly distributed data rate percentages, and $Q = \{q_{1,} q_{2,} q_{3\,,\ldots\ldots,} q_k\}$ be an equivalent set of data rates. Negative and zero values are not assumed as possible target data rates. Therefore, the value of q_i is defined in $]\,0,\ C\,]$, a subset in the conventional set of positive nonzero real numbers, where C represents the maximum channel capacity or regular cellular link data rate.

For $X_m\ and\ Y_n \in Q$, where X_m and Y_n are target data rates of the m^{th} Type I device and the n^{th} Type II device, a Type I-Type II association can be enabled for a cell channel capacity C if:

$$(X_m + Y_n) \times \frac{1}{1 - \mu} \leq C. \qquad (6)$$

The component μ represents the data collection time, and is constrained such that $0 \leq \mu < 1$ second when the data rate is expressed in $x$bit/sec. The variable x is G when the data rate is expressed in Gigabits per second (Gbit/sec) or M for megabits per second (Mbit/sec). Equation 6 is used when the collection time is included in the transmission time frame. When devices collect and format data before the transmission time occurs, the collection time is excluded in the transmission time and then equation 6 reduces to $X_m + Y_n \leq C$. When the Type II device targets a data rate Y_n at i^{th} position in the set Q, and Type I devices target their data rates in the same set, the total number of combinations for Y_n with each element of the set Q such that $X_m + Y_n \leq C$ is held, is equals to $L = k - i$. Therefore, the matching probability in S.He.Env is given by W_j^{He} in equation 7.

$$W_j^{He} = \frac{L}{k} = \frac{k-i}{k}. \qquad (7)$$

Combining equations 4 and 7, the attachment utility (U_D) in S.He.Env is expressed as a sum of individual falling probabilities and matching probabilities products. This is given by equation 8;

$$U_D = \sum_{m=1}^{M} \left(P_r[m|\,A] \sum_{j=1}^{m} W_j^{He} \right), \qquad (8)$$

where U_D represents the attachment utility for a given Type II device D with a D2D coverage area A and a target data rate at the i^{th} position in the set Q. W_j^{He} represents the probability at which D can match with the j^{th} Type I device falling into its coverage area A. The variable $j \in \{1, 2, \ldots, m\}$ when m Type I devices fall in A. As all the target data rates are independently chosen in the same set Q, the same matching probability is applied such that:

$$W_1^{He} = W_2^{He} = W_3^{He} = \ldots = W_m^{He} = \frac{k-i}{k}.$$

Then, equation 8 becomes

$$U_D = \frac{k-i}{k} \sum_{m=1}^{M} m \times P_r[m|\,A]. \qquad (9)$$

The attachment utility U_D in equation 9 is applied when a cell undelays M Type I devices and a single Type II device. Also, the equation is applicable when there are N Type II devices in the cell coverage area and individual Type II devices' coverage areas are disjoint or not overlapping each other. The two scenarios above are ideal because they occur rarely in real environment. Furthermore, when different Type II devices overlap each other's coverage areas, they conflict, the system becomes complex and analysis imposes additional assumptions. Therefore, the attachment utility in a complex homogeneous environment (C.Ho.Env) is derived as in the following subsection.

Complex homogeneous environment

This scenario characterizes a cell with M Type I and N Type II devices, the devices' coverage areas may overlap each other, and each Type II device can attach to any nearest Type I device. Any Type II device influences the attachment utility of a particular device D if it is either in the coverage area A or it is in a coverage area of radius $2R$ taking the position of D as the centre or reference position. Therefore, all devices in the coverage area equivalent to $S = \pi(2R)^2$ impact the attachment utility of D. The probability p_1^S at which at least one Type II device is located in S is expressed in equation 10 by recalling p_1 from equation 3:

$$p_1^S = \sum_{n=1}^{N} P_r[n|\, S]. \tag{10}$$

Up to this point, all the derived attachment utility equations consider that D is alone in the cell. Therefore, its attachment utility is maximum, but when different Type II devices conflict with D, the utility is eventually shared. For the sake of compatibility with the homogeneity concept, the attachment utility is found such that equation 5 is shared equally. Thus, if $n-1$ Type II devices conflict with D, the attachment utility of D is given by U_{Dn}. $U_{Dn} = \frac{1}{n}U$, with $n = 1, 2, \cdots, N$. Equivalently, U_{Dn} can be rewritten as in equation 11.

$$U_{Dn} = \left[1 - \left(\frac{n-1}{n}\right)\right] \sum_{m=1}^{M} m \times P_r[m|\, A]. \tag{11}$$

