IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 4 December 2023, accepted 30 December 2023, date of publication 12 January 2024, date of current version 29 January 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3353680

RESEARCH ARTICLE

Optimizing Cellular Network Binary Rate and Fairness: Examination of a Two-Tier Hybrid Duplex Architecture Employing Full-Duplex and Half-Duplex Modes

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The authors extend their appreciation to the Deputyship for Research and Innovation, Ministry of Education in Saudi Arabia for funding this research work through the project no. (IFKSUOR3–596–5).

ABSTRACT Full-duplex HCNs have emerged as a compelling solution to meet the escalating traffic demands of future fifth-generation networks. Theoretical advantages of full-duplex cellular networks include the potential for doubling throughput compared to half-duplex cellular systems, as base stations can both receive and transmit within the same frequency band, thereby enhancing various performance metrics. However, in practice, achieving this twofold increase in throughput and maintaining other performance metrics can be challenging due to interference from full-duplex base stations, particularly those of large-scale macro BSs. In this study, we explore a two-tier hybrid duplex HCN architecture, where small-scale BSs operate in full-duplex mode while large-scale BSs and user equipment utilize traditional half-duplex communication. This hybrid approach aims to mitigate interference issues and manage costs effectively. We investigate the impact of various network parameters, coupling scenarios, duplexing modes, and association criteria on the performance of the two-tier HCN. Our simulation results reveal the significant influence of user and small-scale BS densities, as well as the maximum user limit, on binary rate and the Jains fairness index. Remarkably, both binary rate and Jains fairness index exhibit optimal performance at specific values of cell range expansion. In the context of downlink and uplink binary rates, FD and hybrid duplex modes outperform other modes, particularly when the association criterion is based on maximizing average received power. However, when considering the Jains fairness index under the nearest association criteria, half-duplex mode consistently outperforms other modes. This research sheds light on the intricate interplay of duplexing modes, association criteria, and network parameters in the context of FD HCNs, providing valuable insights for optimizing network performance in the era of 5G and beyond.

INDEX TERMS 5G, Jains fairness index, full-duplex, hybrid-duplex, HCNs, binary rate, cell range expansion, association criteria.

The associate editor coordinating the review of this manuscript and approving it for publication was Tao Zhou.

NOMENCLATURE

τ	CRE.
FD	Full-duplex.
HD	Half-duplex.
γ	User density factor.
HCN	Heterogenous Cellular Networks.
$5G$	Fifth generation.
BS	Base Station.
UE	User Equipment.
DL	Downlink.
UL	Uplink.
MIMO	Multiple Input Multiple Output.
QoS	Quality of service.
MAC	Media Access Control.
3GPP	Third generation partnership project.
ASE	Area Spectral Efficiency.
JFI	Jains Fairness Index.
β	Ratio of pico to macro BS's density.

I. INTRODUCTION

In the most recent years, the tremendous amount of data movement has been observed on communication networks due to huge amount of mobile applications, the monstrous utilization of social networking, and the enormous use of portable gadgets. A contemporary innovation like 5G is required to suit the exponentially developing interest of versatile movement of data by considering and utilizing a few techniques for improving capacity, for example, densification of the cells or using Multiple-Input and Multiple-Output (MIMO) technology with the innumerable number of antennas. Quality of service (QoS) is a critical parameter in wireless communication systems, as it ensures the delivery of data with excellence and minimal delay to users. Achieving these goals is the primary responsibility of the IEEE 802.11e standard. The work by Bedi, Sharma, and Gupta provides valuable insights into improving the network performance of IEEE 802.11e through the use of various techniques. Their research not only discusses these techniques but also compares the results with existing methods, contributing to a deeper understanding of network performance enhancement in wireless communication systems [1].In legacy communication networks, bi-directional communication is not possible on same channel because of the inner interference from antennas and transmitting circuits which mask the receiving weak signal. Thus, transmission occurs in either time division duplex (TDD) or frequency division duplex (FDD), known as HD communication, to avoid the interference by employing the different frequency channels or time slots for downlink (DL) and uplink (UL) communication. This is a significant limitation to fulfill the imagined prerequisites of cutting edge wireless networks of 5G [2]. However, researchers have endeavored to nullify this long held assumption of half-duplex communication in [3], [4], and [5] and made it conceivable to utilize practically the FD radio communication designs. Authors in [6] dissected the throughput with stochastic geometry for FD radios which they found higher than HD and expected higher throughput with advanced medium access control (MAC) protocols or by utilizing interference management techniques. Theoretically, it seems that the data rate would be doubled in FD as compared to half-duplex but FD designs are actually constrained by self-interference (SI) to provide the twice data rate. However, many researchers worked hard to reduce or completely eliminate the SI. The authors in [4] designed first in-band Full-duplex WiFi radios that can in the meantime receive and transmit on a comparative channel using standard WiFi 802.11ac PHYs and experimentally refined close to the theoretical twice throughput. [7] achieved FD communication with a single antenna via utilizing a common carrier and provided isolation between forward (transmit) and reverse (receive) channels of more than 40 dB. [8] discussed new interference management techniques to improve rate over its HD couterpart, [9] suggested a cell partitioning procedure and demonstrated an improvement in spectral efficiency over half-duplex which grows and reduces according to the the number of users and the number of partitions respectively, [10] reviews an extensive variety of in-band full-duplex SI cancellation techniques, [11] introduced a polarization based digital SI cancellation scheme for FD communication. Thus, analog and digital cancellation techniques enabled to approximately double the throughput by implementing FD radios for next generation 5G networks. In [12], the authors showed that a significant improvement, although not double in downlink (DL) and uplink (UL) channels is possible but an uplink is constrained by interference as DL and UL uses same frequency. In [13], a hybrid scheduler has been suggested which moves between HD and FD modes according to best accessible state and showed that with 85 dB SI cancellation, DL and UL capacity can enhance up to 69% and 81% respectively under FD mode as compared to HD mode with small retribution in energy efficiency. Reference [14] proposed a novel scheduling and interference cancellation strategies which virtually doubled the capacity. Reference [15] have compared the HD and FD capacity using MIMO and showed an enhancement in capacity under FD with certain conditions. Thus, Full-duplex is an auspicious technology for next generation cutting edge 5G networks because of its distinctive attributes such as possibly double ergodic capacity [16], minimize feedback delay [17], better network secrecy [18], and an improvement in network MAC [19].

