Analytical Evaluation of Decoupled Uplink and Downlink Access in TDD 5G HetNets

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***Abstract*—Due to load traffic disparity in downlink (DL) and uplink (UL) in heterogeneous cellular networks (HetNets), dynamic time-division duplexing (TDD) is proposed to dynamically allocate UL and DL resources. Under the same circumstances, decoupled UL/DL access is introduced to balance between UL and DL transmissions and to further improve the overall system performance. In classical HetNets, coupled UL/DL access (CUDA) mode is adopted, where each user is associated in downlink and uplink with a single cell. In the next generation HetNets, rather than belonging to a specific cell, a mobile user can receive the downlink traffic from one base station (BS) and send uplink traffic through another BS. This situation is referred to as downlink and uplink decoupled access (DUDA). In this paper, we analytically investigate a joint TDD and DUDA statistical model based on a geometric probability approach. Taking all possible TDD subframes combinations between the macro and small cells, four coupled and decoupled cell associations strategies are investigated in details. We derive inter-cell interference and capacity expressions for each of these association policies to assess the improvement brought by DUDA mode to TDD HetNets. In this particular DUDA mode, users are associated in UL with the small cell and in DL with the macro cell. Moreover, we identify the small cell offset under which the decoupled mode performs significantly better and maintains a higher spectral efficiency in both DL and UL. Monte-Carlo simulations results are presented to validate the accuracy of the analytical model.**

***Index Terms*—Wireless communications, cellular networks, downlink and uplink decoupled access, HetNets, TDD, spectral efficiency, cell association, capacity analysis.**

I. Introduction

The high growth rate in global mobile data traffic (video streaming, live streaming, etc.) necessitates finding practical solutions to improve quality of service and maximize the network performance. To accommodate these bandwidth intensive applications, an imperative shift from classical HetNets to next-generation HetNets (5G) is emerging in the aim of improving overall system performance. Because of the notable difference in UL and DL traffic load, dynamic time-division duplexing (TDD) ([1], [2]) has been proposed to adjust UL/DL resources according to the instantaneous traffic variation between the UL and DL. 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 mitigate UL interferences, improve UL and DL throughputs and allow as well, a better use of radio resources by providing adequate load balancing among UL and DL. Such an additional feature is the decoupled UL/DL access ([3], [4]). Deriving closed form expressions for inter-cell interference and user capacity in TDD HetNets helps in designing and optimizing advanced enhancement techniques, including but not limited to the decoupled access technique. Deriving these expressions reduces as well the need for time consuming Monte-Carlo simulations. Hence, the focus of this paper is to develop a joint TDD/decoupling model and to highlight the benefits that the decoupling access mode can bring to a HetNet TDD based system, in terms of UL and DL spectral efficiencies.

A. Related Work

Several recent studies introduced the concept of downlink/uplink decoupling. The work in [5] focused on the architectural design and realization, identified and explained some key arguments in favor of DUDA.
A group of articles studied various link association policies and showed their performances based on simulations results. In [6], the notion of DUDA 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 [7] considered the cell-load as well as the available back-haul capacity within the association process. The work in [8] added a cell selection offset to the reference signals in small cells.
Other works focused on the analytical evaluation of a predefined association policy. The research work in [9] and [10] focused on the analytical characterization of the decoupled access, relying on the stochastic geometry framework and applying a specific association criteria (power received or transmitted). Uplink performance improvement brought by a DUDA mode over a conventional CUDA mode, was investigated in [11]. A general analytical framework in a hybrid system (sub-6GHz and millimeter wave) was developed in [12] where the biased uplink and downlink cell association, as well as the rate coverage probability, are derived.

As for the modeling of TDD systems, the work in [13] introduced a statistical framework to model the UL/DL inter-cell interference in TDD networks. The distance distribution probability was scheduling-based and the users were associated according to the conventional downlink received power policy.

B. Contributions and Organization

In this paper, we develop a general model for inter-cell interference and user capacity in a TDD system for various link association policies. This model is based on a geometric probability approach.
The main contributions of this work can be summarized as follows:

- Studying the next-generation wireless 5G HetNets with respect to TDD and UL/DL decoupled access. Other works investigated either a TDD system as in [13] or the decoupled access technique as in [6]-[12]. In fact, considering a TDD scenario jointly with a decoupled association policy appears to be a viable solution to address UL and DL throughput degradation challenges.
- Development of an analytical model covering various user association policies, whereas similar works either developed an analytical model studying one specific association criteria ([9]-[12]) or investigated multiple association strategies based on simulation results ([6]-[8]). In this work, the main focus is to study the improvement that the decoupling access can bring to TDD HetNets among all other association policies.