The component $\left(\frac{n-1}{n}\right)$ represents the impact of conflicting Type II devices on the attachment utility, and it is zero when D is alone $(n = 1)$ in S. Besides, the impact of $\left(\frac{n-1}{n}\right)$ is influenced by the probability of having n devices in S. Therefore, the utility U_{Dn} can be rewritten as an optimized utility $U_{Dn,o}$ by introducing a term $\propto_n$, dependent of n and the falling probability of n, such as in equation 12.

$$U_{Dn,o} = [1 - \propto_n] \sum_{m=1}^{M} m \times P_r[m|\, A], \tag{12}$$

where $\propto_n = \left(\frac{n-1}{n}\right) P_r[n|\, S]$.

As assumed, the base station coverage area contains N Type II devices; they can partially or totally fall into S. Thus, considering the variability of n, the average attachment utility, $U_{Dn,o}^{av}$ of a Type II device is expressed in equation 13.

$$U_{Dn,o}^{av} = \left(\sum_{m=1}^{M} m \times P_r[m|\, A]\right) \times \frac{1}{N}\sum_{n=1}^{N}[1 - \propto_n]. \tag{13}$$

Suppose devices are randomly distributed in the cell coverage area by following a PPP, with two different distribution densities. With this assumption, $P_r[m|\, A]$ and $P_r[n|\, S]$ are replaced by their probability density functions, and equations 5, 9 and 13 yield to equations 14, 15 and 16, respectively.

$$\widetilde{U} = \sum_{m=1}^{M} \frac{(\lambda_M \times A)^m}{(m-1)!} e^{-\lambda_M \times A}, \tag{14}$$

$$\widetilde{U}_D = \frac{k-i}{k} \sum_{m=1}^{M} \frac{(\lambda_M \times A)^m}{(m-1)!} e^{-\lambda_M \times A}, \tag{15}$$

$$\widetilde{U}_{Dn,o}^{av} = \left(\sum_{m=1}^{M} \frac{(\lambda_M \times A)^m}{(m-1)!} e^{-\lambda_M \times A}\right) \times \frac{1}{N} \sum_{n=1}^{N} \left[1 - \left(\frac{n-1}{n}\right) \frac{(\lambda_N \times S)^n}{n!} e^{-\lambda_N \times S}\right], \tag{16}$$

where $\lambda_M = \frac{M}{\pi \times (R_B)^2}$ and $\lambda_N = \frac{N}{\pi \times (R_B)^2}$ are the distribution densities of Type I and II devices, respectively.

Results and Discussions

Numerical simulations were run in MATLAB by varying the number of Type I and II devices in the cell coverage area, the D2D communication range R and devices' target data rates. Equations 14, 15 and 16 were implemented in MATLAB by considering a dense 5G micro cell with a radius $R_B = 1000\,m$ and a matrix $\boldsymbol{H}$ (1×10) was constructed to get a linearly distributed set of data rate percentages and a 1Gbps maximum channel capacity for simple heterogeneous environment. These three equations represent the attachment utility in simple homogeneous, simple heterogeneous and complex homogeneous environments under Poisson Point Process, respectively. Results in Figure 2 represent the overall impact of the number of Type I devices on the attachment utility under different environments. It is observed that the attachment utility increases with the number of Type I devices. This means that, the larger the M, the more a device is likely to find a Type I as its neighbour. The attachment utility in simple homogeneous environment outperforms utilities in other environments, this is because it constitutes the upper bound attachment utility where each Type I device has to support the attachment, and Type II devices' coverage areas are not supposed to overlap or conflict each other.