A. HYBRID MODE OPERATION

In our study, we investigate a hybrid mode of operation within a two-tier HCN. This hybrid mode is designed to find a balance between the advantages of FD communication and the practical constraints associated with large-scale macro base stations (BSs) and user equipment (UEs) in a cellular network. In FD communication, a device or base station can transmit and receive data simultaneously over the same frequency band. This mode promises higher throughput compared to HD systems, where transmission and reception occur at different times. However, it introduces challenges, especially in large-scale macrocell environments. Conversely, HD communication involves devices or base stations taking turns to either transmit or receive data. This mode is commonly used due to its simplicity and lower interference levels but might not fully utilize the potential capacity offered by FD systems. The hybrid mode operation aims to strike a balance between the advantages and challenges of FD and HD communication. It divides the network into two tiers:

1. Small-Scale Base Stations (pico BSs):

These base stations operate in FD mode, allowing them to transmit and receive data simultaneously. This is particularly beneficial in small cell environments where interference can be effectively managed.

2.Large-Scale Base Stations (macro BSs) and User Equipment (UEs):

The macro BSs and UEs continue to use traditional HD communication, taking turns in transmitting and receiving data. The hybrid mode capitalizes on the strengths of FD in small cell deployments while maintaining the simplicity and lower interference levels of HD in large cell environments. This approach helps mitigate interference challenges prominent in large-scale macrocell networks while still benefiting from the throughput advantages of FD in specific scenarios. The specific mechanisms and scenarios for applying the hybrid mode can vary depending on network design and deployment considerations. In our study, we explore the performance implications of this hybrid mode under different network parameters and scenarios to provide insights into its advantages and limitations.

Further, section II contains related work and contribution. Setion III examines the network model arrangement alongside the channel model and users' association criteria. Section IV discusses the performance indicators. Simulation results and work bits of knowledge are investigated in section V. At long last, in section VI, a few of conclusions are outlined.

II. RELATED WORK AND CONTRIBUTIONS

A. RELATED WORK

From the discourse in [20], it was discovered that furnishing full-duplex enabled pico BSs will be most viable and optimistic for FD cellular networks. In [21], a blended small cell network was considered where base stations (BSs) work in either FD or HD mode and all UEs in only HD mode. They calculated the complementary cumulative distribution function for coverage along with an area spectral efficiency (ASE) and found an improvement in ASE but reduction in coverage and vice-versa by increasing a small portion of FD BSs. Further, it was presented that the BS and UE transmit power should be same to obtain the same performance of downlink and uplink, however, a single tier of small cells was considered. In [22], the authors introduced the hybrid HCN where access points (APs) either function in bi-directional FD or HD DL mode. The authors inferred that throughput degrades when both tier APs operate in hybrid mode but it improves when APs operate only in HD or FD mode. This motivated the authors in [23] where the expressions of rate coverage and outage were derived in closed form using stochastic geometry for a Hybrid HetNet of two tiers with FD and HD enabled small cells and macrocells respectively instead of only considering hybrid mode for both tiers. They also analyzed the rate coverage and the outage as a function of small cell density, SI cancellation capability, and ABS transmission factor [24]. The ‘‘ABS transmission factor’’ refers to a parameter in 5G communication systems that governs the allocation of resources for Absolute Radio Frequency Channel Quality Indicator (CQI) reporting. This factor determines the proportion of resources allocated for CQI feedback, which plays a crucial role in resource management and optimization within the network, but studied the network under only one coupled association criteria of maximum average receive power and did not consider any other coupled or decoupled user association criteria. Reference [25] analyzed a hybrid two tier HetNet where small cells use full-duplex BSs while large cells are traditional half-duplex macro BSs under coupled and decoupled association criteria. The authors showed that rate is highest under hybrid mode and coverage is approximately equal to half-duplex and from association point of view, considering hybrid mode, coverage under decoupled association is better than coupled user association criteria. However, they only considered one parameter i.e., fractional power control. Not quite the same as the previously mentioned research work [25], [26], our goal in this paper is to show and investigate a two-tier HetNet with FD enabled pico BSs and conventional HD macro BSs for binary rate and fairness as a function of various system parameters like maximum number of users limit (N_{max}), cell range expansion (CRE), pico density, and user density while considering open-loop user transmit power (P_u) with maximum power limit of user given by third generation partnership project (3GPP) in [27] under realistic path loss models for BS-BS, BS-UE, and UE-UE, specified by 3GPP in [28]. Reference [29] concludes that the developed heuristic resource allocation method effectively addresses the interference threat in cellular network's Device-to-Device (D2D) communication, improving the quality of service (QoS) for both cellular and D2D communication [30]. The work in [31] proposes an improvement in the simultaneous wireless power and data transfer system with full-duplex communication mode. FD communication in cellular networks has gained significant attention in recent research. FD communication allows for simultaneous transmission and reception on the same frequency, potentially doubling the spectrum efficiency and capacity of the network [32]. However, there are challenges in implementing FD communication due to self-interference and interference with other users [33], [34]. The research has focused on techniques to mitigate these challenges and unlock the full potential of FD wireless communications [35]. The use of FD communication in unmanned aerial vehicle (UAV)-assisted cellular networks, showing improved throughput as the coverage of UAVs increases [36]. Furthermore, the concept of flexible duplex has been proposed for 5G mobile communication systems to adapt to the flexible application requirements of uplink and downlink wireless resources. Overall, the latest research in Full-duplex cellular networks aims to overcome challenges and improve network capacity and efficiency.

B. CONTRIBUTIONS

- Investigating various performance indicators across different coupling scenarios, duplexing modes, and association criteria.
- Revealing that user and small-scale BS densities, as well as the maximum user limit, significantly influence binary rate and the Jains fairness index.
- Showing that both binary rate and Jains fairness index exhibit optimal performance at specific values of cell range expansion (CRE).
- Demonstrating that FD and hybrid duplex modes outperform other modes in terms of downlink (DL) and uplink (UL) binary rates, particularly when the association criterion is based on maximizing average received power.
- Highlighting that under the nearest association criteria, half-duplex mode consistently outperforms other modes in terms of the Jains fairness index.