The rest of the paper is organized as follows. In Section II, we introduce some basic notations and the system model of coupled and decoupled modes in TDD HetNet. Then, we develop a statistical framework to model the desired signal and the interference signals, and thus derive the user average capacity in CUDA and DUDA modes, respectively in Section III and IV. In Section V, we present analytical results as well as simulation results to evaluate and compare the performances of the four association strategies at hand. Finally, Section VI concludes this paper.

II. System Model

We consider a HetNet consisting of a small cell and a macro cell. A new area, considered as an extension to the small cell average zone, will be studied in the aim of analyzing the impact of the decoupled UL/DL access and other access policies on the users located inside and outside this expanded area. This model is adequate for this study and provides sufficient information on the system performance under the aforementioned circumstances.
Introducing the DUDA mode necessitates a thorough comparison study with the conventional coupled UL/DL access (CUDA) mode. We first derive the statistics of the interference signal and the signal of interest of both DUDA and CUDA modes and then analyze the system performance of these two access modes. For further analysis and to ensure the generality of our study, the CUDA scenario is analyzed by taking into account two cases:

1) Coupled access in UL and DL with the macro cell.
2) Coupled access in UL and DL with the small cell.

Two cases, as well, can be part of the DUDA mode:

1) Decoupling strategy where users are associated in UL with the small cell and in DL with the macro cell.
2) Reverse Decoupling strategy where users are associated in UL with the macro cell and in DL with the small cell.

In each case and in order to characterize the concurrent inter-cell interference in a TDD HetNet, the proposed model mandates analyzing four interference scenarios by considering all UL/DL TDD possible combinations. For example, Up - Down scenario defines a situation where the macro cell is operating in uplink and the small cell in downlink. Same logic applies to define the other three scenarios. In the coming sections, the radius of the macro cell and the small cell will be denoted by R and R_s respectively. The distance between the macro cell and the small cell will be designated by d. Let R_e be the radius of the expanded area, which will be a tunable variable in our analysis. Figure 1 displays all possible desired links and interfering links for which statistical expressions are derived in the next sections.

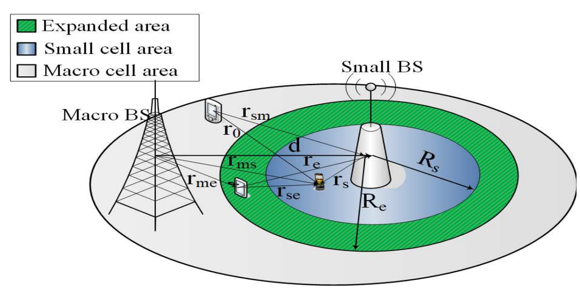

Fig. 1. Geometrical illustration of all possible links distribution.

III. System Analysis with CUDA

In this section, we will consider the users in the expanded area associated in UL and DL with a single cell. Two cases are considered, where users in this area are either coupled to the macro cell or to the small cell (Fig. 2).

A. CUDA with Macro Cell

In this paper, all proposed association strategies (coupled or decoupled), will be compared to the present case since initially and before applying any change to the network configuration, users in the expanded area are considered in DL and UL as associated with the macro cell.
In each of the below possible UL/DL combinations, we derive the statistics of both the small cell and the expanded area users.

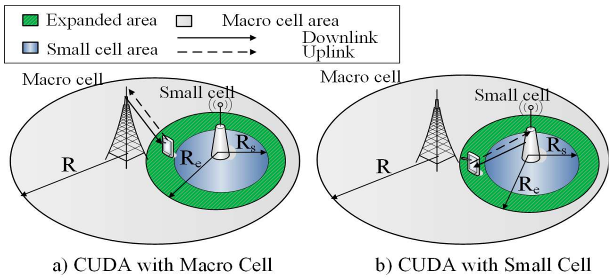

Fig. 2. CUDA illustration.

