An Energy Efficient Mechanism for Downlink and Uplink Decoupling in 5G Networks

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Abstract. In current cellular networks, cell association is heavily based on the Downlink signal power and all devices are associated with the same Base Station in Downlink and Uplink. While as of now this technique has been proved adequate in homogeneous networks where all BSs have similar transmission levels, in increasingly dense heterogeneous networks rate is heavily dependent on the load, which can significantly vary from Base Station to Base Station. Due to increased demands for usage over several devices in heterogenous networks, large disparities in the Downlink pose a threat to the quality of services rendered by the network and this technique seems obsolete. Uplink and Downlink decoupling is the proposed solution, where the Downlink cell association is not necessarily based on the same criteria as Uplink. We propose using SINR and Path Loss with Range Extension as factors for choosing the appropriate Base Station for connection in Downlink and Uplink respectively, taking into consideration the Base Stations' Resource Block availability, to avoid overloading Base Stations and we will use simulations to test our theory.

1 Introduction

Recent 4G cellular networks' design foundations are based on Macro cells (MCells) that featured the same characteristics throughout the network. They were preferred because of their high transmit power, which ensured high Signal to Interference and Noise Ration (SINR). Their similarities extended to the number of users they can support [3]. Their focus was centered on improving peak rate and spectral efficiency to offer the best user experience. This architecture is commonly referred to as Homogeneous Networks. Although until now, this approach was adequate, in recent years network traffic demands keep rising making the deployment of heterogeneous networks (HetNets) necessary in order to adequately correspond to these needs. Heterogeneous networks consist of Macro cell Base Stations (MBSs) and Small cell Base stations (SBSs) that are scattered among a Macrocell Base Station's vicinity [13]. HetNets have been implemented already successfully in 3G and 4G networks, but they were not designed as a part of them from the beginning, making it necessary to implement fundamental

changes in the design of 5G networks to ensure their successful implementation. With the rise in user demands, 5G networks need to be user oriented in order to make them accessible from all users and flexible to work with.

With the shift to hetnets, the connection between Uplink (UL) and Downlink (DL) is differentiated from homogeneous networks and not necessarily based on the same Base Station (BS) [9]. Traditionally the throughput required for DL was vastly higher than the one used in UL, resulting in a lack of symmetry between the resources needed to accommodate network traffic for each one [12]. Moving on to HetNets, the transmit power of all transmitters in the UL is almost identical since most of them are battery powered portable devices. The UL throughput needs keep rising, mostly thanks to applications that make equal use of both uploading and downloading such as social networks, real time streaming or server connection for video games and UL's independency to distance between nodes and the amount of traffic in the network.

Separating UL and DL into two different subnetworks that make up our network enables us to individually design a model for each network for the sake of eliminating interference with neighboring cells and increase cell association as well as throughput. In this design the User Equipment (UE) can decide on how to establish connection with the BSs, either by connecting with the same cell or with different cells (MBSs or SBSs) during Ul or Dl communication. HetNets are already applied, and became denser with more SBSs scattered among the network.

Several papers have explored the notion of Downlink and Uplink Decoupling (DUD). In [2] it is suggested that it is part of a broader "device centric architectural vision", since the set of network nodes used to connect a certain device to the grid as well as the functions of these nodes in a particular communication session, are tailored to that specific device and session [2]. A disruptive architectural design to study the gains of DuD in UL capacity was proposed in [4].

Additionally, previous attempts have studied the energy efficiency of this method since UL/DL decoupling allows for more flexibility in switching-off some BSs and also for saving energy at the terminal side [10]. Worth mentioning is Range Extension (RE) for UL, by adding a selection offset to the reference signals of Smallcells (Scells) to increase coverage and alleviate traffic from Macrocells (Mcells). Offsets greater that 3–6 dB cause interference on the DL, leading to the development of methods to try and combat these interferences [8]. On the pursuit of energy efficiency for non peak periods, [11] suggest two types of algorithms, for application to any network type, centralized and distributed.

In this paper, we try to improve existing models on this subject, which propose that different BSs are set responsible for UL and DL connection with users, not limiting MBSs and SBSs to DL or UL connections in any way. We will provide an allocation algorithm that will efficiently match a UE to a BS on either UL or DL or both. The proposed mechanism suggests that unused BSs be shut down to minimize resource and energy usage, while still providing adequate QoS and allowing more users to access and connect to the network.

