Performance Analysis of Flexible Duplexing-enabled Heterogeneous Networks Exploiting Multi Slope Path Loss Models

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***Abstract*—The increasing demand for data traffic can be met by effective utilization of spectrum through flexible duplexing in heterogeneous networks (HetNets). By effectively switching the transmission modes between full duplex (FD) and half duplex (HD), an elevated system performance can be achieved as HD mode provides better results in regions where self interference for FD is much higher than the desired power. We, in this paper, investigate a distance-based duplexing scheme in a two-tier HetNet that exploits dual slope path loss model in both tiers. In our proposed scheme, a user connects to a base station (BS) based on maximum received power after which it decides to operate in either FD or HD depending upon a thresholding distance. Simulation results show that the performance of the system depends upon the thresholding distance for flexible duplexing mode and the path loss exponents of dual slope model. Results for sum rate and outage probabilities are provided for both uplink and downlink transmissions.**

***Index Terms*—Hybrid Duplexing, Duplex thresholding, Multi slope path loss, Power Control, Resource Optimization**

I. Introduction

Mobile data is increasing at a faster pace on daily basis. According to industry experts, growth in traffic volume will increase by 1000 folds by the end of 2020. The surging demands for connectivity provide opportunities as well as unprecedented risk for network operators. Network operators are trying hard to meet these requirements by increasing network coverage and capacity but with limited resources. Although long-term evolution (LTE) is delivering quantum gains, however this is not enough to meet the ever increasing demands. Network operators have to find new and efficient ways of increasing capacity, coverage and quality by reducing the cost requirements.

One of the ways to meet these stringent demands is to add more spectrum to the system or use the current spectrum efficiently. The latter can be addressed by optimizing radio links and by evolving the network towards small cells [1]. Similarly for effective usage of available spectrum, the communication networks have to move towards efficient radio link techniques such as full duplex (FD) communication. FD systems are emerging as attractive solutions for catering spectral efficiency problems and they theoretically double the capacity by using same resource for signal transmission and reception. An emerging strategy in this context is the use of FD-based Heterogeneous networks (HetNets), where HetNets have already been proven to provide higher data rates.

FD-enabled HetNets have shown recently growing interest [2]. Mathematical expressions are derived for finding the throughput of HetNets capable of operating in both HD and FD. FD-enabled HetNets composed of K-tiers, with base stations operating in each tier with different transmit powers is presented in [3]. The authors in [4] present FD-assisted cross-tier inter-cell interference (ICI) mitigation scheme, which operates on small cells. The performance of FD degrades in the cases where self interference is higher than the desired received power. The closed-form expression for finding the critical value of the self-interference attenuation power is derived in [5]. The effect of FD cells on the performance of the hybrid system is presented in [6] for a single tier network in which BSs in small cells can operate in either FD or HD with users operating in HD. Analysis is carried out without considering an interference coordination scheme. A novel hybrid-duplexing scheme based on distance for HetNets has been presented in [7], where a user can choose between half or full duplex mode based on the maximum received power.

Performance analysis of cellular networks, especially the ones using optimization theory uses single-slope path loss model for characterizing the propagation environment[8]. Analysis with standard path loss models is easy but they cannot characterize all the links in a cell with a single path loss exponent (PLE) correctly. Single slope path loss models lack precision in urban areas where environment is dense[9]. Authors in [10] derived the coverage probability and network throughput for downlink of a cellular network by using multi-slope path loss model. Similarly, the authors in [11] calculated coverage probability with varying small cell densities using dual slope path loss model.

In this paper, we consider a flexible duplexing-enabled

HetNet where dual slope path loss model is assumed for both macro and small cells. The users operating in both uplink (UL) and downlink (DL) are considered, where they can switch to FD/HD modes depending upon their distances from associated BSs. Extensive Monte-Carlo simulations have been conducted for finding the optimal uplink and downlink rates based on PLEs and duplexing modes. Outage probabilities with varying thresholding distances are also calculated for both HD and FD cases.

