Uplink/Downlink Decoupled Access with Dynamic TDD in 5G HetNets

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***Abstract*—Dynamic time-division duplexing (TDD) enables flexible adjustments of uplink (UL) and downlink (DL) resources according to the instantaneous traffic load. However, it also brings new challenges in heterogeneous cellular networks (HetNets) because of the introduction of cross-link interference i.e., uplink to downlink interference and downlink to uplink interference. One step further in the optimization of HetNet, is the interdependency between UL and DL and how the association policies affect the system performance on both links in a way to mitigate the cross-link interference. In classical HetNets, coupled UL/DL access (CoUD) mode is adopted, where each user is associated in downlink and uplink with a single cell. However, the power imbalance between the macro cells and the small cells motivates the decoupling of both links. In the next generation HetNets, instead of being connected to a specific cell, a mobile user can independently receive the downlink traffic from one base station (BS) and transmit uplink traffic through another BS. This situation is referred to as decoupled uplink and downlink (DeUD) access. The optimization of a HetNet based system according to time-variant traffic loads necessitates finding a system level simulator where we can present the motivation and accurately assess the role of both decoupling and dynamic TDD techniques. In this paper, we resort to a system level simulator under which we develop a new module that investigates the dynamic TDD technique along with multiple association policies in a dense HetNet deployment. We create appropriate simulation environment that is relative to real scenarios i.e. simulations where multiple small cells are deployed in a heavy loaded HetNet system and under various traffic loads.**

***Index Terms*—Wireless communications, cellular networks, HetNets, dynamic TDD, 5G, spectral efficiency, outage probability, uplink/downlink decoupling, cell association, system level simulator.**

I. Introduction

The high rate of growth in global mobile data traffic and multimedia services (voice over IP, video, real time streaming, etc.) necessitates finding viable solutions to improve service quality and maximize the network performance. To deal with this issue, HetNets [1] were introduced in 3GPP as one of the main features to meet these advanced requirements. Operators have adopted HetNet solutions to offload traffic from a macro BS to a small cell BS.

Yet, because of the load traffic disparity in DL and UL expected in the next HetNets generation, it becomes essential to dynamically adjust UL/DL resources. In particular, the rapid growth in video streaming traffic results in asymmetric and dynamically changing UL and DL traffic loads. To support this new approach, dynamic time-division duplexing (TDD) ([2]-[4]) has been proposed. However, the importance of UL arises along with the evolution of social networking and cloud solutions. Therefore, it is of great interest to introduce novel techniques that has potential benefits including network load balancing and improvement of performance in UL without any degradation of performance in DL. Such technique is the decoupled UL/DL access ([5] - [11]). In a conventional UL/DL coupled user association policy, a mobile user is associated in UL and DL with the same node. However, in the new design approach with decoupled access, UL and DL are basically treated as separate network entities and a mobile user can connect to different serving nodes in the UL and DL.

In order to address the aforementioned challenges, an important shift from classical HetNets to next-generation HetNets (5G) is emerging in the aim of improving overall system performance. Hence, it is worth mentioning that statistical modeling of both dynamic TDD and decoupling techniques in a next generation HetNet plays an imperative role in evaluating the system performance metrics [12]. However and in order to analytically model an environment relative to a real case scenario, the derived expressions in [12] must be updated to include the following: high number of small cells, scheduling strategies, dynamic resource allocation algorithm, various channel models and load traffic disparity. Such an enhanced analytical model will incur huge computational complexity and any assumption made at this stage in the design parameters, aiming to reduce complexity will lead to non-realistic results. In this context and in order to overcome this limitation, we propose a 5G HetNet system level simulator that supplements an existing LTE simulator [13]. This combination allows for detailed simulation of both dynamic TDD and decoupling techniques and to study their impact in real case scenarios. Our aim is to analyze the outcome of a joint optimization of TDD and decoupling policy compared to conventional HetNets. In this context, we consider one conventional UL/DL coupled user association policy and two types of decoupled UL/DL link association policies. With regard to the dynamic TDD approach, our objective is to find

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the optimal combination between both the macro cell and the small cells TDD configurations with respect to any change in the system, especially in the UL/DL traffic ratio.

