Decoupled UL/DL Association in Wireless-Powered Massive MIMO-Aided IoT Heterogeneous Networks

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Abstract—In this paper, we investigate the performance of downlink-uplink decoupled (DUDe) user association in wireless-powered full-duplex (FD) heterogeneous networks (HetNets), where different association strategies are deployed for uplink and downlink. We consider a two-tier HetNet with half duplex (HD) massive multiuser multiple-input multiple-output (MIMO) macrocell base stations (MBSs) to relax the coverage reduction, FD small cell base stations (SBSs) and FD user equipments (UEs) to improve spectral efficiency. During the energy transmission phase, UEs are associated to MBSs/SBSs based on the mean maximum received power (MMP) scheme and charge their batteries. During the data transmission phase, each UE downloads packets from the same MBSs/SBSs, while UEs upload packets to the nearest SBSs using the harvested energy. We develop an analytical framework to analyze the average UL power transfer and derive closed-form expressions for the UL and DL coverage probabilities of the proposed DUDe in massive MIMO aided HetNets.

Index Terms—Heterogeneous networks, decoupled user association, full-duplex communications, energy harvesting.

I. INTRODUCTION

The internet of things (IoT) has been recognized as a promising technology for the fifth generation (5G) and beyond mobile communication networks [1]–[3]. IoT enables information exchange among heterogeneous applications and millions of devices. However, in practice, implementation of IoT imposes strict limitations on energy and cost [3]. Therefore, how to provide energy for a huge number of heterogeneous IoT devices is a major challenge. In this context, energy harvesting (EH), especially radio frequency EH (RF-EH) which harvests energy from RF signals, is regarded as a promising technology to replenish the batteries of IoT devices [4]. Moreover, deployment of low-powered cellular IoT devices, such as femto- and picocells, termed as small-cells (SCells), at the macro-cell (MCell) edge, has been regarded as a cost-effective solution to satisfy coverage and capacity needs of future mobile communication networks [2].

Heterogeneous networks (HetNets) has been emerged as key propellent to meet the ever increasing demands of future wireless networks, wherein a diverse set of SCells with different applications deployed within the coverage of the traditional MCell. Specifically, different mobile applications such as smart meters, remote sensors, consumer devices, vending machines, and vehicular applications are enabled through the use of low power femto/pico base stations (BS). These applications are closely associated with the emerging IoT, and envisioned the trend of IoT underlaying heterogeneous SCell networks [5].

In order to enhance the spectral efficiency of the HetNets, full-duplex (FD) communication, which enables simultaneous transmission and reception over the same frequency band, has been widely applied in such networks [6]–[9]. However, FD communication introduces self-interference (SI) and inter-node interference in the network due to the simultaneous operation of uplink (UL) and downlink (DL) nodes in the same cell [10]. Moreover, due to the complicated interference scenarios as well as significant disparity in the transmit power of different BSs and non-uniform traffic loads of different BSs in both the DL and UL transmissions, new technical challenges emerge for user association in FD-enabled HetNets. In other words, traditional/coupled association scheme, which considers the same user association criterion (e.g., DL maximum received signal power) for both UL and DL transmissions, is highly inefficient in FD HetNets. Therefore, the idea of DL and UL decoupling (DUDe) has been proposed for 5G [11]. According to DUDe scheme, a wireless device that sees multiple BSs may access the infrastructure in a way that it receives the DL traffic from one BS and sends UL traffic through another BS.

The performance of DUDe in FD HetNets has been investigated in [12]–[18]. Specifically, the seminal simulation study in [12] demonstrated that DUDe could outperform the coupled association scheme in two-tier cellular networks. Authors in [13], analyzed the performance of DUDe association problem in multi-tier FD networks, using stochastic geometry. The work in [13] has been extended to two-tier HetNets consisting of multi-antenna BSs in [14]. In [15], a decoupled rate-optimal user association scheme was characterized for FD HetNets and the corresponding UL and DL rates were evaluated. In [16], a contract theory based distributed approach was proposed for decoupled user association in an FD cellular networks. The authors in [17], presented an optimization scheme of frequency allocation and power control to improve the communication quality of users in the DUDe HetNets. In [18], a novel transmission scheme was proposed to mitigate pilot contamination and intra-cell interference in a two-tier multi-cell HetNets with DUDe.

Different from the aforementioned literature (e.g., [12]–[18]), where DUDe was investigated in FD HetNets without energy...
harvesting, we study the performance of DUDe in presence of wireless power transfer (WPT). Specifically, each user equipment (UE) first harvests the energy from its serving BS (as a dedicated RF energy source) in the DL and uses the harvested energy for wireless information transfer (WIT) in the UL. By leveraging tools from stochastic geometry, we analyze the average UL power transfer and derive closed-form expressions for the UL and DL coverage probabilities of DUDe in two-tier FD HetNets. Our findings reveal that, DL and UL coverage probability of the considered system is first increased and then decreased as the SCell base station (SBS) density is increased. On the contrary, in the FD HetNet counterpart without EH, the DL coverage is increased while the UL coverage is decreased when the SBS density is increased.