II. System Model

Consider a single cell two-tier HetNet where the macro BS (MBS), constituting tier 1, is overlaid by small cells, where the small cell BS (SCBS) locations are distributed as an independent homogeneous Poisson point process (PPP) Φ_k having density λ_k as shown in Fig 1. Let $\mathbf{B} = \{1, 2, \cdots, B\}$ be the set of SCBSs and $\mathbf{U} = \{1, 2, \cdots, U\}$ be the set of users. The location of users also follows an independent PPP Φ_u with density λ_u. The system bandwidth, B_w, is divided among both macro and small cell BSs in such a way that the users connected with a particular BS do not interfere with each other as they are allocated orthogonal bands. The same bandwidth B_w, is, however, also allocated to all BSs which introduces cross-tier interference between small and macro cell users. The average number of users in the system are U, where a user can operate in either DL or UL mode depending upon a Bernoulli trial where the user is an UL user with probability p and DL with probability $1-p$, respectively.

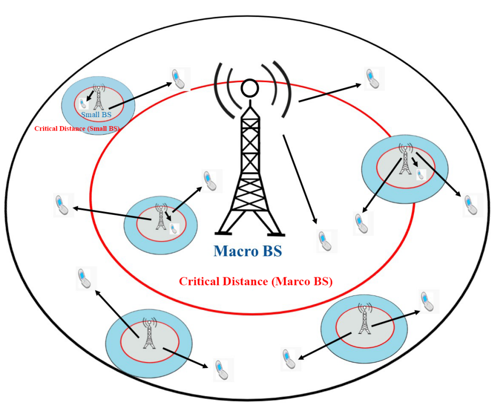

Fig. 1. A snapshot of two-tier network where dual slope path loss model is used for both tiers

Small-scale Rayleigh fading is assumed to be present in the environment whereas the path loss is characterized by a dual slope model. In general, a single slope path loss model can be expressed as

$$L(d)[dB] = 20log_{10}\left(\frac{4\pi}{\lambda_c}\right) + 10\alpha\log(d), \tag{1}$$

where λ_c represents carrier wavelength, α is path loss exponent and d represents the distance between a transmitter and a receiver. However, in many topographic environments and because of irregular cell patterns, single slope model doesn't yield accurate characterization. Hence we consider a dual slope path loss model in this study, where the general form of a dual slope path loss model is expressed as

$$L(d)[dB] = \begin{cases} \beta + 10\alpha_1\log_{10}(d) & d \leq r_c \\ \beta + 10\alpha_1\log_{10}(r_c) + 10\alpha_2\log(d/r_c) & d > r_c \end{cases} \tag{2}$$

where r_c is the critical distance, α_1 and α_2 are path loss exponents with distinct values, and β denotes the fixed path loss. Note that the value of critical distance is different for different tiers in a HetNet [12], [13].

The channel between a b^{th} BS and u^{th} user on c^{th} subcarrier is denoted by $h_{bu}[c]$, whereas the distance between them is denoted by d_{bu}. Therefore, the received power on the c^{th} subcarrier at a user in DL is given as

$$P_r[c] = \frac{P_k\left|h_{bu}[c]\right|^2}{L(d_{bu})}, \tag{3}$$

where P_k, $k \in \{1, 2\}$ denotes the transmit power of MBS for k=1 and for SCBS for k=2, respectively. In (3), the channel coefficient h_{bu} is drawn from a complex Guassian distribution with zero mean and unit variance. Note that same expression of received power is also valid for UL transmission with the only difference that the transmit power of mobile station will be used to evaluate the received power at a BS.

A. User Association

An open access association policy is considered in which a user can connect to any BS, i.e, MBS or SCBS. A user operating in DL is connected to a BS that provides maximum DL received signal power, i.e, an n^{th} user is connected to the m^{th} BS that maximizes

$$\underset{m}{\operatorname{argmax}} \frac{1}{L(d_{mn})}, where\ m \in \{MBS, \mathbf{B}\}. \tag{4}$$

A similar scenario holds for the UL association. Note that user association is either DL or UL depends on the dual slope path loss model, which in turns depends on the value of critical distance.