A. Related Work

Several recent studies considered analyzing the UL/DL decoupling technique with simulations based on specific network simulators. A set of articles studied various link association policies (including the decoupled policy) and showed their performances based on simulations results. In [14], the concept of DeUD is studied, where the downlink cell association is based on the downlink received power, while the uplink is based on path loss. The follow-up work in [15] considered the cell-load as well as the available back-haul capacity within the association process. The work in [16] added a cell selection offset to the reference signals in small cells.
Other works considered the analysis of both decoupling and TDD techniques under the same system level simulator or trial network. In [17], the problem of decoupled uplink and downlink in time division duplexing (TDD)-based small cell networks is studied. This work focused on the user association technique to solve the problem of dynamic user association in UL/DL decoupled small cell networks with dynamic TDD.

B. Contributions and Organization

In this paper, we conduct simulations using a system level simulator where we consider analyzing a system supporting a dynamic TDD resource allocation along with UL/DL decoupled access in a dense HetNet deployment. Other works proposed various link association policies (coupled and decoupled policies) and showed their performance gain with simulations based on LTE field trial network, without considering any dynamic TDD configuration.
Few studies considered simulating both decoupling and dynamic TDD techniques as in [17], however these techniques were not implemented under a system simulator with scheduling decisions to dynamically allocate UL/DL resources. Note that the implementation of scheduling algorithms plays an important role in ensuring a fair and efficient distribution of resources, whether in the uplink or downlink. Moreover, the work in [17] did not consider the case of a HetNet deployment in the presence of macro cells, it considered small cell networks instead.

The remainder of the paper is organized as follows. In Section II, we describe the network model. Section III introduces the proposed UL/DL link association policies. In Section IV, we present the dynamic TDD approach adopted in this work. Section V introduces the simulation setup, and simulation results are discussed in details in Section VI. Finally, Section VII concludes the paper.

II. Network Model

We consider a two-tier heterogeneous cellular network consisting of one macro cell and multiple small cells as shown in Fig 1. We denote by N_s the number of small cells. In the coming sections, the radius of the macro cell and the small cell will be denoted by R and R_s, respectively. All users are uniformly distributed between the macro cell and the small cells. They are using a full buffer traffic model in UL as well as in DL. We define η in dB, as the UL to DL traffic ratio between the users operating in UL and those operating in DL. The total number of active users equipment (UEs) is denoted by N_u.
As simulation setup, we consider the LTE-sim simulator [13] to which we have added customized features in order to be aligned with our system model. The added modules include, but not limited to, decoupling and dynamic TDD techniques. More details about the customization will be described in Section V.

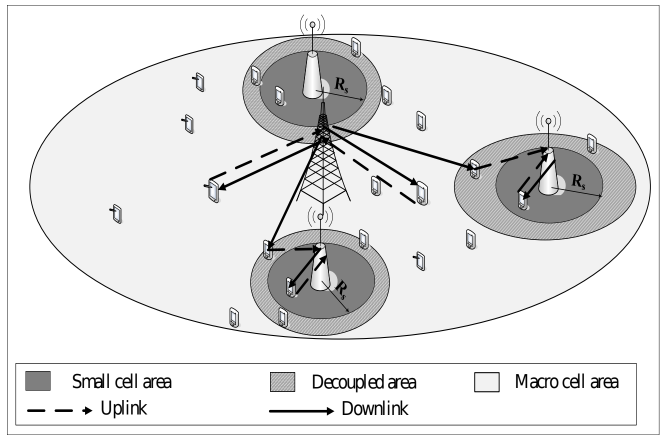

Fig. 1. Illustration of the proposed system model.