In remaining sectors, we will complete our proposal. Specifically in Sect. 2 we will take a look on the system model of DUD. In Sect. 3 we propose a more efficient algorithm for matching users to the right BS. In Sect. 4 we will analize our simulations setup. In Sect. 5 we will present and analyze the results from our simulations and finally in the end, in Sect. 6 we draw our conclusions and propose our suggestions for future work.

2   System Model

Small Cells become smaller (nano, pico etc) so transmit power differences between MBSs and SBSs are constantly rising, raising the need to optimally match a UE with the appropriate BS for its UL/DL needs. With this technology a UE will now be able to effectively choose Small or Macro Cells to connect to, based on its requirements. That means that even if it is connected to a certain BS in one channel, it can still choose a different BS to connect to.

Traditional cell association suggests that both UL and DL is based on the maximum DL Received Power (RP) as measured at the UE [11]. In our research we assume that DL association is based on SINR, while UL association is based on pathloss, where we also apply Range extension (PLRE). Each user calculates their desired rate and then computes the number of RBs necessary from the BSs to achieve such rate, and tries to connect with their desired BSs.

We consider a multi-tier HetNet that consists of Macro cell Base Stations (MBs), Small cell Base Stations (SCs) and User Equipments (UEs). Suppose that we have a set of MBSs (M $= 1, ..., \mid M \mid$), a set of SMSs (S $= 1, ..., \mid S \mid$) and a set of UEs (U $= 1, ..., \mid U \mid$). All users want to transmit and receive to both directions (UL,DL) that can be considered as separate channels in the network. We consider that users are arranged in space following homogeneous Poisson point process (PPP) ϕ of intensity λ_S, λ_N. Finally each BS has a maximum number of users that it can serve simultaneously quoted as n_i, i $= 1, ..., \mid U \mid$ and also features a number of available Resource Blocks (RBs).

The main focus of UL/DL Decoupling is to offload MBSs and distribute load among remaining SBSs in the MBSs vicinity, enabling better performance for users. In a traditional coupled example each user would link to a single BS, based solely on best DL performance regardless of UL performance. In decoupled models each user will connect to the best possible BS for DL and UL respectively. In our case users connect to a MBS for DL based on DL SINR and to a SBS based on Path loss with RE, seeking the BS that can provide their desired Data Rate (DR) with the least amount of RBs.

In our research we will assume a typical metropolitan area network scenario. We assume that MBSs are mostly mounted above rooftop levels in order to provide continuous uninterrupted coverage in Large Cells. SBSs are based below rooftop levels city-wide to cover up for Non-Line-Of-Sight (NLOS) conditions, that stationary users, or users roaming the streets may experience. These SBSs are able to provide high throughput in areas with high user density especially for indoor terminals, by increasing spatial reuse and thus reducing the number of users per cell [10].

We assume that there is no interference between two users located within the same cell as they can be each assigned to non-interfering sets or resource blocks (RB). A RB a flexible resource structure, where the time-frequency spectrum is divided into orthogonal RBs [3]. First, we calculate Data Rate (DR) as:

$$DR = B_{\mathrm{RB}} * log_2(1 + SINR_{\mathrm{j,i}}),\qquad(1)$$

where B_{rb} corresponds to the bandwidth of a specific RB and $SINR_{\mathrm{j,i}}$ is the signal to interference and noise ratio between user j and Base Station i. The total DR for the whole system is equal to the sum of the DR_M (Mcell DR) and DR_S (Scell DR).

This allows for more flexible resource allocation schemes enabling us to achieve higher spectral efficiency. To compute the number of RBs that a user (suppose user j) needs from a specific Base Station, in order to achieve the desired rate, we will use the following equation:

$$R_{\mathrm{j,i}} = \left\lceil \frac{g_j}{B_R B * log_2(1 + SINR_{\mathrm{j,i}})} \right\rceil,\qquad(2)$$

where g_j denotes the UE throughput demands and DR_i the desired Data Rate for the user j.