1) Down - Down Scenario: The downlink interference from the small cell BS to the mobile user in the expanded area is defined as $I_e = KP_s r_e^{-\gamma}$, with γ the path-loss exponent, r_e the distance of the user in the expanded area from the small cell BS, P_s the transmit power of the small cell BS per channel, and K the composite fading channel. Since we consider uniformly distributed users, the distribution of the distance r_e of users in the expanded area bounded between R_s and R_e is given by:

$$f_{r_e}(r) = \frac{2r}{R_e^2 - R_s^2}, \quad R_s \leq r \leq R_e. \tag{1}$$

The signal of interest of the mobile user in the expanded area is defined as $S_e = KP_m r_{me}^{-\gamma}$ with r_{me} the distance of the user in the expanded area from the macro cell BS and P_m the transmit power of the macro BS per channel. Based on [14], let $f(r)$ be the result of the cell intersection with the circle of radius R_e:

$$f(r) = \pi r - 2r\arcsin(\frac{d^2 + r^2 - R_e^2}{2dr}),$$

and $g(r)$ the result of the cell intersection with the circle of radius R_s:

$$g(r) = \pi r - 2r\arcsin(\frac{d^2 + r^2 - R_s^2}{2dr}).$$

Consequently, the probability density function (PDF) of r_{me} can be written as:

$$f_{r_{me}}(r) = \begin{cases} \frac{f(r)}{(\pi R_e^2 - \pi R_s^2)}, & d - R_e \leq r \leq d - R_s \\ \frac{f(r) - g(r)}{(\pi R_e^2 - \pi R_s^2)}, & d - R_s \leq r \leq d + R_s \\ \frac{f(r)}{(\pi R_e^2 - \pi R_s^2)}, & d + R_s \leq r \leq d + R_e. \end{cases} \tag{2}$$

Note that in the third case where $d + R_s \leq r \leq d + R_e$, the PDF of r_{me} (denoted by $f_{r_{me}}(r)$) is obtained from its corresponding cumulative distribution function (CDF), defined as:

$$F_{r_{me}}(r) = \frac{F_3(r) - \pi R_s^2}{(\pi R_e^2 - \pi R_s^2)},$$

where $F_3(r)$ is the CDF resulting from the cell intersection with the circle of radius R_e [14] and πR_s^2 the area of the small cell. Applying the derivative to $F_{r_{me}}(r)$, $f_{r_{me}}(r)$ will be:

$$f_{r_{me}}(r) = \frac{f(r)}{(\pi R_e^2 - \pi R_s^2)}.$$

As for the statistics related to the small cell users, the downlink interference from the macro BS to the small cell users is defined as $I_s = KP_m r_{ms}^{-\gamma}$ with r_{ms} the distance of the macro BS from the small cell user. Based on [14], the PDF of r_{ms} can be obtained as a result of the cell intersection with the circle of radius R_s:

$$f_{r_{ms}}(r) = \frac{1}{\pi R_s^2}\Big(\pi r - 2r\arcsin(\frac{d^2 + r^2 - R_s^2}{2dr})\Big). \tag{3}$$

The signal of interest of the small cell user is defined as $S_s = KP_s r_s^{-\gamma}$ with r_s the distance of the small cell user from the small cell BS. Since we consider uniformly distributed users, the distribution of the distance r_s of a small cell user is given by:

$$f_{r_s}(r) = \frac{2r}{R_s^2}, \quad 0 \leq r \leq R_s. \tag{4}$$

Note that the same expressions of S_s and r_s apply when tackling the small cell user's statistics in all coming scenarios, where the transmit power varies depending on the link direction, either UL or DL.

2) Up - Down Scenario: The uplink interference from the small cell BS to the macro BS is defined as $I_e = KP_s d^{-\gamma}$ with d the distance of small cell BS from the macro cell BS. The uplink desired signal of the mobile user in the expanded area is defined as $S_e = KP_{um} r_{me}^{-\gamma}$ with P_{um} the transmit power of the macro cell user per channel. The PDF of r_{me} can be given by iterating the same analysis as in (2).