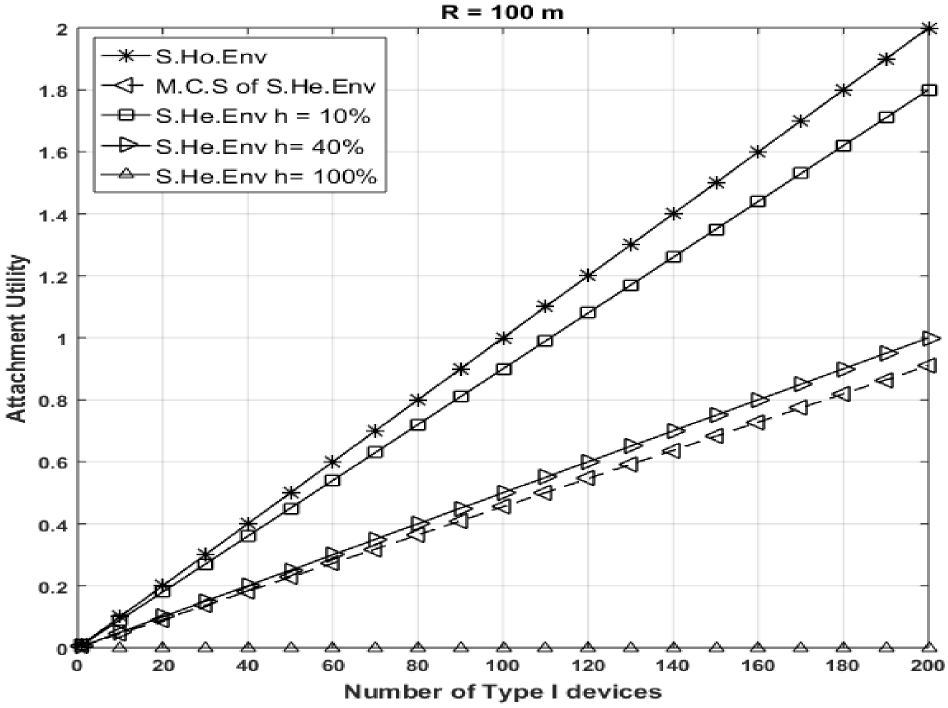

Figure 2: Impact of the number of Type I devices on the attachment utility.

When devices are targeting small percentages of the maximum channel capacity, the attachment utility in simple heterogeneous environment is getting closer to the simple homogeneous environment, and this is zero when the entire channel capacity is assumed. A total of 1000 trials Monte Carlo simulations of the simple heterogeneous environment (M.C.S of S.He.Env) have been performed for fair comparison between the simple homogeneous and simple heterogeneous environments. Results from M.C.S of S.He.Env show that the generalized attachment utility in a simple heterogeneous environment is less than the attachment utility of a device which targets 40% of the maximum channel capacity and it is around 45% of the upper bound attachment utility. This aspect elucidates the constraint of the matching probability on the attachment utility.

Figure 3 shows the variation of the attachment utility with the D2D communication range. It is observed that the increase in D2D communication range improves the attachment utility. The improvement is based on the aspect that devices are randomly distributed in the cell coverage area and they can be located at any position in the cell. Therefore, a large D2D coverage area gives the potentiality of embedding a large number of Type I devices, this in return increases the attachment utility.

Furthermore, the attachment utility in a complex homogeneous environment is quasi constant with respect to the number of conflicting Type II devices. With the attachment utility expressed in terms of average as in equation 13, the impact of a large number of conflicting Type II devices on the averaged attachment utility is minimized by a small falling probability. Therefore, graphs in Figure 3 appear straight combined for different values of conflicting Type II devices.