Next we shall define the parameters suggested for DUD, PL and SINR. We will define PL for the distance dependent Path loss model, when a user is connected with MBSs (PL_M) as well as SBSs (PL_S). Pathloss is a metric to measure the signal loss in our wireless communication network. The equations that describe them are given below, both for UL and DL:

$$PL_M = 128.1 + 37.6 * log_{10}d\qquad(3)$$

$$PL_S = 140.7 + 36.7 * log_{10}d\qquad(4)$$

And SINR for DL can be calculated as:

$$SINR_{\mathrm{i,j}}^{\mathrm{DL}} = \frac{P_j g_{\mathrm{i,j}} d_{\mathrm{i,j}}^{\text{-a}}}{\Sigma_{\mathrm{kB}}},\qquad(5)$$

3   Matching Algorithm

3.1   Our Approach

Taking into consideration that each BS has an upper bound on its RB capacity we consider as W the number of Resource Blocks (RBs) available for each BS. In this research we consider that all users are equal, with no user having a priority for serving, even though they have different needs and requirements from their respective matched BS. Each user obviously wants to receive and send data and do so with a desired Rate. We assume that all MBSs share the same capacity and all SBSs share the same capacity as well. This issue greatly resembles the Knapsack Problem (KP), on which each Base Station resembles a knapsack,

while users are different objects. We want to maximize Data Rate, so dr can be considered as the profit for selecting a user and the RBs that each user asks for, can be considered as the weight of each user. We will analyze the Knapsack problem for a complete overview later.

Since we focus on UL, we will try to apply Range Extension only on Path loss (our metric for UL association), to satisfy as many users as possible. Range Extension means that while each BS has their own UL border and DL border, now all SBSs are provided with a positive offset, an advantage over MBSs to expand their UL border in order to offload MBSs from some users. Prioritizing SBSs over MBSs in Uplink is expected to yield positive results in the total number of users satisfied and lead to a more uniformally distributed user allocation over the network.

3.1.1   The Knapsack Problem

In the KP we have a set of objects, each one with a specific value (v_i) and its respective weight (w_i). We also have a knapsack, with a limited space of W and the goal is to fit as many objects in the knapsack as we can in order to achieve the maximum profit. Each object can either be selected or not selected, so the problem is usually referred to as the 0–1 Knapsack Problem. Obviously since the carrying capacity of the knapsack is limited, subsequently the amount of objects we can carry is limited.

Given a set of items (suppose n items) we want to maximize our profit [1]:

$$\sum_{i=1}^{n} U_i X_i \tag{6}$$

Suppose that we can carry a set of m $(m < n)$ objects. For all objects we define (X_i) and $X_i = 1$ when an object belongs in the set of chosen objects or $X_i = 0$, when an object is not selected. Obviously for our set of selected objects:

$$\sum_{i=1}^{n} U_i X_i \leq W \tag{7}$$

3.2   The Associations

An association denotes a connection between a user and BSs. This connection can be either on UL or on DL and a user can be connected to different BS for their UL and DL connections, or the same BS for both.

Each user i $\supseteq$ N, can sign a "contract" which includes the identities of the associated with the user BSs for UL and DL connection. Think of a two BS example. Let possibilities for association be the following: user 1 prefers an association with BS 1 in the UL direction and BS 2 in the DL direction based on the utility function we use, so user 1 has a preferred association of $\{UL1, DL2\}$. For the two BS example, we define the preferences as following: $\{UL1, DL2\} > \{UL1, DL1\} > \{UL2, DL1\} > \{UL2, DL2\}$.

For each BS j $\supseteq$ B, we define two separate lists of preferred relations for UL and DL direction, over the set of possible associations.

3.3   The Algorithm

The proposed algorithm aims to provide a stable algorithm that optimizes produced results. The network starts with no users associated with any BS and we consider that there are no limitations to the assignments of users. Each user creates a list consisting of pairs, one for their UL connection and one for their DL connection where each user selects their preferred BS for UL and DL based on PLRE for UL and on SINR on DL. In the UL channel we apply Range Extension on PL, meaning SBSs are favored over MBSs with a positive offset. Range extension is applied if the user attempts a connection with a MBs only, to favor SBSs, in an attempt to offload MBSs. Regarding BSs, users eligible for matching are selected based on the number of RBs they (the BSs) have available.