III. NETWORK DEPLOYMENT AND ASSOCIATION CRITERIA

A. NETWORK MODEL

The research focuses on a mobile network characterized as a two-tier HCN. In this network, two distinct tiers, denoted as Tier-1 (t1) and Tier-2 (t2), are established, each comprising different types of base stations (BSs) with varying operating functionalities, particularly in terms of duplexing modes. In Tier-1, large-scale BSs operate in HD mode to mitigate excessive interference. These BSs are labeled t1 and transmit with a fixed power of PW1. Tier-2 consists of small-scale BSs of the pico type, which communicate in FD mode. This mode is preferred in Tier-2 due to its cost-effectiveness and lower transmit power compared to the macrocellular counterparts (t1). The BSs in Tier-2 are denoted as t2 and transmit with a lower power level, PW2, than those in Tier-1. Both Tier-1 and Tier-2 BSs are independently distributed in a homogeneous Poisson point process (PPP). The intensity of Tier-1 is denoted as λ_{t1}, while that of Tier-2 is denoted as λ_{t2}. ϕ_{BS} (Base Station Distribution), represents a critical spatial modeling framework that characterizes the spatial distribution of base stations within a wireless network. This mathematical model employs a Homogeneous PPP to describe the random but uniform deployment of BSs across a specified geographic area. In our case, the collective network density, λ_T, is derived from the summation of individual densities, λ_{t1} and λ_{t2}, each associated with a distinct source or category of BSs (e.g., macro and pico cells). ϕ_{BS} provides a foundational structure for our research, allowing us to explore the spatial arrangement, density, and coverage of BSs. It enables the quantitative analysis of BS deployment patterns, helping us to assess network performance, interference management, and the overall quality of service. This spatial perspective is instrumental in designing and optimizing wireless networks, as well as in investigating the influence of BS distribution on network performance metrics, such as capacity, coverage, and interference levels. ϕ_{tu} (User Equipment Distribution), serves as an essential counterpart to ϕ_{BS} and is used to model the spatial distribution of UE or mobile devices within the same wireless network. Like ϕ_{BS}, ϕ_{tu} is represented as a Homogeneous PPP and is characterized by its own intensity, reflecting the density of UEs within the network. ϕ_{tu} enables us to analyze the geographic locations and the density of UEs, providing valuable insights into the deployment of end-user devices. This spatial model is vital for various aspects of our study, including capacity planning, interference analysis, and resource allocation. It assists us in evaluating how the distribution of UEs impacts network performance and how resources should be allocated to serve users efficiently. When the two PPPs are superimposed, the resulting overall network is also a homogeneous PPP, denoted as ϕ_{BS}, with a total intensity of λ_T which is given as

$$\lambda_T = \lambda_{t1} + \lambda_{t2} \tag{1}$$

A separate PPP, denoted as ϕ_{tu}, represents all user equipment (UE) in the network. It is assumed that all UEs operate in HD mode due to the hardware requirements. FD pico cells are equipped with a single antenna, and they achieve FD communication based on previous research findings. Moreover, advancements in analog and digital signal processing have enabled FD BSs to effectively cancel self-interference (SI = 0) from their own transmitted signals. The proportion of pico BSs to large-scale BSs density is represented as β [37], [38], calculated as:

$$\beta = \frac{\lambda_{t2}}{\lambda_{t1}}. \tag{2}$$

This parameter plays a crucial role in the network's performance. The channel conditions in the network are subject to Rayleigh fading, and the path loss is inversely proportional to the distance between nodes, raised to the path loss exponent α. The path loss for various links, including BS-to-BS, UE-to-UE, and BS-to-UE, follows the 3GPP channel model [28]. The slopes and exponents for path loss are defined by PS and α, which are specific to each link type.

In our network model, UE0 plays the role of the primary user, being associated with macro BS number two (MBS2) to receive its intended signal. This UE0, however, contends with interference originating from all other BSs in the network, including both macro and pico cells. Additionally, it faces interference from half-duplex users transmitting data to their

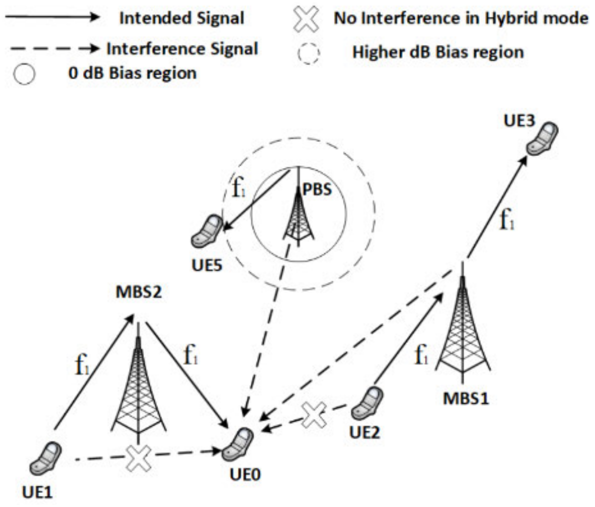

FIGURE 1. Illustration of Full Hybrid Duplex Cellular Network Deployment with the CRE considered. Solid arrows depict intended signals while dashed arrows represent interference signals.

respective associated BSs during the uplink, all within a full-duplex environment. In contrast, in the hybrid mode where macro BSs operate in half-duplex, there is no interference stemming from uplink users UE1 and UE2 of macro BSs, as indicated by the cross symbol in our network model. We've also integrated the concept of Cell Range Expansion (CRE) bias into our network model. An example of this is evident with UE5, which initially connected to MBS2. However, with the introduction of a fixed bias in the downlink for the pico BS (PBS), UE5 offloaded from MBS2 and associated with the PBS. This strategic move serves to distribute network traffic more evenly. In the uplink, when UE0 transmits its data to MBS2, it's essential to consider the interference scenario. In full-duplex mode, MBS2 experiences interference from all full-duplex BSs and their associated users. However, it does not face intra-cell interference from UE1, thanks to the full-duplex mode of operation. Conversely, in the hybrid mode, interference from macro BSs is nonexistent since they operate in half-duplex mode, providing a different interference landscape for MBS2.