As for the statistics related to the small cell users, the downlink interference from the macro cell user to the small cell user is defined as $I_s = KP_{um} r_0^{-\gamma}$. The PDF of r_0 is derived by averaging over the PDF of r_{sm} ($f_{r_{sm}}(r_{sm})$):

$$f_{r_0}(r) = \int_{r-R_s}^{r+R_s} f_{r_0}(r)_{|r_{sm}} f_{r_{sm}}(r_{sm}) dr_{sm}, \tag{5}$$

where r_{sm} is the distance of the small cell BS from the macro cell user and $f_{r_0}(r)_{|r_{sm}}$ denotes the PDF of r_0 conditioned on r_{sm}. Consequently, $f_{r_0}(r)_{|r_{sm}}$ can be derived as follows:

$$f_{r_0}(r)_{|r_{sm}} = \frac{1}{\pi R_s^2}(\pi r - 2r\arcsin(\frac{r_{sm}^2 + r^2 - R_s^2}{2r_{sm} r})).$$

As for the derivation of the r_{sm} statistics, and since $R > d$, two cases must be taken into account based on [14]:

$$f_{r_{sm}}(r_{sm}) = \begin{cases} \frac{2\pi r_{sm}}{\pi R^2 - \pi R_s^2}, & R_s \leq r_{sm} < R - d \\ k(r_{sm}), & R - d \leq r_{sm} \leq R + d, \end{cases} \tag{6}$$

$$k(r_{sm}) = \frac{1}{\pi R^2 - \pi R_s^2}(\pi r_{sm} - 2r_{sm}\arcsin(\frac{d^2 + r_{sm}^2 - R^2}{2dr_{sm}})).$$

3) Up - Up Scenario: The uplink interference from the small cell user to the macro BS is defined as $I_e = KP_{us} r_{ms}^{-\gamma}$. The PDF of r_{ms} is given by (3). The uplink signal of the mobile user in the expanded area is defined as $S_e = KP_{um} r_{me}^{-\gamma}$. The PDF of r_{me} can be defined similarly as in (2).

As for the statistics related to the small cell users, the uplink interference from the macro cell user to the small cell BS is defined as $I_s = KP_{um}r_{sm}^{-\gamma}$. The PDF of r_{sm} is defined similarly as in (6).

4) Down - Up Scenario: The downlink interference from the small cell user BS to the mobile user in the expanded area is defined as $I_e = KP_{us}r_{es}^{-\gamma}$ with r_{es} the distance of the user in the expanded area from the small cell user and P_{us} the transmit power of the small cell user per channel.

Since r_{es} refers to the distance between two randomly selected nodes in concentric circles and in this case the two nodes are uniformly distributed, the PDF of r_{es} can be derived using the closed form expression obtained in [15]. The inner concentric circle is the one in which the small cell users are located and its radius is equal to $a = R_s$. The users in the expanded area are located in the outer concentric circle with radius equal to $b = R_e$. In this context, the PDF of r_{es} can be written as:

$$f_{r_{es}}(r) = \begin{cases} \frac{2r}{b^2}, & 0 \le r \le b-a \\ \frac{r}{\pi}\Big(\frac{2v(r)-\sin(2v(r))}{b^2}+ & \\ \frac{2w(r)-\sin(2w(r))}{a^2}\Big), & b-a \le r \le b+a, \end{cases} \tag{7}$$

where $v(r) = \arccos(\frac{r^2-b^2+a^2}{2ra})$ and $w(r) = \arccos(\frac{r^2+b^2-a^2}{2rb})$.

The signal of interest of the mobile user in the expanded area is defined as $S_e = KP_m r_{me}^{-\gamma}$. Repeating the same analysis as in (2), we can define the PDF of r_{me}.

As for the statistics related to the small cell users, $I_s = KP_m d^{-\gamma}$ and $S_s = KP_{us}r_s^{-\gamma}$.

B. CUDA with Small Cell

1) Down - Down Scenario: The downlink interference from the macro BS to the mobile user in the expanded area is defined as $I_e = KP_m r_{me}^{-\gamma}$. The PDF of r_{me} is given by (2). The signal of interest of the mobile user in the expanded area is defined as $S_e = KP_s r_e^{-\gamma}$. The distribution of r_e is given by (1).

As for the statistics related to the small cell users, the downlink interference from the macro BS to the small cell users is defined as $I_s = KP_m r_{ms}^{-\gamma}$. The PDF of r_{ms} is given by (3).