III. UL/DL user association policies

Three different association policies have been implemented in this work; they can be dynamically selected as input parameters for the simulations that follow. In these simulations, we compare the conventional UL/DL coupled user association policy with two types of decoupled UL/DL link association policies as follows:

- Cell association criteria in DL and UL is based on DL Reference Signal Received Power (RSRP) which is the conventional LTE user association policy. This case is referred to as **CoUD**.
- Cell association criteria in DL is based on DL Reference Signal Received Power (RSRP) whereas the criteria in UL is based on the uplink received power with cell selection offset in case of a small cell. A cell selection offset is added to the received power at the small cells to increase their coverage in UL and thus, to offload UL traffic from the macro cell. In this work, we consider an offset equal to 13 dB. This case is referred to as **DeUD_PO**.
- Cell association criteria in DL is based on DL Reference Signal Received Power (RSRP) whereas the criteria in UL is based on the path loss. This case is referred to as **DeUD_PL**.

IV. Dynamic TDD approach

In the 3GPP standard, dynamic TDD is supported by seven configurations with respect to different uplink and downlink traffic ratios [2]. As shown in Fig. 2, each radio frame consists of 10 subframes, and the UL/DL ratio is different for each TDD frame configuration. This enables either the macro cell or the small cells base stations to select different configurations according to the traffic variation. For example, we denote by (0,5) a joint TDD configuration between macro and small cells where 0 and 5 are the UL/DL TDD configurations adopted in the macro cell and the small cells respectively (see Fig. 2). In this context, we define the following notations:

- m denotes the UL/DL TDD configuration in the macro cell.
- s denotes the UL/DL TDD configuration in all small cells.
- $T = (m, s)$ denotes the joint UL/DL TDD configuration in the system.

TDD UL-DL Configuration	**DL-UL Switch-point periodicity**	**Subframe number**									
		0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

Fig. 2. Supported TDD configurations in 3GPP [2].

V. Simulation Setup

For our simulation-based evaluation, we use the LTE-Sim [13] system level simulator to which, the following new enhancements are added:

- Instead of using the CQI indicator for downlink and uplink scheduling, a new metric named uplink channel quality is implemented in the uplink scheduling.
- Updating the conventional TDD framework to include the dynamic TDD feature.
- Calculating the cross-link interference (UL to DL and DL to UL). This interference results from applying the dynamic TDD approach.
- Developing two types of decoupled UL/DL link association policies: one based on UL path loss and the other based on UL received power assisted with cell selection offset.
- Creating and configuring multiple instances of small cells in a HetNet dynamic TDD based system.

For the selected scheduling algorithms, there are various scheduling methods that have been developed over time to enhance the process of data distribution. In this work, we shall be concentrating on two algorithms in particular: Round Robin as uplink scheduler and Proportional Fair as downlink scheduler. As for the selected propagation loss model, the large scale shadowing fading has been modeled through a log-normal distribution with 0 mean and a standard deviation of 8 dB. The penetration loss is set to default value of 10 dB. The fast fading is conceived for all the implemented propagation loss models by the Jakes model [18] for the Rayleigh fading, taking into account the user speed, the sub-carrier frequency, and a number of multiple paths uniformly chosen in the set [6, 8, 10, 12]. As for the pathloss, the implemented models can be grouped under one expression that can be written as follows:

TABLE I
Simulation parameters

Parameter	**Value**
Macro cell radius (R)	1 Km
Small cell radius (R_s)	250 m
Min. distance between small cell and macro cell	50 m
Carrier frequency	2.0 GHz
Duplex mode	Dynamic TDD
TDD frame length	10 subframes
Sub-frame duration	1 ms
System bandwidth	20 MHz
Max. macro BS transmit power	46 dBm
Max. small cell BS transmit power	30 dBm
Max. UE transmit power	23 dBm
Thermal noise	-148.95 dBm/Hz