B. ASSOCIATION CRITERIA

In this study, we adopt the coupled and decoupled user association strategies as introduced in [25] and [39]. In our study 'coupled' users are those who are closely associated with the small-scale base stations (BSs) in full-duplex mode. These users tend to have a strong connection with the nearby small-scale BSs, which allows for full-duplex communication with these BSs, thus influencing the network's performance. In contrast, 'decoupled' users are those who are not closely associated with the small-scale BSs in full-duplex mode. These users operate under different duplexing modes or associations within the network, which can affect their interaction with base stations and, in turn, network performance. These approaches pertain to both the downlink and uplink, and they can be categorized as either coupled or decoupled. Coupled user association encompasses criteria such as physical proximity and maximum average power, while decoupled association relies on the minimum path loss criterion. For simplicity, we refer to these user camping rules as 'Nearest' [40], 'Average' [41], and 'MPL' [42], [43], [44], [45], respectively. The choice of camping criteria significantly influences how BSs allocate users among themselves. Given the heterogeneous nature of our network, the distribution of UEs among specific BSs, known as load [40], [41], [42], [43], [44], [45], is inherently uneven among the BSs. "MPL" stands for "Minimum Path Loss" association criteria, which is used to determine the association of user equipment (UE) with base stations (BSs) in the network. In the Minimum Path Loss criteria, UEs connect to the BS with the minimum path loss, optimizing the link quality. Additionally, 'nearest' and 'average power' association criteria are terms that describe how UEs associate with BSs in the network. 'Nearest' Association Criteria, Under the nearest association criteria, UEs connect to the BS that is physically closest to them in terms of proximity, without considering signal strength or interference. This criterion is often used to minimize propagation delays. 'Average Power' Association Criteria, the average power association criteria involve UEs connecting to the BS that provides the best average received power, considering factors such as signal strength and interference. This criterion aims to optimize network performance by selecting the BS with the most favorable overall signal quality. To address this imbalance, we employ Cell Range Expansion (CRE) denoted by τ in the downlink, where $\tau_1 = 1$ and $\tau_2 = \tau$. In the uplink, we utilize Fractional Power Control (FPC), represented by α with values ranging from 0 to 1. Here, 0 signifies no power control, while 1 indicates full power control, following the guidelines in [25] and [39]. Mathematically, the camping rules for associations, namely "Nearest," "Average," and "MPL," can be expressed as shown in equations 3, 4, and 5, respectively, where "z" and "BS" represent the user and base station, and are defined as:

$$BS_z^{dl}(N) = \arg \min_{BS\in\phi_{BS}} d_z^{BS} \tag{3}$$

$$BS_z^{dl}(A) = \arg \max_{BS_z^t, t\in 1,2} \tau_t Pw_t PS_t^l d_z^{BS_z^t -\alpha_t^l} \tag{4}$$

$$BS_z^{U}(M) \arg \max_{BS_z^t, t\in 1,2} PS_t^l d_z^{BS_z^t -\alpha_t^l} \tag{5}$$

In equation 3,$BS_z^{dl}(N)$ represents the base station selected for downlink (dl) communication by user z under the 'Nearest' association criterion.d_z^{BS} denotes the distance from user z to the selected base station measured in meters (m) and ϕ_{BS} set of available base stations. In equation 4, $BS_z^{dl}(A)$ is the base station chosen for downlink (dl) communication by user z using the 'Average power' association criterion. τ_t is coefficient or weighting factor related to the duplexing mode t. Pw_t is power of the base station in duplexing mode t typically measured in decibels (dB). PS_t^l is signal strength (received power) from the base station BS_z^t to user z typically measured in dB. $d_z^{BS_z^t}$ is the distance between user z and the base station BS_z^t typically measured in meters (m). α_t^l is Path loss exponent associated with duplexing mode t. In equation 5, $BS_z^U(M)$ represents the base station selected for uplink (U) communication by user z under the 'MPL' association criterion. PS_t^l is signal strength (received power) from the base station BS_z^t to user z measured in decibels (dB). $d_z^{BS_z^t}$ is the distance between user z and the base station BS_z^t measured in m. α_t^l is Path loss exponent associated with duplexing mode t. The maximum power, represented as P_{max}, is transmitted by the UE, adhering to the 3GPP guidelines outlined in [27], where it is set at 23 dBm. Consequently, the power transmitted by the user, respecting its maximum limit denoted as P_{max}, as specified in [25] and [39], is expressed in equation 6.

$$P_t^z = \min[P_u(PL_z^{BS})^{\epsilon}, P_{max}] \tag{6}$$

In equation 6, P_t^z represents the power allocation for user z in duplexing mode t. P_u is UE power in dB. PL_z^{BS} is Path loss between user z and the selected base station measured in dB. ϵ is parameter that influences power allocation. P_{max} is maximum allowable power measured dB.

Where $P_u(PL_z^{BS})^{\epsilon}$ is the path loss between the UE z and uplink associated BS, ϵ is the fractional power control having values of 0 to 1, and P_u is the open loop user transmit power.

IV. PERFORMANCE INDICATORS

A. BINARY RATE

In assessing the performance of our HCN, several key indicators come into play. Among these, the binary rate, as identified by [13], is of paramount importance, especially when considering half or full-duplex modes. The binary rate, denoted as $R_{HD}^{N,A,MPL}$ for the half-duplex mode and $R_{FD}^{N,A,MPL}$ for the full-duplex mode, is mathematically expressed as follows:

$$R_{HD}^{N,A,MPL} = W\log_2(1 + SINR_{HD}^{N,A,MPL}) \tag{7}$$

$$R_{FD}^{N,A,MPL} = 2W\log_2(1 + SINR_{FD}^{N,A,MPL}) \tag{8}$$

Here, N, A, and MPL respectively represent Nearest, Average, and Minimum path loss associations. The Signal-to-Interference-plus-Noise Ratio (SINR) in the downlink, when UE0 is designated as the intended user, can be calculated as per [21] and [25], and is defined by:

$$SINR_{FD}^{DL} = \frac{P_r, UE}{I_{DLB} + I_{UE} + N_0} \tag{9}$$

The accounting of interference from UE_1 in the SINR equation (Equation 9). In the equation, the interference from UE_1, denoted as I_{UE}, is accounted for as follows:

- I_{UE} represents the cumulative interference from all other User Equipment (UE) in the network, including UE_1. The interference from UE_1 is part of this cumulative interference term.
- In practice, I_{UE} accounts for the total interference power generated by all UEs that are active and sharing the same frequency resources, including UE_1 and any other UEs in the vicinity of the system.
- The specific power contributions from individual UEs, including UE_1, to I_{UE}, depend on factors such as their transmit power, distance from the receiving UE (UE in focus), path loss, channel conditions, and any interference mitigation techniques in place.

The SINR equation (Equation 9) considers I_{UE} as the collective interference from all UEs, which inherently encompasses the interference from UE_1 and other UEs in the network. In Equation 9, P_r, UE denotes the received power by the intended UE from its serving BS in the downlink. I_{DLB} and I_{UE} represent the interferences from all full-duplex pico and macro base stations in the downlink, along with interferences from users transmitting in half-duplex mode in the uplink to their associated BSs, including intra-cell interference from UE1. N_0 is the thermal noise power.