When a user's (let's assume user i) connection with the BS (assuming BS j) is accepted in the UL direction we use UL_j to suggest a connection, or DL_j to suggest a connection with the user on DL direction. In other words we have a list for each BS stating a connection on UL or DL with each user. At an initial stage we can assume that neither users nor BSs have a reason to drop a possible connection.

In the main phase, users will rank their preferences (with the available contracts) using the proposed scheme (UL: PLRE, DL: SINR). At this point each user has created a preference list. Then each user will submit a request at the BSs for acceptance in the UL or DL direction. It is obvious that each user wants to connect with its most preferred BS in each direction, namely the first match in their matching list. As some BSs may not accept some users' connection, each rejected user attempts to connect with their next most preferred BS, based on the same parameters, meaning that their list of preferences is taken into account in descending order. Now each BS will have to prioritize its available connections and accept requests or decline them.

We consider that each user must connect to some station both on UL and on DL direction. Which means that for user i there should be at least two connections with BSs (let's assure BS j and BS k, where j and k are not necessarily different). After each user produces its preference list, they calculate the number of RBs needed to achieve their desired rate. Each UE transmits to its preferred BS along with their needed RBs. Each BS builds its preference list over the available set of connections based on the number of RBs that each user requests. Each BS has its own limit of users it can accept. All BSs accept users, until they can no longer accept any more users.

Algorithm 1. Pseudocode for the Matching Algorithm

```
 1: U: Denoting all users
 2: MB: Denoting all Macrocell Base Stations (29)
 3: SB: Denoting all Smallcell Base Stations (45)
 4: for num of users= 100, 200, 500, 1000,2000 do
 5:     for i = 1 to MB do
 6:         ACCM(i): Empty;
 7:     end for
 8:     for i = 1 to SB do
 9:         ACCS(i): Empty;
10:     end for
11:     for i = 1 to U do
12:         Create BS preference list for DL over SINR;
13:         Create BS preference list for UL over PL,
14:         applying RE in favor of SBs;
15:         Transmit request to most preferred BS for DL, UL;
16:         Calculate number of RBs to achieve wanted Rate;
17:     end for
18:     for J = MB and J = SB do
19:         for i = 1 to J do
20:             If total BS RBs < user wanted RBs => accept;
21:             If(best PL BS accepts user) then subtract user given RBs from total BS
                RBs
22:             If(no BS accepts user) then check next user
23:         end for
24:     end for
25:     for i = 1 to MB do
26:         If MBS(i) serves no users
27:         Then shutdown;
28:     end for
29:     for i = 1 to SB do
30:         If MBS(i) serves no users
31:         Then shutdown;
32:     end for
33: end for
```

As users are rejected by a BS, then they submit a contract proposal to their next set of preferred BSs for connection. Again each BS shall create a new waiting list (consisted of all the users that can connect with them). The algorithm only concludes when there are no users left unassociated with a BS. Base Stations with no users matched to them, shut down to reduce energy waste.

4   Simulation Setup

For the evaluations performed in this paper, we will model a 5G System in a MATLAB based network simulator following the distance dependent pathloss model for macro cells and small cells. MATLAB provides standard functions

and an intuitive GUI for the design, simulation and verification of Advanced Communication Systems such as mobile networks. It is usually used for research and educational use. MATLAB simulations allow us to perform evaluations that are more difficult or impossible to perform with real systems and study the behavior of our mechanism in a highly controlled, reproducible environment.

We executed simulations for as low as 100 users and as high as 2000 users for a network approach of 29 (fixed) macro cell BSs and 36 or 45 small cell BSs. Our network consists only of the colored hexagons, and all grey colored hexagons are not considered part of our simulation network. At the center of each hexagon we encounter the MBs displayed as a large triangle and two or three small triangles that represent SBs.
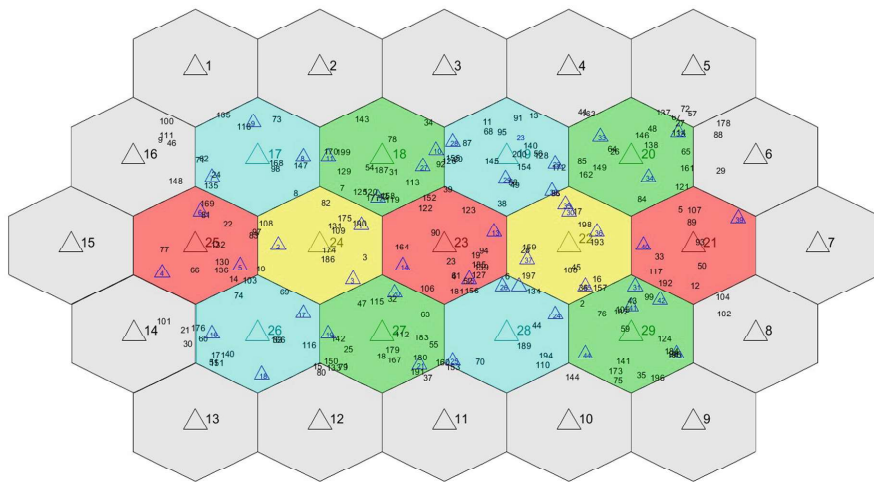