$$PL(dB) = A + 37.6 log_{10} r \text{ @ 2GHz},$$

where r is the distance between the transmitter and the receiver in kilometers and A is a constant that is set to 140.7 in urban areas, to 128.1 in suburban areas and to 100.54 in rural areas. The simulation parameters in Table I have been considered so as to create the most appropriate simulation environment that is relative to real scenarios. To note that on both downlink and uplink scenarios, only one flow per user was initiated, transmitting an infinite buffer application on top of UDP transport protocol. Resource allocation in each simulation is carried out over a period of 1 second (i.e. 100 LTE frames). In order to obtain accurate and stable results, simulation output values are averaged over 100 iterations. In the conducted simulations, we follow the procedure elaborated in Algorithm 1 to jointly implement a dynamic TDD based system with coupled/decoupled user association policies and to analyze the outcome resulting from this joint implementation. The algorithm starts by initializing the design parameters to their conventional values. The joint TDD configuration between macro and small cells is set to (0,0) and the association policy is set to CoUD. V captures any change in the system variables, e.g. traffic load. This change triggers a while loop till finding the optimal UL/DL average throughput (C_{opt}). At each step, the iteration changes at least one of the design parameter: m, s or the association policy. The calculated UL/DL total throughput resulting from this iteration is compared to the previous values of C_{opt}. The algorithm terminates by finding the optimal combination of TDD configuration and association policy that offers the highest (C_{opt}) throughput.

Algorithm 1 Joint implementation of dynamic TDD with coupled/decoupled user association policies

procedure SIMULATION PROCEDURE
  T=(m,s) $\leftarrow$ Joint TDD configuration
  $ua \leftarrow$ User association policy
  $V \leftarrow$ System input variables
  $C_{opt} \leftarrow$ UL and DL optimal average throughput
  $C_{opt} \leftarrow$ Calculate(ua,(m,s),V)
  while V changes **do**
    for $m \leftarrow 0$ to 6 **do**
      for $s \leftarrow 0$ to 6 **do**
        $ua \leftarrow$ CoUD
        if Calculate(ua,(m,s),V) $> C_{opt}$ **then**
          $C_{opt} \leftarrow$ Calculate(ua,(m,s),V).
        $ua \leftarrow$ DeUD
        if Calculate(ua,(m,s),V) $> C_{opt}$ **then**
          $C_{opt} \leftarrow$ Calculate(ua,(m,s),V).

VI. SIMULATION RESULTS

In this section, we evaluate first the performance of a HetNet system adopting the conventional TDD configuration (i.e. an UL/DL fixed configuration) with coupled/decoupled association policies. Then, we will follow the procedure in Algorithm 1 and assess the improvement brought by the joint implementation of dynamic TDD and UL/DL decoupled access to the system, in terms of UL and DL throughputs.
Figure 3 shows the evolution of UE average uplink throughput as a function of the number of small cells for various association criteria with T = (0,0). We notice that the decoupling case with path loss option (DeUD_PL) outperforms CoUD and DeUD_PO cases regardless of the number of deployed small cells. This is due to the fact that users are dispersed and not centralized in one area (cell edge area or cell center area). Moreover, it came to our attention that CoUD case tends to progress similarly to DUDe when the number of small cells significantly increases. This can be explained by the fact that, when increasing the number of small cells, the users in coupled mode are now in the range of small cells in terms of DL signal received power, without the need to refer to the UL path loss option.

Figure 4 depicts the 5^{th} percentile uplink throughput in a conventional TDD HetNet under various small cells density. It can be observed that the DeUD_PL case prevails over the DeUD_PO case when deploying two to four small cells, however and after adding increasingly more small cells, we notice a drastic change in the behavior of both cases. The DeUD_PL case outperforms the DeUD_PO for dense small cells networks i.e. when number of deployed small cells is greater than four. This is due to the fact that, when adding more small cells, the cell edge users will be more subject to harmful interference from close macro users. Consequently, and in order to mitigate the UL interference caused by the macro users, the path loss association policy is no more able to do the job. Instead, applying the association policy that