2) Up - Down Scenario: The downlink interference from the macro cell user to the small cell user that is located inside the area bounded by R_e, is defined as $I_e = KP_{um}r_0^{-\gamma}$. The PDF of r_0 is given by replacing R_s with R_e in (5):

$$f_{r_0}(r) = \int_{r-R_e}^{r+R_e} f_{r_0}(r)_{|r_{sm}} f_{r_{sm}}(r_{sm})dr_{sm}, \tag{8}$$

where $f_{r_0}(r)_{|r_{sm}} = \frac{1}{\pi R_e^2}(\pi r - 2r\arcsin(\frac{r_{sm}^2+r^2-R_e^2}{2r_{sm}r}))$ and $f_{r_{sm}}(r_{sm})$ is formulated as:

$$f_{r_{sm}}(r_{sm}) = \begin{cases} \frac{2\pi r_{sm}}{\pi R^2-\pi R_e^2}, & R_e \le r_{sm} < R-d \\ s(r_{sm}), & R-d \le r_{sm} \le R+d, \end{cases} \tag{9}$$

with $s(r_{sm}) = \frac{1}{\pi R^2-\pi R_e^2}(\pi r_{sm} - 2r_{sm}\arcsin(\frac{d^2+r_{sm}^2-R^2}{2dr_{sm}}))$. The signal of interest of the mobile user in the expanded area is defined as $S_e = KP_s r_e^{-\gamma}$. The distribution of r_e is given by (1).

As for the statistics related to the small cell users, the downlink interference from the macro cell user to the small cell user that is located inside the area bounded by R_e, is defined as $I_s = KP_{um}r_0^{-\gamma}$. The distribution of r_0 is given by (8). For simplicity, we consider that the distance from the macro user to either the small cell user or the user in the expanded area is the same and denoted by r_0. This approximation is acceptable since small cells are notably smaller than macro cells.

3) Up - Up Scenario: The uplink interference from the macro cell user that is located outside the area bounded by R_e to the small cell BS, is defined as $I_e = KP_{um}r_{sm}^{-\gamma}$. The PDF of r_{sm} is derived as in (9) where R_e replaces R_s.

As for the statistics related to the small cell users, the uplink interference is considered as $I_s = KP_{um}r_{sm}^{-\gamma}$. The same distance r_{sm} as in (9) will be studied for simplicity. The accuracy of this approximation will be validated in the next sections using Monte-Carlo simulations.

4) Down - Up Scenario: The uplink interference from the macro cell BS to the small cell BS is defined as $I_e = KP_m d^{-\gamma}$ and the signal of interest as $S_e = KP_{us}r_e^{-\gamma}$. The distribution of r_e is given by (1).

As for the statistics related to the small cell users, they can be modeled by replacing r_e with r_s in the aforementioned expressions derived for the mobile users in the expanded area.

IV. System Analysis with DUDA

In this section, we will consider the users in the expanded area simultaneously connected to two cells, one for the downlink and one for the uplink. Two cases are considered, the decoupling access and the reverse decoupling access (Fig. 3).

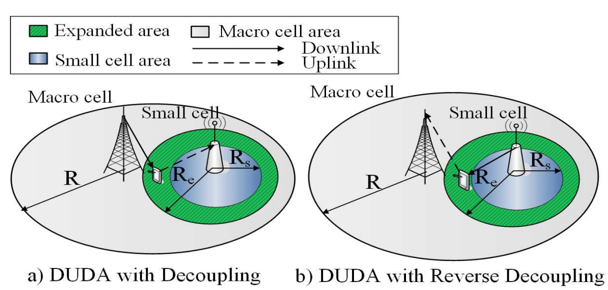

Fig. 3. DUDA illustration.

A. DUDA with Decoupling

1) Down - Down Scenario: In this scenario, the same expressions will be derived as in the Down - Down scenario defined for the CUDA with the macro cell case.

2) Up - Down Scenario: In this scenario, users with a decoupled access will be in silent mode. Consequently, the average throughput for users in the expanded area will not be considered.

As for the statistics related to the small cell users, the downlink interference from the macro cell user to the small cell user that is located inside the area bounded by R_e, is defined as $I_s = KP_{um}r_0^{-\gamma}$.
The distribution of r_0 is given by (8) where R_e replaces R_s.

3) Up - Up Scenario: In this scenario, the same expressions will be derived as in the Up - Up scenario defined for the CUDA with the small cell case.