Fig. 1. Our MATLAB simulated network, consisting of 29 MBSs, 45 BSs and a total of 200 users

In our simulations we will consider an area that consists of Macrocell Base Stations (omni-directional with an inter-site distance of 375 m) and Smallcell Base Stations (omni-directional with a radius equal to 50 m). As for our simulation deployment scenario, we will simulate a network and model its performance for different numbers of users. That way we hope to create a model to study the network's scalability potentials. At first, we consider 100 users that seek to use the resources of our network and later this number escalates to 200, 500, 1000 and finally 2000 users. All users have are randomly generated with a personalized chance of appearing inside our area of interest that is served from a cell and a small chance to appear beyond our network. In the downlink network as well as the uplink network, all users have their personalized demands for data rate that range from 2048 (Kbps) to 32768 (Kbps) for the downlink and for the uplink, their demands range from 2048 (Kbps) to 16384 (Kbps). All our simulation parameters will be later presented in the following array (Table 1):

Table 1. Simulation parameters

Parameter	Setting
Propagation model	Macro cell propagation model
DL Bandwidth	100 MHz
UL Bandwidth	100 MHz
User distribution	Poisson point process
Network deployment	29 Mcells and 45 Scells
Number of users	100/200/500/1000/2000
Carrier frequency	3.5 GHz DbM,
Modulation UL Scheme	64QAM

5   Simulation Results

Applying Range Extension on the UL results in an increased number of successful user associations. DRs are proven to be lower in PLRE, by a small margin in comparison to simply applying PL for DUD in the UL channel. The similar DRs with the increased number of associations, result in an increased total network throughput and leads to higher user satisfaction. Channel quality is quite important in the overall satisfaction of throughput demands and as the number of users increases, it is all the more difficult for a large percentage of users to connect to a BS, let alone their preferable BS, which results in setting an upper bound for the total produced DR.

While Small Cells have a large coverage in the UL and they are in fact, able to satisfy a respectable amount of users, as the number of users increases, we notice that the DR for PLRE is following the same pattern as the DR based on simple PL association. It is important to note how DRs seem to increase and decrease as the number of users increases. This not only due to channel quality but it also indicates the need for Adaptive Range Extension (ARE) with different offsets dependent on the BS load or the number of users and possibly indicates that each network should feature different numbers of SBs dependent on the expected user load.

Applying PLRE as the UL metric, we see that more users are connected with Small cells in comparison to simple DUD with PL for UL. Considering that increasing the number of network SBSs is a viable option, this ensures a more homogeneous distribution of UEs between the network nodes and less congestion on Mcells, which, in turn, leads to a better distribution of the network resources. Small cells are used increasingly and steadily by the proposed method, which combined with the increased total user associations, can prevent network congestion in extreme scenarios. Additional studies could examine the best positioning of Scells in order to maximize user allocation, DRs and/or total throughput.