III. Radio Resource Management Exploiting Flexible Duplexing Scheme

In this section, we propose an algorithm that provides an optimal resource allocation strategy for maximizing the sum rate of the system. Interference minimization is one of the key design parameters in wireless networks. The scheme used in this section is based on minimizing the interference power to a receiving entity in order to increase the signal-to-interference plus noise ratio (SINR). Recall that the users distributed randomly in the cell become DL or UL depending upon the Bernoulli trial. Then each user associates itself with the BS as described in Section II-A. Initially, the total available bandwidth B_w is divided into M subcarriers, where M is the number of users (either DL or UL) connected with the MBS. This ensures that there is no co-tier interference for the MBS users. After the user's connection with MBS, a SCBS user is allocated a subcarrier that provides minimum

interference to that user. If there are other tier 2 users on the same subcarrier, interference on this SCBS user is calculated from all those users. This interference level is determined based on the received signal power on a test user.
Mathematically, for on i^{th} DL user connected to a BS b_o we find

$$\min\left(\sum_{\substack{u=1\\u\neq i}}^{U_{UL}} P_u[c]g_{ui}[c] + \sum_{\substack{b=1\\u\neq b_0}}^{B_{DL}} P_b[c]g_{b_0 i}[c]\right) \quad (5)$$

where $g_{ui}[c]$ is the product of magnitude squared of channel gain and inverse path loss between considered i^{th} user in DL and a user u operating in uplink with some other BS in subcarrier c, and $P_u[c]$ is the transmit power of interfering user. Similarly, the second term in (5) represents the interfering power for BSs operating in DL with same subcarrier c. Note that in (5), U_{UL} is the total number of users in operating in UL and B_{DL} is the total number of BSs with connections to DL users.

An SCBS user gets placed in subcarrier from where it receives minimum interference according to above discussion. As the number of users connected with SCBS is small as compared to MBS due to difference in transmit power, SCBS users are given more than one subcarrier to experience better data rates. However, this optimization also caters on interference on the MBS user as well. The process continues until all users are assigned their optimum subcarriers.

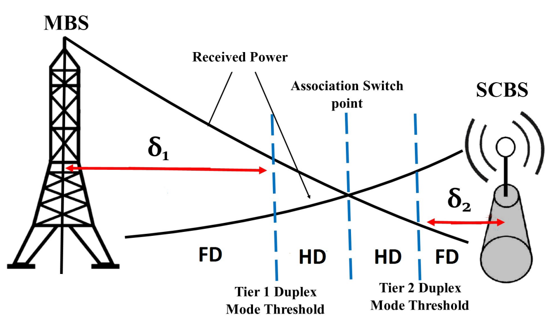

Fig. 2. Distance-based duplexing scheme

A. Flexible Duplexing

After BS association and subcarrier assignments, users are assigned duplexing based on the distance from their respective BSs as shown in Figure 2. In this process if the distance between a user and its serving BS is less than $\delta_k, k \in \{1, 2\}$, the user and BS communicate using FD mode. On the other hand, if it is greater than δ_k then HD mode will be used. As shown in Figure 2, if a user is is in proximity of MBS and its distance is less than δ_1, it operates in FD with MBS. As the distance between the user and MBS goes beyond δ_1, the user will operate in HD mode with MBS.

The reason behind such a duplex mode selection policy is that with imperfect self interference cancellation (SIC), the full-duplex SINR of a user may be worse than the half-duplex one especially if it is far away. Hence, it may not be suitable for the cell edge users to operate in FD. Besides, considering a distance measure to determine the duplex mode can also reflect the user SINR performance, since the small-scale fading could be averaged, however the path loss remains the main factor influencing the SINR in long term. The same phenomenon is applied for SCBS user as shown in Figure 2. Note that there is no specific relation between δ_k and γ_c, i.e, critical distance for dual slope modeling. It is also pertinent to note that although a user is either DL or UL initially, however, we assume that if a user qualifies for FD mode, then the user and its associated BS has the data available to transmit/receive simultaneously on the same assigned subcarriers.