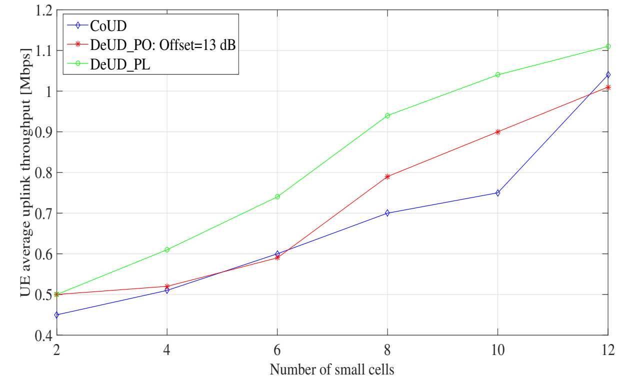

Fig. 3. Comparison of the UE average uplink throughput between CoUD, DeUD_PO and DeUD_PL cases while increasing the number of small cells with $N_u = 100$, $\eta = 0$ dB and T = (0,0) (conventional TDD).

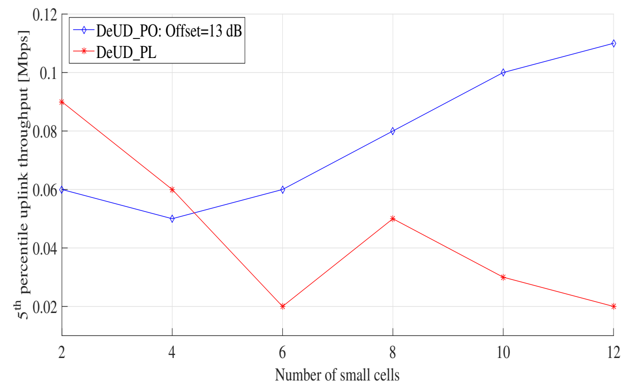

Fig. 4. 5^{th} percentile uplink throughput comparison between DeUD_PO and DeUD_PL cases while increasing the number of small cells with $N_u = 100$, $\eta = 0$ dB and T = (0,0) (conventional TDD).

extends the small cell coverage by adding a specific bias i.e. the DeUD_PO policy will reduce the UL interference and thus, improve the 5^{th} percentile uplink throughput.

Figure 5 shows the 5^{th}, 50^{th} and 90^{th} percentile uplink throughput for the three association polices in comparison. We can observe that the 5^{th} percentile uplink throughput in the DeUD_PO case is increased by 37.5 % compared to the CoUD case and by more than 400 % compared to the DeUD_PL. The small cell expansion caused by the DeUD_PO plays an imperative role in decreasing the level of UL interference by attaching the macro users to the nearest small cell. This will explain the improvement in 5^{th} percentile uplink throughput brought by the DeUD_PO case to the cell edge users. As for the 50^{th} percentile uplink throughput, we notice that the DeUD_PO case outperforms both the CoUD and DeUD_PL cases by 120 % and 41 % respectively. Note that the gains in the 5^{th} and 50^{th} percentile are resulting from the higher coverage of the small cells in the DeUD_PO case with an offset equal to 13 dB. Looking at the 90^{th} percentile UL throughput, we can see that the DeUD_PL case achieves the

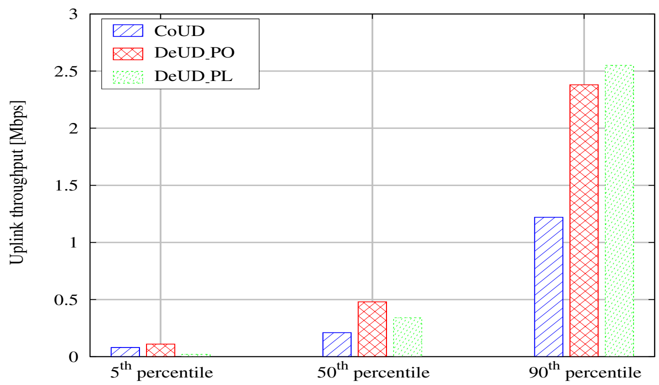

Fig. 5. 5^{th}, 50^{th} and 90^{th} percentile uplink throughput comparison of CoUD, DeUD_PO and DeUD_PL cases with $N_u = 100$, $N_s = 12$, $\eta = 0$ dB and T = (0,0) (conventional TDD).