The fact that the UEs connect to the node to which they have the lowest PL results in reduced UL interference. As a result, users are provided with a higher UE SINR allowing the use of higher modulation schemes which results in higher
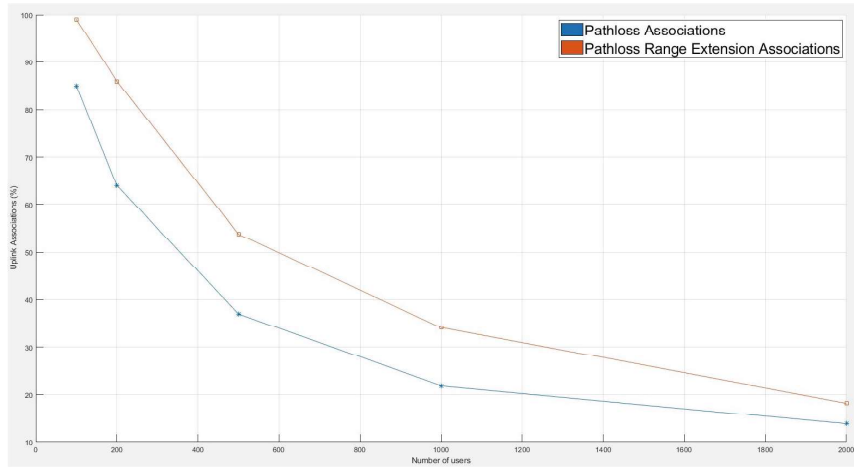
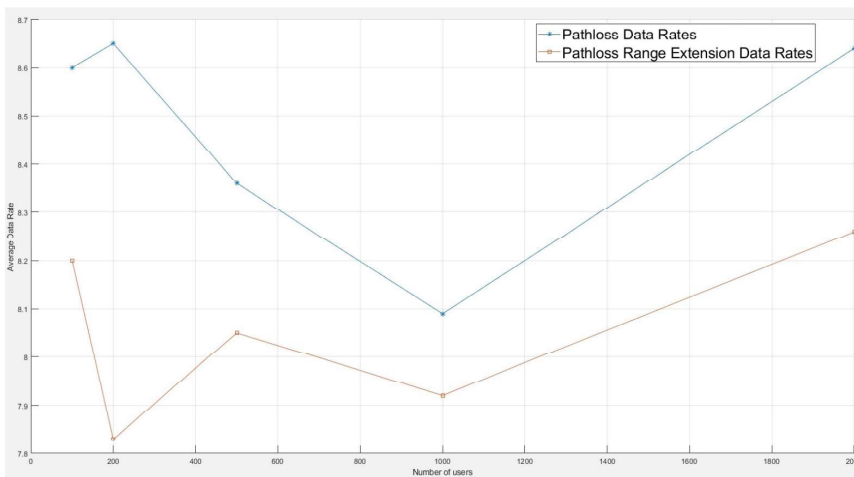**Fig. 2.** Association percentage for PLRE over PL as UL metric

Fig. 3. Average DRs for PLRE over PL as UL metric

speeds for the UL channel. In the DUDe case, UEs are distributed more evenly between the nodes. As the number of UEs increases, all the available nodes are heavily congested in extreme scenarios, but for lower congestion scenarios, some BSs may be able to shut down, and since PLRE favors SBSs, MBSs can lower their transmit power for energy efficiency. The produced results indicate that Range Extension in PL, seems promising in DUD, which in turn, especially for future networks where the network load is expected to increase in the UL and Macro layer.
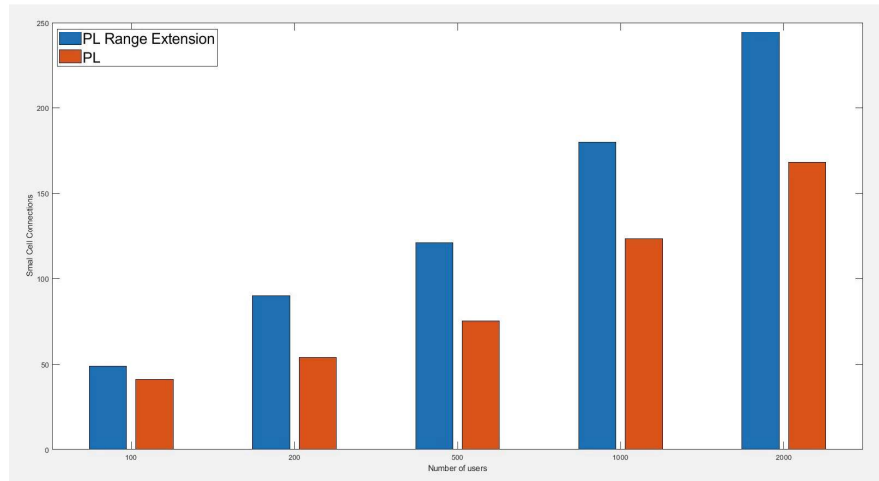
Fig. 4. Number of small cells associations for PLRE vs PL as UL metric