In the downlink, the total interference experienced by UE0 is the summation of I_{DLB}, I_{UE}, and N_0. When hybrid mode is considered, the SINR calculation in the downlink follows a similar procedure, with the exception that no interference is observed from users associated with half-duplex macro BSs, as indicated by the cross signs in the network model. Turning to the uplink, when UE0 transmits information to its associated BS MBS2, the SINR can be expressed using the formula:

$$SINR_{FD}^{UL} = \frac{P_r, BS}{I'_{DLB} + I'_{UE} + N_0} \tag{10}$$

In this equation: P_r, BS represents the power transmitted by the associated UE to macro BS MBS2 in the uplink. I'_{DLB} and I'_{UE} are the interferences from the total number of full-duplex pico and macro BSs, as well as from all half-duplex UEs communicating in the uplink with their affiliated BSs, excluding intra-cell interference from UE1. N_0 signifies the thermal noise power.

Under the hybrid mode, no interference is considered from macro BSs, as these BSs communicate in half-duplex mode in the hybrid configuration.

The binary rate calculations are guided by equations 7 and 8, where the choice between HD or FD modes depends on the tier to which the UE is attached. When a user is connected to the macro tier, the binary rate is computed using equation 7; otherwise, equation 8 is employed for rate determination.

B. JAIN'S FAIRNESS INDEX

Jain's Fairness Index (JFI) is a critical metric for assessing the equitable distribution of users among base stations (BSs) in HCNs. It is commonly employed to evaluate the fair allocation of system resources. Mathematically, JFI is expressed as follows:

$$J(r_1, r_2, \ldots, r_n) = \frac{(\sum_{i=1}^{n} r_i)^2}{n\sum_{i=1}^{n} r_i^2} \tag{11}$$

TABLE 1. Variable network parameters, symbols and default system simulation values.

Variable Parameter	Symbol Parameter	default value
User density factor	γ	10
pico to macro BS density ratio	β	4
Cell range expansion bias	$\tau_1 = 1, \tau_2 = \tau$	0 dB
Maximum quantity of active users per BS	N_{max}	50
UL UE transmit power (open loop)	P_u	0 dBm
Fractional power control index	ϵ	0

TABLE 2. Fixed network parameters, symbols, and default system simulation values.

Fixed Parameter	Symbol Parameter	Default Value
BS Transmission Power	PW_1, PW_2	46, 24 dBm
Max UL UE Transmit Power	P_{max}	23 dBm
Path Loss Slopes ($t = 1, 2$)	PS_t^l dB	20dB/decade [28]
Path Loss Exponents	α_1, α_2	2, 4 [28]
Spectral Density of Noise	N_0	-174 dBm/Hz
BS Density in Total	λ_t	0.24 (BS/Km^2)
Utilized UL/DL Bandwidth	W^U, W^D	10 MHz

Here: n represents the total number of User Equipment (UEs). r_i corresponds to the rate of the ith UE.

In the context of JFI:

- The best fairness scenario yields a value of 1, indicating that all UEs receive an equal share of the network's resources.
- In the worst-case scenario, JFI takes on the value of $\frac{1}{n}$, signifying that resource allocation is extremely unequal.
- Maximum fairness is achieved when all users are allocated resources at an equal rate. If k UEs share resources equally, the fairness index will be $\frac{k}{n}$, while the remaining $n - k$ UEs receive no resource allocation, typically due to being in outage or inactive.

Jain's Fairness Index is a valuable tool for evaluating the degree of resource fairness in HCNs, ensuring a more equitable distribution of network resources among users.

These performance indicators play a crucial role in evaluating the effectiveness of our network model.

V. SIMULATION RESULTS AND DISCUSSION

The simulation results are presented through tables and figures to analyze various aspects of network performance under different scenarios and parameters.

Table 1 and Table 2 provide an overview of the simulation parameters. Table 1 lists the variable parameters, while Table 2 presents the fixed parameters with their default values. Notably, the simulations focus on varying one parameter while keeping the others at their default values.

A. IMPACT OF USER DENSITY (γ)

1) BINARY RATE AS A FUNCTION OF USER DENSITY (γ)

The binary rate decreases as more users are added to the network due to increased load on Base Stations (BSs). This is a common phenomenon in wireless networks. As more users are added, the available resources (e.g., frequency spectrum and power) need to be shared among them. With higher user density, each user gets a smaller share of these resources, leading to a decrease in binary rate. This is also known as network congestion.

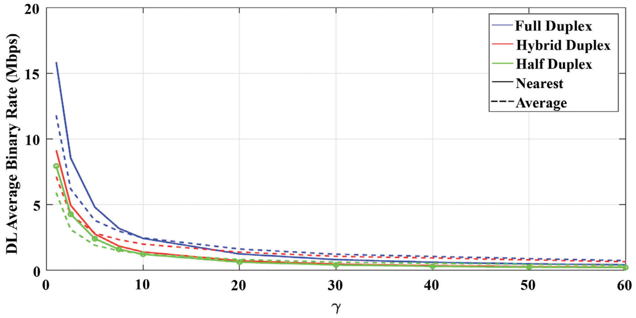

FIGURE 2. Impact on Downlink average binary rate with user density γ.

The binary rate is highest in the DL under full-duplex mode as shown in Figure 2, and it's calculated using spectral efficiency. In DL FD mode, the BSs can simultaneously transmit and receive data, allowing for efficient use of resources. This leads to a higher binary rate as compared to other modes where the BSs have to alternate between transmission and reception, causing some resource wastage.

In the UL, the binary rate is highest in hybrid mode as shown in Figure 3, whereas it's lowest in FD mode due to excessive interference experienced by User Equipment (UE). Hybrid mode combines aspects of both half-duplex and full-duplex modes. It allows UEs to transmit and receive data simultaneously on separate frequency bands, reducing interference and increasing the binary rate. In FD mode, interference from simultaneous transmission and reception by UEs can degrade performance.

The joint rate (combined rate for all users) is highest under hybrid mode when symmetric applications are considered. Hybrid mode strikes a balance between efficient use of resources (similar to FD in DL) and reduced interference (similar to half-duplex). This makes it an optimal choice for achieving the highest joint rate when users are transmitting symmetric data, as it maximizes resource utilization while minimizing interference.