4) Down - Up Scenario: In this scenario, users in the expanded area can operate at the same time in uplink and downlink. The downlink interference from the small cell user to the mobile user in the expanded area is defined as $I_e = KP_{us}r_{es}^{-\gamma}$. The PDF of r_{es} is given by (7).
The downlink desired signal of the user in the expanded area is defined as $S_e = KP_m r_{me}^{-\gamma}$. The PDF of r_{me} is given by (2). As for the uplink transmission, the interference from the macro BS to the small cell BS is defined as $I_e = KP_m d^{-\gamma}$ and the uplink desired signal as $S_e = KP_{us}r_s^{-\gamma}$.

As for the statistics related to the small cell users, $I_s = KP_m d^{-\gamma}$ and $S_s = KP_{us}r_s^{-\gamma}$.

B. DUDA with Reverse Decoupling

1) Down - Down Scenario: In this scenario, the same expressions will be derived as in the Down - Down scenario defined for the CUDA with the small cell case.

2) Up - Down Scenario: In this scenario, users in the expanded area can operate at the same time in uplink and downlink. The downlink interference from the macro cell user to the small cell user that is located inside the area bounded by R_e, is defined as $I_e = KP_{um}r_0^{-\gamma}$.
The PDF of r_0 is given by (8). The downlink desired signal of the user in the expanded area is defined as $S_e = KP_s r_e^{-\gamma}$. The uplink interference from the small cell BS to the macro BS is defined as $I_e = KP_s d^{-\gamma}$ and the uplink desired signal as $S_e = KP_{um}r_{me}^{-\gamma}$.

As for the statistics related to the small cell users, the downlink interference from the macro cell user to the small cell user that is located inside the area bounded by R_e, is defined as $I_s = KP_{um}r_0^{-\gamma}$.
For simplicity, we consider that the distance of the macro user from either the small cell user or the user in the expanded area is approximately the same and denoted by r_0. This approximation is valid due to the notably smaller size of small cells in comparison with the macro cell.

3) Up - Up Scenario: In this scenario, the same expressions will be derived as in the Up - Up scenario defined for the CUDA with the macro cell case.

4) Down - Up Scenario: In this scenario, users with a reversed decoupled access will be in silent mode. Consequently, the average throughput for users in the expanded area will not be considered.

TABLE I
SYSTEM PARAMETERS

Parameter	Value
Macro cell radius R	1000 m
Small cell radius R_s	200 m
Expanded area radius R_e	300 m
Distance between small and macro cells d	600 m
Path-loss exponent γ	2
Thermal noise power variance σ^2	10^{-12} W/Hz
Macro BS transmission power per sub-channel P_m	40 W
Small cell BS transmission power per sub-channel P_s	0.25 W
Macro user transmission power per sub-channel P_{um}	0.22 W
Small cell user transmission power per sub-channel P_{us}	0.2 W

As for the statistics related to the small cell users, $I_s = KP_m d^{-\gamma}$ and $S_s = KP_{us}r_s^{-\gamma}$.

V. NUMERICAL AND SIMULATION RESULTS

In this section, we first define the system parameters and discuss the Monte-Carlo simulation results that are provided to demonstrate the effectiveness of the derived analytical expressions. Our objective is to investigate analytically a TDD-based HetNet by applying various link association policies for a comprehensive performance comparison between DUDA and CUDA modes. Based on the statistical expressions derived for the interference and the desired signals in the previous sections, the average UL/DL capacity of users in the small cell along with users in the expanded area will be computed by following the method described in Appendix A. The main performance metric that is being measured, in both UL and DL, is the average capacity per unit bandwidth (C_{es}). It is calculated based on the average users capacity in the small cell area added to the average users capacity in the expanded area. Both throughputs have been evaluated and averaged over the period of a defined TDD frame.

A. System Parameters

The default system parameters are listed in Table I. The users are uniformly distributed in both cells and the composite fading is set as constant. In this analysis, we consider frame structures where all uplink/downlink combinations between the macro and small cells are taken into account, as shown in Fig. 4. It is important to note that, relying on this model that encloses all possible inter-link interferences, any other TDD configuration with different length can be easily investigated. The Monte-Carlo results are averaged over 10 000 iterations.