TABLE I
SIMULATION PARAMETERS

Paramter	Value	Parameter	Value
Operating frequency	2.4 GHz	Noise power	-174 dBm/Hz
Residual self interference	-75 dB	Tx Power of MBS	46dBm
p (probability of UL)	0.5	Radius of Macro cell	500 meters
r_{c_1} for MBS	200 meters	$[\alpha_1, \alpha_2]$ for MBS	[2.5, 3]
Tx Power of SCBS	30 dBm	Small cell far field distance	0.4 meters
Radius of small cell	200 meters	r_{c_2} for SCBS	70 meters
$[\alpha_1, \alpha_2]$ for SCBS	[2.7, 3.2]	Tx power of user	23 dBm
r_c for a user in UL	50 meters	$[\alpha_1, \alpha_2]$ for user	[2.5, 3]

The SINR of a HD user connected with BS b on subcarrier c can be expressed as

$$SINR_{c,DL}^{HD} = \frac{P_k |h_{bu}[c]|^2 L^{-1}(d_{bu})}{\sigma^2 + I_c}, \quad (6)$$

where P_k is transmit power of corresponding tier, σ^2 is the noise variance and I_c is cumulative interference received to the user on subcarrier c. Note that this interference may arrive because of other BSs transmitting on DL to other users, or from an UL user who is transmitting to a BS on subcarrier c. Similarly, the UL HD SINR is also given using (6), however P_k is replaced by P_u, where P_r is the user transmit power. The SINR of an FD DL user is given as

$$SINR_{c,DL}^{HD} = \frac{P_k |h_{bu}[c]|^2 L^{-1}(d_{bu})}{\sigma^2 + RSI_u + I_c}, \quad (7)$$

where RSI_u is the residual self interference of user in FD mode on subcarrier c.

IV. SIMULATION RESULTS

In this section, simulation setup and corresponding results are provided. A single macrocell with a radius of 500 meters is considered, where the MBS is placed at the origin of the coordinate system, whereas small BSs are distributed uniformly within the area with an average density λ_k =6. An average of 100 users are also distributed within this area. More details of the assumed parameters are mentioned in Table I. A simulated snapshot of the system model is shown in Figure 3. The outage probability of any user in either UL/DL mode is given as

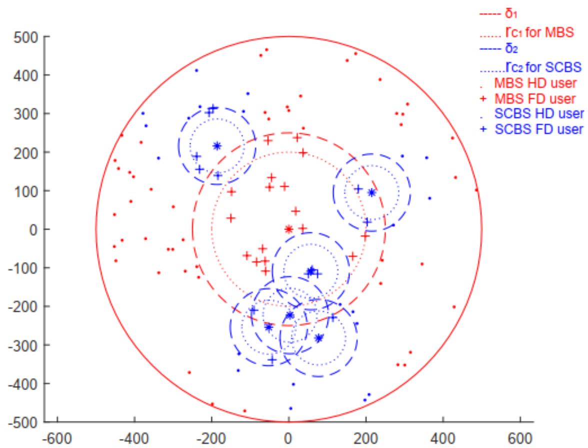

Fig. 3. A single cell HetNets with FD enabled duplexing mode exploiting dual slope path loss models

$$O_j^i(\eta) \triangleq \mathbb{P}(SINR_j^i < \eta), \quad (8)$$

where $i \in \{HD, FD\}$ and $j \in \{UL, DL\}$ and η is the SINR threshold. Similarly, the sum rates of a user is given as

$$R_j^i \triangleq \mathbb{E}\left[\frac{B_w}{N_c^k}\log(1 + SINR_j^i)\right] \quad (9)$$

where N_c^k denotes number of users that are sharing the bandwidth B_w.