2) EFFECT OF γ ON JAINS FAIRNESS INDEX (JFI)

Figure 4 and Figure 5 shows the fairness for downlink and uplink as a function of γ. Fairness decreases as the parameter γ increases because users become inactive when the user limit (N_{max}) is reached to 50. γ likely represents a threshold or a parameter that affects user activity. As γ increases, more users may reach the maximum limit, causing others to become inactive. This can lead to a decrease in fairness as some users experience network congestion while others have ample resources.

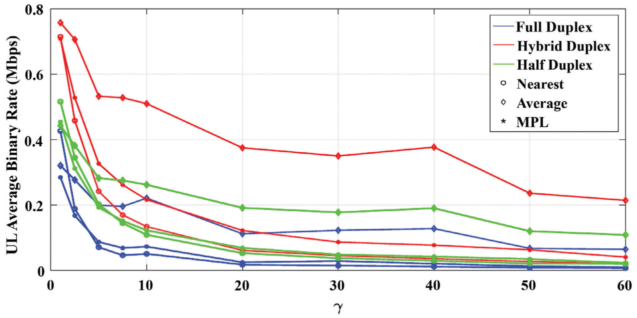

FIGURE 3. Impact on Uplink average binary rate with user density γ.

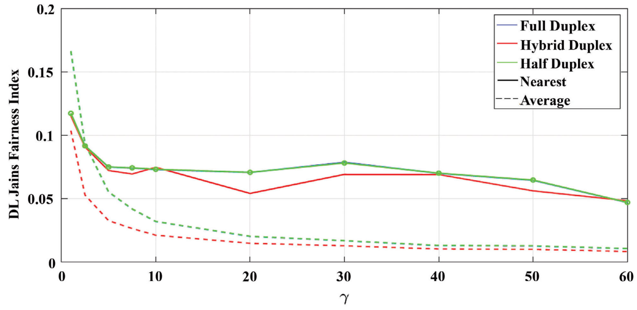

FIGURE 4. Effect of user density γ on Downlink JFI.

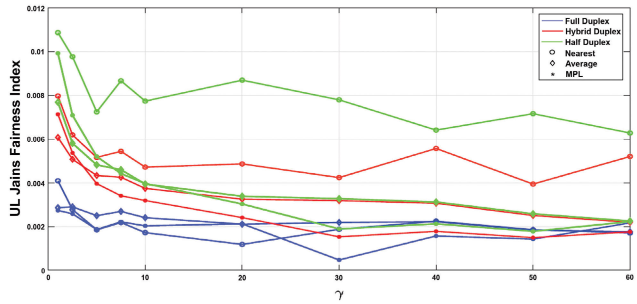

FIGURE 5. Effect of user density γ on Uplink JFI.

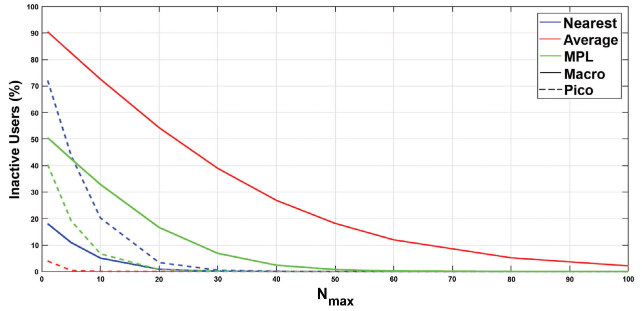

FIGURE 6. Inactive users in percentage with variation of users limit N_{max}.

Fairness is highest in half-duplex mode when the ‘‘Nearest’’ association scheme is used, but it’s lower in other modes for different associations. Half-duplex mode can provide fairness in resource allocation because it avoids the simultaneous transmission and reception that can cause interference. The ‘‘Nearest’’ association scheme assigns users to the nearest BS, which can further enhance fairness by reducing variations in signal strength and interference levels among users.

B. IMPACT OF USER LIMIT (N_{MAX})

1) OPTIMIZING LOW AVERAGE BINARY RATES AND REDUCING INACTIVE USERS CONCERNING N_{MAX} VARIATIONS

In our study, we have explored methods to optimize low average binary rates in uplink and downlink and to reduce the number of inactive users, particularly in the context of varying N_{max} values. Here are some key observations and strategies

a: ADAPTIVE RESOURCE ALLOCATION

One approach to address low binary rates is through adaptive resource allocation. This method dynamically allocates resources such as bandwidth and power based on user demand and network conditions. By adapting the resource allocation, we can improve binary rates for active users, ensuring more efficient use of available resources.

b: DYNAMIC POWER CONTROL

Dynamic power control mechanisms allow for efficient power management, particularly in FD and hybrid modes. By adjusting transmission power based on the channel quality and distance, we can optimize the signal quality and binary rates for active users.

c: LOAD BALANCING

Load balancing strategies distribute user traffic more evenly among base stations. This can prevent network congestion and resource underutilization, leading to improved binary rates and reduced inactivity among users.

These strategies are essential for achieving higher binary rates and reducing the number of inactive users. Our simulations and analysis have demonstrated the effectiveness of these methods in improving network performance and user experience, particularly when N_{max} values vary.

By incorporating these strategies, we aim to ensure that the network operates efficiently, and resources are effectively utilized, resulting in better binary rates and reduced user inactivity.

2) EFFECT OF N_{MAX} ON BINARY RATE

Varying N_{max} has a significant impact on user activity. With strict user limits, many users become inactive as shown in Fig. 6. However, binary rates remain nearly constant across different modes.

Binary rates are higher in FD and hybrid modes, particularly in DL as shown in Figure 7 and Figure 8. This is because FD mode takes advantage of stronger DL BS power, resulting in improved data rates.

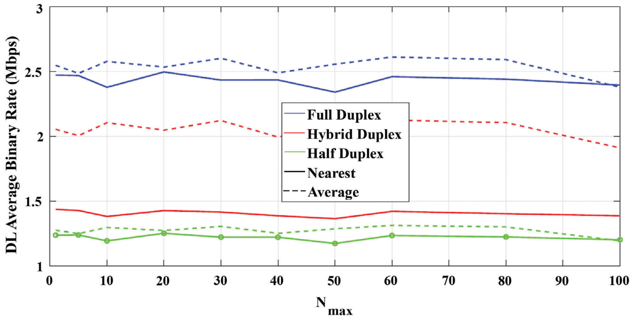

FIGURE 7. Impact on Downlink average binary rate with variation of users limit N_{max}.