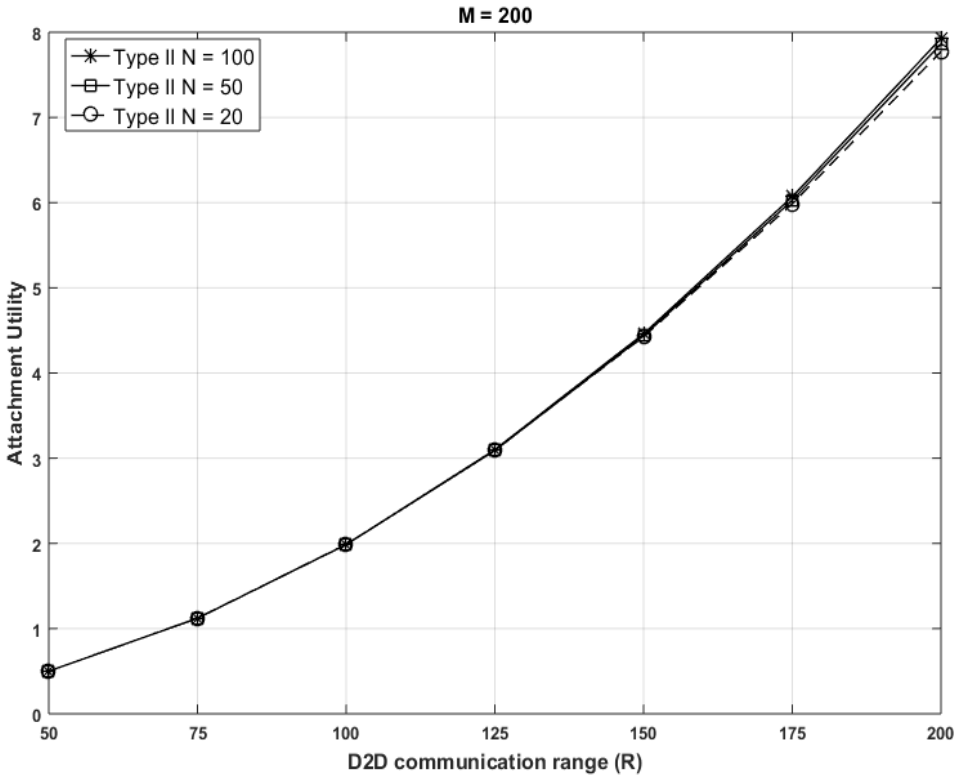

Figure 3: Impact of the D2D communication range on the attachment utility.

Figure 4 illustrates the impact of the number of Type II devices on the attachment utility for different D2D communication ranges. As the D2D communication range increases, the attachment utility also increases. The attachment utility decreases at a small scale with respect to the number of conflicting Type II devices. However, above a certain value of N, the attachment utility increases as in Figure 4 (b), (c) and (d). This is due to the fact that the impact of conflicting Type II devices and the likelihood at which they fall into S are varying at different scales.

In other words, for a certain value of n, the influence starts decreasing and thus, the attachment utility starts increasing. The impact of conflicting devices increases linearly with n while the falling likelihood decreases exponentially with n, this refers to the component $\propto_n$ in equation 12. For small values of n, the impact of conflicting devices and their falling probability as given by $\propto_n$ are closer to each other, and hence the increase of n results into the decrease of the attachment utility, for example, when the number Type II devices is less than or equal to 50 in Figure 4 (b) and less than or equal to 20 in Figure 4 (c). However for large values of n or when the number Type II devices is greater than 50 in Figure 4 (b) and greater than 20 in Figure 4 (c), the impact of conflicting devices and their falling probability mismatch, the falling probability significantly decreases and hence the attachment utility starts increasing.

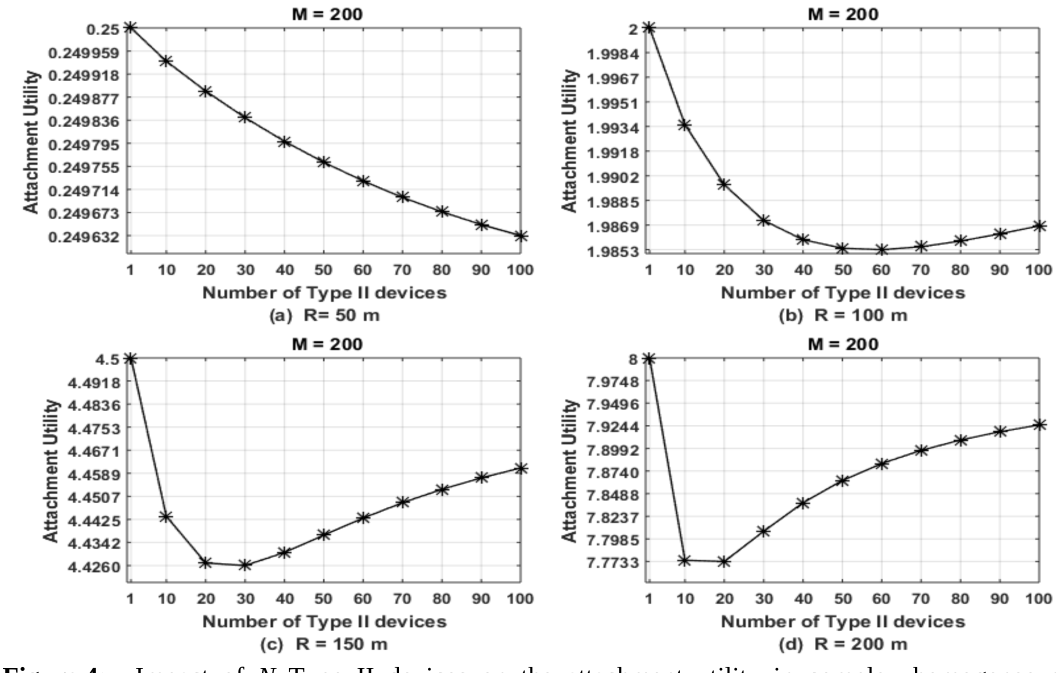

Figure 4: Impact of N Type II devices on the attachment utility in complex homogeneous environment.