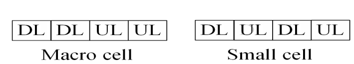

Fig. 4. TDD frame structure in macro and small cells.

B. Analytical and Simulation Results

Since the coupled access with the macro cell (CM) case represents the current system status before applying any change to the network configuration, our objective is to enhance the performance of the system in downlink and uplink by adopting three different association policies and comparing their performances in terms of spectral efficiency with the CM case.

Figure 5 depicts numerical values of C_{es} for each association strategy and in both UL/DL. We can conclude from this graph that the decoupling case shows an improvement in UL spectral efficiency (SE) around 1.2 bps/Hz in comparison with the CM case where the uplink SE is 0.9 bps/Hz. The same improvement in UL is observed for the coupled access with small cell case. The normal coverage area of the small cell, in this case (coupled with small cell), is expanded and the small cell users along with the users in the expanded area are now connected in UL and DL to the small cell BS. This situation is referred to as cell range expansion (CRE) technique [16]. However and as expected, the coupled access with small cell case or what is called the CRE technique, leads to a degradation in downlink SE which is due mainly to the macro BS downlink interference affecting the users in the CRE region. This harmful downlink interference in the range expansion area is usually solved by applying the Almost Blank Subframe (ABS) technique [17]. This degradation can be easily observed in Fig. 5 where the downlink SE is reduced from 2 to 1.28 bps/Hz, whereas the decoupling case is showing a slight DL improvement from 2 to 2.05 bps/Hz. Moving to the reverse decoupling case, we can notice a degradation in SE for both directions, from 0.9 to 0.8 bps/Hz in UL and from 2 to 1.28 bps/Hz in DL.

The aforementioned results indicate that the DUDA mode with decoupling access brings greater benefits in the uplink and maintains the same improvement in the downlink without any degradation.

Figures 6 and 7 show the uplink and downlink spectral efficiencies, for various association policies while varying R_e, the distance offset factor, between R_s and $R-d$. In both figures, we denote by (Th.) the theoretical results and by (M.C.) the Monte-Carlo simulation results. As expected, the decoupling case among all the other cases, maintains a higher SE in uplink and downlink for all offset values. We can observe in Fig. 6 that the uplink SE, for the decoupling case, shows a considerable degradation for R_e values greater than 280 m, whereas the downlink SE, for the same case, shows a continuous improvement for all offset values as shown in Fig. 7. When increasing the offset value, the decoupled users attached to the macro cell in the downlink and to the small cell in the uplink, are now closer to the macro cell and further away from the small cell. Thus, the downlink received power from the macro BS will be effectively increased and the uplink received power by the small cell BS will be decreased. This explains the degradation in uplink SE and the improvement in downlink SE. Consequently, it is paramount to find out the trade-off between the uplink SE and the downlink SE which is in our case 260 or 280 m. Last but not least, it can be concluded from these two figures, that Monte-Carlo simulation results match nearly perfectly the derived capacity expressions for various link association policies.

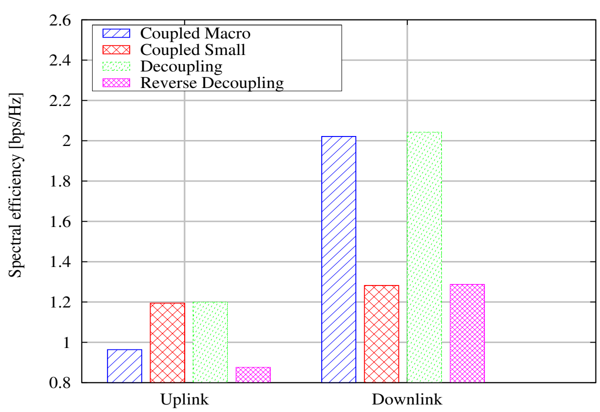

Fig. 5. Capacity per unit bandwidth (C_{es}) in both UL/DL directions for various link association policies.