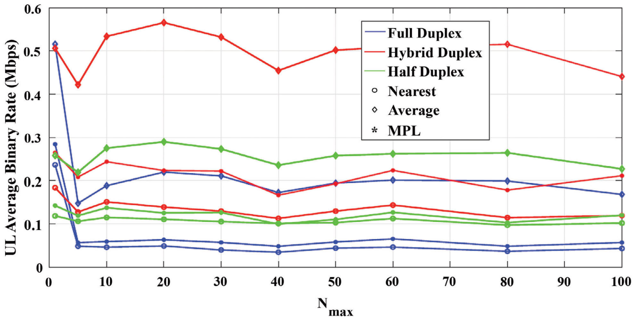

FIGURE 8. Impact on Uplink average binary rate with variation of users limit N_{max}.

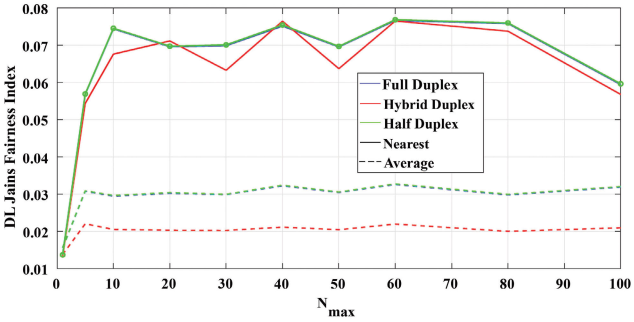

FIGURE 9. Impact on Downlink JFI with variation of users limit N_{max}.

3) EFFECT OF N_{MAX} ON JFI

Fairness (equal distribution of resources among users) improves with higher values of N_{max} as shown in Figure 9 and Figure 10. As more users become active, resources are more evenly shared. However, for strict N_{max} values, there can be fluctuations in fairness due to the limited number of active users.

C. IMPACT OF β (PICO-TO-MACRO BS DENSITY RATIO)

1) EFFECT OF β ON BINARY RATE

Adjusting the ratio of pico to macro BS densities (β) changes the network's BS composition. Higher β values lead to more pico BSs and fewer macro BSs. Increasing β results in reduced binary rates. This is because UEs associated with pico BSs experience higher path losses. With more pico BSs, users are farther away from BSs, leading to reduced signal quality and data rates.

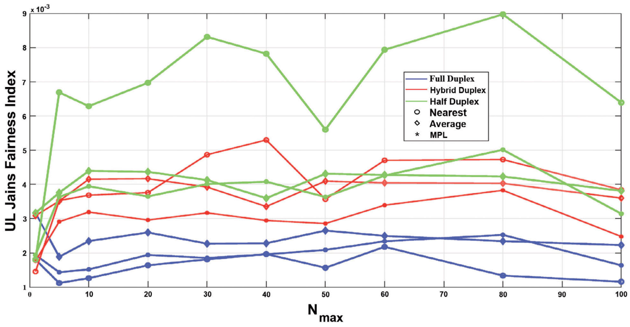

FIGURE 10. Impact on Uplink JFI with variation of users limit N_{max}.

D. IMPACT OF CELL RANGE EXPANSION (τ)

In this section, the impact of cell range expansion (τ) on network performance is discussed, and the results are presented in Figures 11, 12, and 13. Effective Cell Range represents the range within which a UE can effectively communicate with a base station, considering various factors such as signal strength, interference, and network conditions. CRE, on the other hand, is a dynamic mechanism employed by 5G networks to adjust this range for specific UEs based on their requirements and network optimization objectives. By modifying the ECR for specific UEs, CRE plays a pivotal role in optimizing network performance, resource allocation, and interference management. When CRE is applied, the ECR for certain UEs is expanded or reduced, allowing for more efficient network operation. Understanding this relationship is crucial for enhancing network efficiency and user experience in 5G deployments. Let's elaborate the results for effect of τ on Binary rate and JFI and provide justification for the observed trends:

1) EFFECT OF τ ON BINARY RATE

Range expansion (τ) is used to evenly distribute users between BSs, offloading users from large macro BSs to smaller-scale BSs. Uneven distribution of users among BSs can lead to resource imbalance, where some BSs are heavily loaded while others are underutilized. Range expansion helps alleviate this problem by encouraging users to connect to smaller BSs, leading to more balanced resource utilization. With range expansion (e.g., $\tau \approx 22$ dB), the load decreases due to even distribution among BSs, resulting in rate improvement in the downlink for average association. Even distribution of users reduces congestion and allows each user to access resources more efficiently. This leads to an improvement in the downlink rate, as there is less contention for resources.

In our study, we observed that varying Cell Range Expansion (CRE) had a pronounced impact on the binary rate within our two-tier hybrid duplex Heterogeneous Cellular Network (HCN). The binary rate, which represents the data

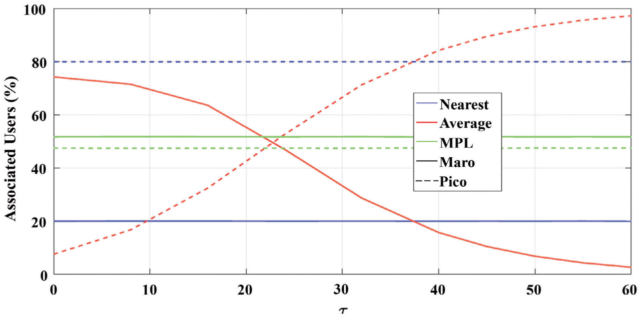

FIGURE 11. Associated users in percentage with variation of CRE τ.

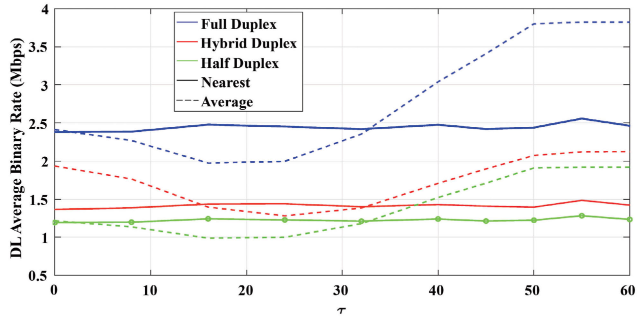

FIGURE 12. Impact on Downlink average binary rate with variation of CRE τ.

rate experienced by individual users in the network, exhibited a strong sensitivity to changes in the CRE parameter. As CRE increased, the binary rate demonstrated a notable improvement. This effect can be attributed to the dynamic adjustments in cell range for user equipment (UEs) that CRE facilitates. By expanding the cell range for specific UEs, they can connect to base stations (BSs) at a greater distance, resulting in higher achievable data rates. This expansion in cell range allows UEs to access resources from base stations that were previously outside their reach, leading to increased binary rates. Conversely, when CRE was reduced, the binary rate experienced a corresponding decrease. The reduction in cell range limited the access of UEs to resources, particularly from small-scale BSs operating in full-duplex mode. As a result, the achievable binary rate for UEs located farther from the BSs decreased.