Open loop power control is used for path loss compensation in the downlink.

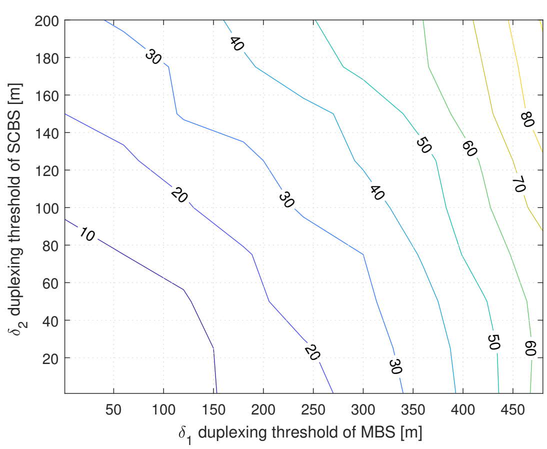

Fig. 4. Contour plot for number of FD users for different values of duplexing threshold for MBS (δ_1) and for SCBS (δ_2).

Figure 4 shows the number of FD users for different values of δ_1 and δ_2, i.e., macro and small cell's duplexing threshold distances. It can be seen that for smaller values of δ_1 and δ_2, number of users operating in FD mode will be small. However, as duplexing threshold distance for both tiers increases, the number of users in FD mode increases. This is because, more users reside under thresholding distance hence operate in FD.

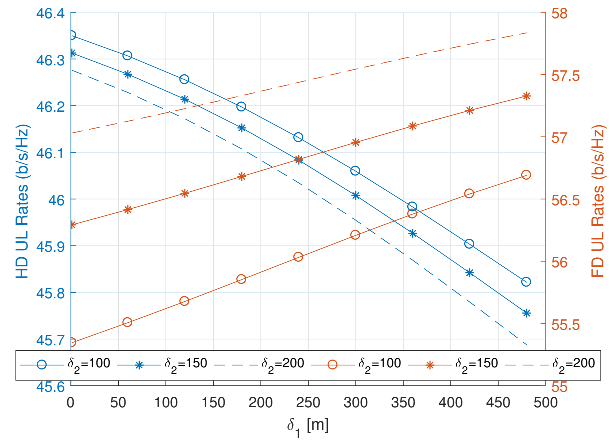

Fig. 5. UL rates for different values of duplexing threshold for MBS (δ_1) and for SCBS (δ_2)

Figure 5 shows the uplink rates for both FD and HD for different values of small cell and macro cell duplexing threshold distances. Firstly, it can be noticed that the FD rates are always better than the HD rates because of two obvious reasons, i) FD users are in close proximity to the BS and ii) users are utilizing full resource block in both UL and DL directions. Furthermore, it can be seen that as δ_1 increases, which amounts to getting more users in FD mode, the FD rates increases and the HD rates drop. This is because of of the fact that as δ_1 increases, more users operates in FD, therefore the rates increases.

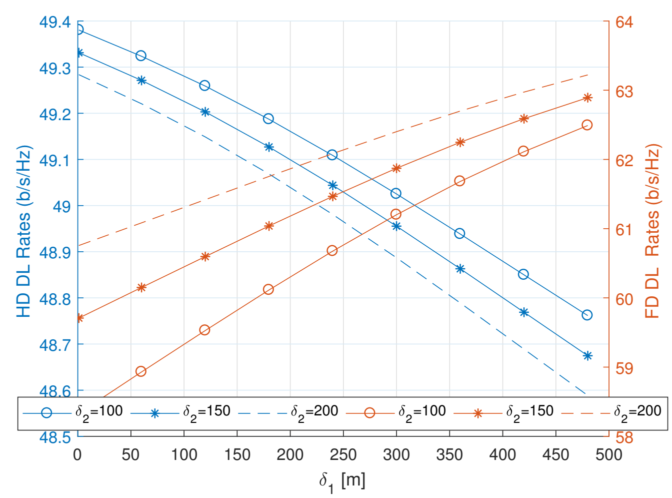

Fig. 6. DL rates for different values of duplexing threshold

Figure 6 shows a similar trend for the downlink rates for FD and HD. In downlink case, FD rates are always better than FD rates in uplink because the transmit power of BSs (either MBS or SCBS) is always higher than mobile stations. respectively. But with the increasing macro cell duplexing threshold , FD rates becomes greater than HD rates despite being different values of small cell duplexing threshold distances.