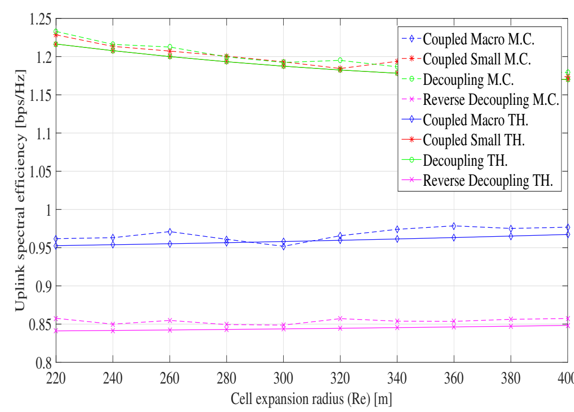

Fig. 6. Comparison of the uplink spectral efficiency between CUDA and DUDA modes for various (R_e) offset factor.

VI. Conclusion

In this paper, we have conducted both downlink and uplink performance comparison study for four various cell association rules in TDD HetNet. This study was based on a geometric probability approach. Two cases were considered with UL/DL coupled access and two others with decoupled access. We have observed that the decoupling case (part of DUDA mode) brings higher uplink and downlink throughputs for various offset values and thus, improves the overall system performance when being combined with a dynamic TDD technology. Furthermore, we have found out that our modeled network can be further optimized when choosing a specific small

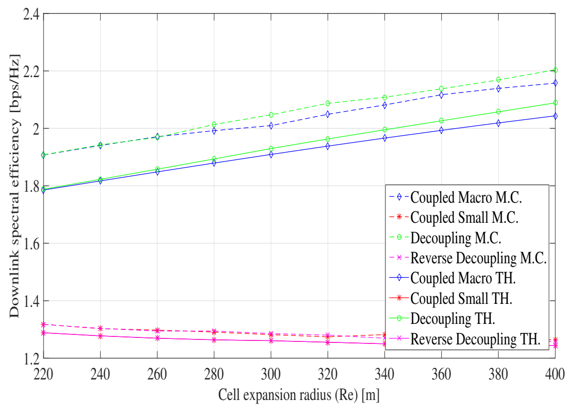

Fig. 7. Comparison of the downlink spectral efficiency between CUDA and DUDA modes for various (R_e) offset factor.

cell offset as a trade-off between UL and DL spectral efficiencies. This research will help provide more insight into the benefits of decoupling mode in different network deployments. In addition, the provided numerical results will help in optimizing and designing cellular network under various conditions.

In future work, we plan to consider various composite fading channel models in both macro and small cells. 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].

Appendix A
Capacity Calculation

The interference can be written as: $I = KPr^{-\gamma} = Cr^{-\gamma}$ where $C = KP$, r denotes the interfering link distance, P the transmitted power and K the composite fading. Applying the chain rule to the CDF of I, the corresponding PDF can be written as $f_I(x) = \frac{1}{x\gamma} f_r\Big((\frac{x}{C})^{-\frac{1}{\gamma}} \Big) (\frac{x}{C})^{\frac{-1}{\gamma}}$. Accordingly, a closed-form expression for the moment generating function (MGF) of the interference I can be formulated as $M_I(t) = \int_0^\infty e^{-tx} f_I(x) dx$. Note that the same steps apply for the derivation of the MGF of the signal of interest $(M_S(t))$. Based on the MGF expressions derived for S and I, the average capacity per unit bandwidth can be calculated using the lemma proposed in [18] as follows:
$C = \mathbb{E}[\ln(1 + \frac{S}{I+\sigma^2})] = \int_0^\infty \frac{M_I(t) - M_S(t)M_I(t)}{t} e^{-(\sigma^2)t} dt$
$= \int_0^\infty \frac{M_I(t) - M_S(t)M_I(t)}{te^{-at}} e^{-(\sigma^2+a)t} dt.$
This expression can be solved efficiently by expressing it in terms of the weights w_e and abscissas x_e of a Laguerre orthogonal polynomial as follows:

$$C = \sum_{e=1}^{n} w_e \Big(\frac{M_I(x_e/(\sigma^2 + a))}{x_e e^{-(ax_e)/(\sigma^2+a)}} - \frac{M_S(x_e/(\sigma^2 + a)) M_I(x_e/(\sigma^2 + a))}{x_e e^{-(ax_e)/(\sigma^2+a)}} \Big).$$

In this work, the a parameter was introduced to meet the best convergence level of Laguerre expression. It is equal to 10^{-4} in the scenarios where the macro cell is in a DL mode and 10^{-6} in the scenarios where the macro cell is in a UL mode.

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