6   Future Work and Conclusion

From the produced results, we see that as the number of network users rises, Base stations are increasingly having problems satisfying most of the users. In this regard, we applied Range Extension on Path Loss for association in the Uplink channel to valorise Small cell Base Stations. The results are promising, with a homogeneous user distribution across the network and higher association rates. The DRs of the proposed mechanisms show potential of improvement, which we expect to be possible by applying Adaptive Range Extension on Path Loss.

User association on wireless mobile networks is a matter of intensive scientific research activities, which makes it essential to study this matter in conjunction with other study fields. As possible candidates, we expect machine learning and game theory to help us understand the mechanics behind overcomplicated network scenarios, to refine existing mechanisms and radically increase efficiency in these networks. Game theory can model existing and possible scenarios and enable us to provide different allocation mechanisms for different scenarios based on the users' needs and strategies, while machine learning can provide us with the tools to alternate these mechanisms in real time or predict these scenarios.

References

1. Lee, C., Lee, Z., Su, S.: A new approach for solving 0/1 Knapsack Problem. In: 2006 IEEE International Conference on Systems, Man and Cybernetics, Taipei, pp. 3138–3143 (2006)
2. Boccardi, F., Andrews, J., Elshaer, H., Dohler, M., Parkvall, S., Popovski, P., Singh, S.: Why to decouple the uplink and downlink in cellular networks and how to do it. IEEE Commun. Mag. **54**(3), 110–117 (2016)

3. Boostanimehr, H., Bhargava, V.K.: Unified and distributed qosdriven cell association algorithms in heterogeneous networks. IEEE Trans. Wireless Commun. **14**(3), 1650–1662 (2015)
4. Elshaer, H., Boccardi, F., Dohler, M., Irmer, R.: Downlink and uplink decoupling: a disruptive architectural design for 5G networks. In: 2014 IEEE Global Communications Conference, pp. 1798–1803 (2014)
5. Cao, J., Zhu, D., Lei, M.: Uplink-downlink interference alignment in TDD-based cellular networks. In: 2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), pp. 353–357 (2013)
6. Zhang, J., Soldati, P., Liang, Y., Zhang, L., Chen, K.: Pathloss determination of uplink power control for UL comp in heterogeneous network. In: 2012 IEEE Globecom Workshops, pp. 250–254 (2012)
7. Samdanis, K., Kutscher, D., Brunner, M.: Self-organized energy efficient cellular networks. In: 21st Annual IEEE International Symposium on Personal, Instanbul, Indoor and Mobile Radio Communications, pp. 1665–1670 (2010)
8. Liu, L., Chang, Y., Qin, R., Zhang, C., Yang, D.: On UL-DL imbalance mitigation for HSPA heterogeneous network. In: 2014 IEEE 80th Vehicular Technology Conference (VTC2014-Fall), pp. 1–7 (2014)
9. Shi, M., Yang, K., Xing, C., Fan, R.: Decoupled heterogeneous networks with millimeter wave small cells. IEEE Trans. Wireless Commun. **17**(9), 5871–5884 (2018)
10. Rost, P., Maeder, A., Perez-Costa, X.: Asymmetric uplink-downlink assignment for energy-efficient mobile communication systems. In: 2012 IEEE 75th Vehicular Technology Conference (VTC Spring), pp. 1–5, May 2012
11. Singh, S., Zhang, X., Andrews, J.G.: Joint rate and SINR coverage analysis for decoupled uplink-downlink biased cell associations in HetNets. IEEE Trans. Wireless Commun. **14**(10), 5360–5373 (2015). https://doi.org/10.1109/TWC.2015.2437378
12. Sun, S., Adachi, K., Tan, P.H., Zhou, Y., Joung, J., Ho, C.K.: Heterogeneous network: an evolutionary path to 5G, pp. 174–178, October 2015
13. Feng, Z., Feng, Z., Li, W., Chen, W.: Downlink and uplink splitting user association in two-tier heterogeneous cellular networks, In: 2014 IEEE Global Communications Conference, pp. 4659–4664, December 2014