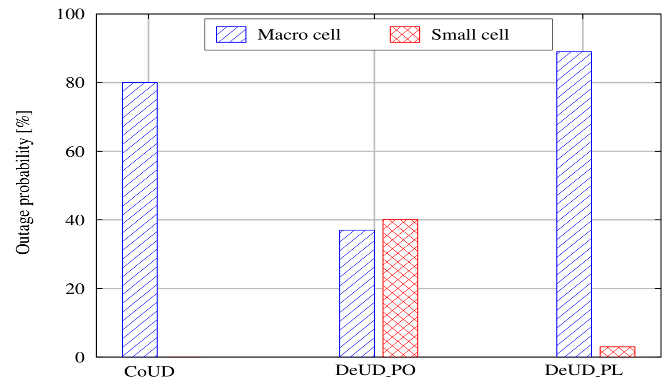

Fig. 6. Outage probability in macro and small cells between CoUD, DeUD_PO and DeUD_PL cases with $N_u = 100$, $N_s = 4$, $\eta = 0$ dB and T = (0,0) (conventional TDD).

highest throughput which can be explained by the fact that that small cells serve less users than the DeUD_PO case so these users get a higher throughput but on the expense of the 5^{th} and 50^{th} percentile users.

Figure 6 captures the average outage probability of the users associated to the macro cell from one side and those attached to the small cells from the other side. In this work, we define the outage probability in one cell as the percentage of users that fail to reach the minimum throughput demand (considered as equal to 250 Kbps) out of the total number of users attached to that cell. As expected, it can be noticed that the macro cell has a very high outage rate (more than 80 %) in the coupled CoUD case. This is basically due to the fact that the macro cell is very congested in the UL because of the adopted association policy that is based on the downlink received power. Hence, macro cell BS won't have enough resources to serve all of its associated users with a high throughput level. However, in the decoupled case, users are distributed more evenly between the macro and the small cells. This is reflected more obviously in the DeUD_PO case where the macro cell reaches an outage probability of 37 % and the small cells achieve an average outage rate of 40 %. In this case, macro users who used to suffer from low throughput are moved to the edge of the small cells, causing a state of evenness in the outage probability between macro cell and small cells.

In Fig. 7, we show the performance of different schemes in different traffic load conditions. This figure investigates a joint UL and DL system throughput optimization between the following four schemes: 1) Conventional TDD, in which we consider the same synchronized TDD configuration between the macro cell and small cells (T = (0,0) in this case), along with the conventional CoUD association policy. 2) Conventional TDD with DeUD. We consider the DeUD_PL case as the association policy adopted in the next simulations to represent the decoupled access technique (DeUD). 3) Dynamic TDD, in which we consider unsynchronized and dynamic TDD configuration between the macro cell and the small cells that will vary according to UL/DL traffic demands. A conventional CoUD policy is considered in this case. 4) Dynamic TDD with DeUD, in which we consider a joint implementation of dynamic TDD with decoupled UL/DL user association. The purpose is to find the optimal scenario that will jointly improve the UL and DL throughputs in a HetNet TDD based system. Figure 7 shows the performance for the case of four small cells. The number of users operating in UL and DL is varied by changing the UL to DL traffic ratio (η), expressed in dB. As an example, $\eta < 0$ means that the downlink traffic is greater than the uplink traffic, whereas $\eta > 0$ means the opposite. It can be noticed that increasing either the UL or DL traffic load degrades the performance of the different schemes. Comparing the first two schemes, we can observe that the conventional TDD with decoupling outperforms the conventional TDD with CoUD case. However, it is worth noting that the average gain achieved for $\eta > 0$ (around 16 %) is higher than the one reached for $\eta < 0$ (around 4 %). This is due mainly to the higher UL interference levels experienced when $\eta > 0$ and knowing that the main role of DeUD is to reduce that type of interference. It is obvious as well that the dynamic TDD scheme outperforms both conventional TDD schemes since as expected, adjusting the TDD configuration dynamically according to the instantaneous traffic load will improve the overall system performance. For example, when $\eta = 6$ dB i.e. the UL traffic is around four times the DL traffic, the system adjusts the TDD configuration to T = (3,3) by following the procedure in Algorithm 1 in a way to improve the system performance in terms of both UL and DL throughputs. However, for $\eta = -6$ dB i.e. the DL traffic is around four times the UL traffic, T is adjusted to (5,5). Moving to the fourth scheme, we can observe that implementing jointly both dynamic TDD and DeUD techniques will further improve the system performance, mainly in high load conditions for $\eta > 4.8$ dB and $\eta < -3$ dB. This can be explained by the fact that the DeUD is more effective while dealing with higher interference levels mostly experienced in high load conditions.