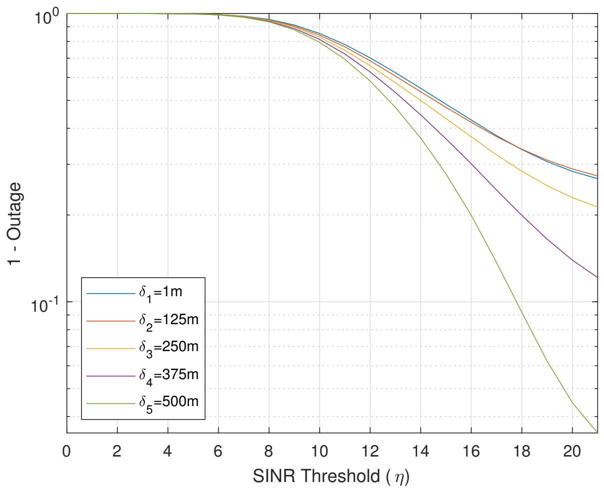

Fig. 7. Outage probability of HD UL user

Figure 7 shows the outage probabilities for HD DL users. It can been seen from the figure that with increasing δ_1, outage probability also increases. This is due to the fact that when δ_1, number of users in FD mode increases which results in increased interference. Number of users in outage also increases due to increased interference.

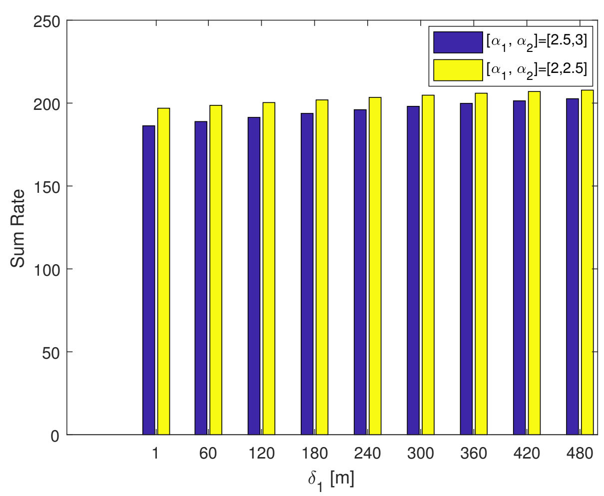

Fig. 8. Sum Rate for fixed δ_2=50m

Figure 8 presents results for sum rates, i.e, the sum of UL rates (both FD and HD) and DL rates (both FD and HD) after varying α_1 and α_2. It can be seen that as the values of δ_1 increases, the sum rate of system increases. This is because more number of user in FD mode with the increase of δ_1. Also the effect of PLE is obvious. The system with high PLEs for both macro and small cell tiers attributes lower sum rate than system operating at lower values of PLEs.

V. Conclusion

This study investigated the performance of a two-tier HetNet where both tiers were using dual slope path loss models and a flexible duplexing was considered for the user equipments. It has been shown that the critical distance in dual slope path loss models and the thresholding distance in the flexible duplexing mode are important parameters that have a direct impact on the sum rates of the system. A heuristic-based subcarrier allocation scheme was proposed to allocate subcarriers to users in such a way that the overall interference is minimized. Simulation results have been provided to show the impacts of various parameters on the sum rates and outage probabilities. As a future work, an analytical framework for optimization can be derived to get better performance of the system. Furthermore the analysis can be carried out for multi-cell scenarios.

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