2) EFFECT OF τ ON JFI

Fairness improves as users are treated more fairly due to even distribution, with the highest fairness value at approximately 32 dB. Even distribution of users reduces the likelihood of some users experiencing network congestion while others have ample resources. This contributes to improved fairness in resource allocation among users. Other association results remain constant and are shown for comparison purposes. The results for other association schemes are included to provide a baseline for comparison. Range expansion's impact on different association schemes can vary, and comparing them helps evaluate its effectiveness.

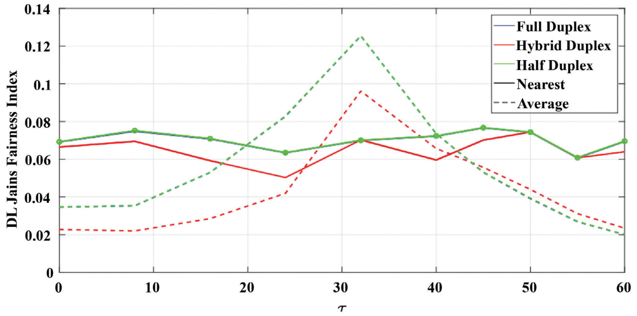

FIGURE 13. Impact on Downlink JFI with variation of CRE τ.

τ is a technique used to improve network performance by evenly distributing users among BSs. This can lead to decreased load, improved data rates, and enhanced fairness in resource allocation. The specific value of τ (e.g., 22 dB) and its impact on performance should be carefully tuned based on network characteristics and objectives. These results provide valuable insights for network optimization and resource management in wireless communication systems. Our study also explored the impact of varying CRE on JFI, a metric used to assess the fairness in resource allocation among users in the network. The JFI represents how evenly resources are distributed among UEs. We observed that the effect of CRE on JFI was nuanced and dependent on the specific association criterion used. Under the nearest association criterion, where UEs are connected to the nearest BS, half-duplex mode consistently outperformed other modes in terms of JFI. This is because under half-duplex mode, the allocation of resources to UEs was more evenly distributed, resulting in a higher fairness index. However, when the association criterion was based on maximizing average received power, we observed that FD and hybrid duplex modes outperformed other modes, leading to higher JFI values. This is because the CRE adjustments allowed UEs to connect to base stations that offered superior signal quality, resulting in more balanced resource allocation and enhanced fairness.

The observed trends in binary rate and JFI in response to changes in CRE underscore the intricate interplay of duplexing modes, association criteria, and network parameters within our two-tier hybrid duplex HCN. The choice of CRE values can significantly impact network performance, binary rates, and the fairness of resource allocation, highlighting the importance of careful parameter selection in the context of 5G and beyond.

E. OPTIMIZATION ACTIONS FOR 5G RAN AND HARDWARE

1) CRE VARIATIONS IN DOWNLINK

1) **CRE Adjustment:** Optimizing CRE in the downlink involves dynamically adjusting the cell range to suit the specific requirements of user equipment (UE). By expanding or contracting the cell range, network

resources can be allocated more efficiently, reducing interference and improving coverage for UEs at different distances.

F. CRE VARIATIONS IN UPLINK (FPC)

1) **FPC (Fractional Power Control):** In the uplink, FPC is used to regulate the transmit power of UEs. By adjusting the power levels based on the signal quality, FPC helps to minimize interference and improve spectral efficiency. To optimize FPC, fine-tuning the power control algorithms and thresholds can be essential.

G. NMAX VARIATIONS

1) **Resource Allocation:** To optimize network performance under different Nmax scenarios, resource allocation strategies must be adjusted. For higher Nmax values, more resources may be allocated to accommodate additional users. Dynamic resource allocation algorithms can be used to ensure fair and efficient utilization.

H. USER DENSITY VARIATIONS

1) **Dense Network Deployments:** In high-density scenarios, network optimization often involves deploying more small cells, such as pico and femto base stations, to offload traffic from macro cells. These small cells are strategically placed to enhance capacity and reduce congestion.

I. JOINT OPTIMIZATION:

1) **Interplay between Parameters** In practice, optimization often involves an interplay of CRE, Nmax, and user density. These parameters can be jointly optimized to find the right balance that maximizes network capacity, coverage, and spectral efficiency. Machine learning algorithms and self-organizing networks (SON) can assist in this complex optimization process.

VI. CONCLUSION

In conclusion, our investigation into FD HCNs in the context of 5G and beyond networks has yielded several noteworthy findings and insights. We explored the trade-offs associated with different duplexing modes, including FD and hybrid duplex, compared to traditional half-duplex communication. While FD promised the potential for doubling throughput, our results indicated that its impact on various performance metrics is complex and highly dependent on network parameters. One of the key takeaways from our study was the significance of Cell Range Expansion (CRE) in achieving optimal network performance. We found that specific values of CRE played a critical role in maximizing binary rate and the Jains fairness index, highlighting the importance of careful tuning in network design. The choice of association criteria, such as maximizing average received power or selecting the nearest BS, had a substantial impact on network performance. These criteria influenced the performance of different duplexing modes and need to be tailored to specific network objectives. Our research underscored the profound influence of user and small-scale BS densities, as well as the maximum user limit, on network performance. Managing these parameters effectively is crucial for achieving desired outcomes in terms of binary rate and fairness. While FD and hybrid duplex modes demonstrated superior binary rates, the choice of half-duplex mode consistently yielded better fairness results under certain association criteria. These findings emphasize the importance of carefully balancing performance trade-offs based on network objectives and constraints. In essence, our study provides valuable insights into the design and optimization of FD HCNs for 5G and beyond. Achieving the full potential of FD communication requires a nuanced understanding of network parameters, duplexing modes, and association criteria. By leveraging these insights, network operators and designers can work towards building more efficient and equitable wireless networks to meet the ever-increasing demands of modern communication systems.

ACKNOWLEDGMENT

The authors extend their appreciation to the Deputyship for Research and Innovation, Ministry of Education in Saudi Arabia for funding this research work through the project no. (IFKSUOR3–596–5).

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