The sum throughput represents the aggregate throughput of all attached devices in the cell (Pradhan et al. 2018). In this paper, the sum throughput is estimated by the sum target data rate of devices which are supported by the base station. In regular cellular communication the sum throughput is therefore the sum of regular devices' target data rates. In the proposed mixed mode D2D communication the sum throughput sums both regular devices' target data rates and the D2D communication devices' target data rates. The D2D association rate in Figure 5 illustrates the extent to which D2D associations are performed in the investigated mixed D2D communication whereas a single cellular link is assumed for a pair of associated devices instead of a specific cellular link for each device in order to reduce the number of direct connection at the base station. This figure shows the number of created D2D pairs based on complex homogeneous environment scenario. It is observed that the rate of association increases on average by 15.9% when the D2D communication range is doubled.

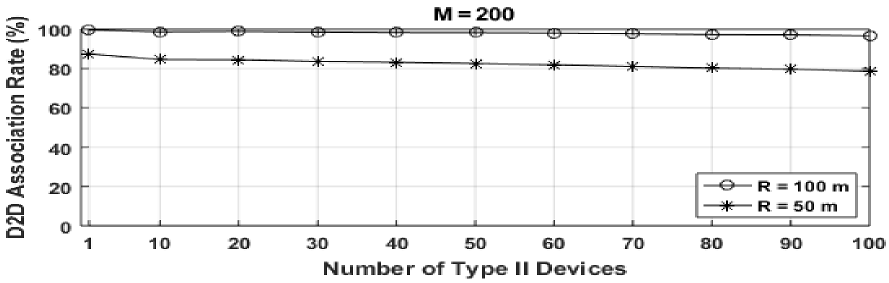

Figure 5: D2D association rate in the proposed mixed mode D2D communication.

Also the throughput expectation increases in the cell with mixed mode D2D communication compared to the regular cellular communication scenario. During simulations, the sum throughput was randomly varying in single simulation trial. This led to the use of Monte Carlo simulations that estimate a random varying entry through repeated experiments. With 1000 Monte Carlo simulations trials, it is observed in Figure 6 that the sum throughput of proposed mixed mode D2D communication outperforms the regular cellular communication on average by 14.2% when the same number of communication channels is assumed for the two communication modes. The outperformance is due to the channel sharing consideration that optimizes the channels usage probability and hence increases the sum throughput in mixed mode D2D communication. In addition, the throughput expectation improves in the cell by 4.9% when the D2D communication range is doubled.

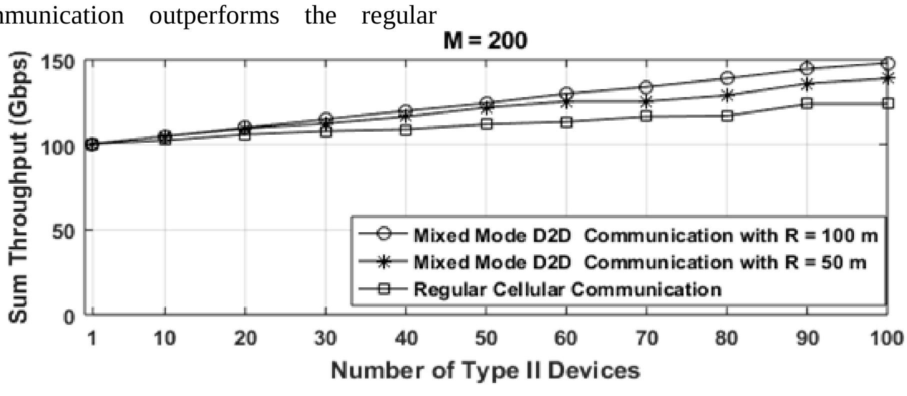

Figure 6: Sum throughput estimation in the micro cell.

Conclusions

This paper proposes a statistical probabilistic analysis of opportunistic attachment in mixed mode D2D communication based on 5G network expectations. Results provide clear evidence that devices which missed the attachment can participate in mixed mode transmission by adjusting their utilities through target data rate tuning. In other words, a device which missed the channel is likely to aggregate its content with a near device which does not fully utilize the allocated channel when it reduces its target data rate. Also, its chances increase when the D2D communication range is increased in the cell. It is observed that the D2D communication range has a considerable impact on the attachment utility and the number of D2D pairs. Therefore, its normalization is of great interest to permit the adjustment of the attachment utility in order to attach a balanced number of devices. The D2D communication range normalization, however, remains an open research problem. Simulation results show that the proposed mixed mode D2D communication improves the throughput expectation in the cell by 14.2% compared to the conventional regular communication. Investigations for the utility in complex heterogeneous environment and channel state information are not presented. These additional gaps remain open problems and will inspire our future investigations.

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