Next, we investigate in Fig. 8 the benefits that the four schemes can bring to a dense HetNet with high number of

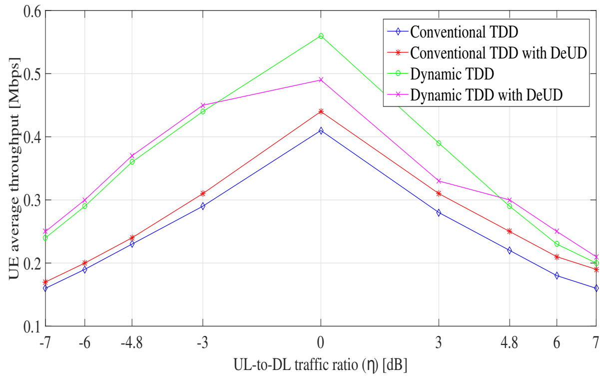

Fig. 7. Uplink and downlink UE average throughput in different traffic load conditions with conventional TDD or dynamic TDD, with decoupling or without decoupling considering $N_s = 4$.

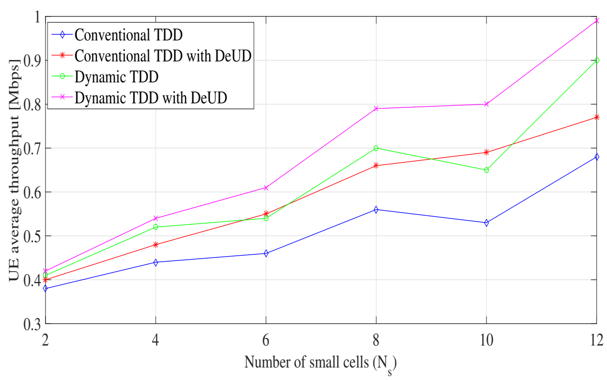

Fig. 8. Uplink and downlink UE average throughput with conventional TDD or dynamic TDD, with decoupling or without decoupling while increasing the number of small cells with $N_u = 100$ and $\eta = 0$ dB.

deployed small cells. We can clearly see that, even in lightly loaded systems where $\eta = 0$ dB, the proposed algorithm i.e. the fourth scheme also achieves high throughput gain that significantly improves as the number of small cells increases.

VII. Conclusion

The focus in this paper was to study and assess the gains that different association policies can bring to a dynamic TDD HetNet system. We have presented simulation results based on a system level simulator under which additional modules have been developed to motivate our system model. Relying on the proposed algorithm, we have shown the performance results of a joint dynamic TDD with coupled/decoupled user association policies in a dense HetNet deployment. The findings confirm that the DeUD_PO policy can achieve high gains in the 5^{th} and 50^{th} percentile throughput. Also, we have observed that the DeUD_PO policy causes a balance in the users' outage probability between macro cell and small cells, contrary to CoUD and DeUD_PL association policies. Moreover, it is further observed that the proposed algorithm (Dynamic TDD with DeUD) yields significant performance improvements in UL and DL throughput compared to a number of conventional schemes, especially in dense HetNet deployment and in highly loaded systems.

In future work, we plan to consider non-uniform users distribution including the case where the users can be in the same place at the exact same time. Moreover, it is interesting to investigate the performance of the decoupling mode in TDD systems with hybrid HetNet deployment, where mmWave small cells are supposed to be deployed as an overlay to traditional sub-6GHz macro cells [19].

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