Notation: We use $\mathbb{E}\{X\}$ to denote the expected value of the random variable (RV) $X$; we use the notation $X \sim \exp(\mu)$ to denote the Gamma distribution with shape $\theta$ and scale parameter $\mu$, $\Gamma(a, x)$ is upper incomplete Gamma function [19, Eq. (8.350)]; $\beta F_+(\alpha, \gamma; \cdot; \cdot)$ denotes Gauss hypergeometric function [19, Eq. (9.111)].

II. SYSTEM MODEL

A. Network Topology

We consider a two-tier time-division duplex (TDD) HetNet that consists of MCell base stations (MBSs), SBSs and UEs. The location of MBSs, SBSs and UEs are modeled as 2-D independent homogeneous Poisson Point Processes (PPPs). Let $\Phi_M \triangleq \{X_{M,i} \in \mathbb{R}^2 : i \in \mathbb{N}_+\}$, $\Phi_S \triangleq \{X_{S,i} \in \mathbb{R}^2 : i \in \mathbb{N}_+\}$ and $\Phi_u \triangleq \{U_j \in \mathbb{R}^2 : j \in \mathbb{N}_+\}$ represent the PPPs for MBSs, SBSs and UEs respectively, where $X_{M,i}$ denotes $MBS_i$, $X_{S,i}$ denotes $SBS_i$, $i \in \{M,S\}$ denotes BS $i$ in the nth tier and its location and $U_j$ denotes user $j$ and its location. Furthermore, let $\lambda_M$, $\lambda_S$, $\lambda_u$ be the density of $\Phi_M$, $\Phi_S$ and $\Phi_u$, respectively. We assume that MBSs are equipped with a large antenna array, operating in half duplex (HD) mode, and support $S$ UEs in DL, while SBSs are equipped with dual-antenna and operating in FD mode. The transmit power of a MBS and SBS are represented by $P_M$ and $P_S$ respectively, where $P_M > P_S$. Each UE can perform either FD or HD transmission mode - it performs the HD mode if it wants to simultaneously exchange information with its associated BS (SBSs); otherwise it performs the HD mode to merely receive or transmit data [15]. In order to cope with the challenges of densification of nodes (including UEs and SBSs), DUDe is applied in the considered model. Therefore, FD UE $k$ can associate with a BS $\ell$ in the UL but a different BS $\ell'$ in the DL.

B. User Association

Each UE first harvests the energy from its serving BS (as a dedicated RF energy source) in the DL and uses the harvested energy WIT in the UL [20]. We remind that for the UL transmission, the UEs can only associate with the FD SBSs. We assume that in DL each UE is associated to the serving BS during the EH phase, while in UL it can associate to a different BS. Assume that all users adopt the following generalized user association strategy to associate to their DL/UL BS [15], [21]

$$X^* = \arg \max_{m \in \Phi_M} P_m(X_{m,i} | X_{S,i}, X_{M,i}, X_{S,i}) = \arg \max_{m \in \Phi_M} P_m(X_{m,i} | X_{S,i}),$$

where $\|X\|$ is the Euclidean distance from node $X$ to the typical user, $\Psi_m(i)$ is the user association function of BS $X_{m,i}$, $\Psi_m(i) = \{m \in \{M,S\}, i \in \mathbb{N}_+\}$ is the user association function of BS $X_{m,i}$ and $\Psi_m(i) = \{m \in \{M,S\}, i \in \mathbb{N}_+\}$ is the user association function of BS $X_{m,i}$.

For UL user association, we consider the nearest BS association (NBA) scheme [8], [13]. In this scheme we have $\Psi_m(i) = 1$ and we thus have $\Psi_m(i) = \|X_{S,i}\|^{−\alpha_m}$ that makes users associate with a BS that provides them with the maximum mean received power. In this case, the generalized user association scheme is called the MMP association (MMPA) scheme [15], [21].

For UL user association, a UE is associated with the BS based on the mean maximum received power (MMP). In this scheme, $\psi_m(i) = P_m$, where $P_m$ is the transmit power of the nth tier BS. Therefore, we have $\Psi_m(i) = P_m \|X_{m,i}\|^{−\alpha_m}$ that makes users associate with a BS that provides them with the maximum mean received power. In this case, the generalized user association scheme is called the MMP association (MMPA) scheme [15], [21].

C. Signal Transmission Model

Let $T$ be the duration of a communication block. During the first fraction $\tau$, $(0 < \tau < 1)$ of time frame, BSs deliver energy and UEs harvest energy from the received signal. During the remaining $(1-\tau)$ fraction of the time frame, the UEs upload packets to SBSs and at the same time download packets from MBS/SBSs.

D. Energy Harvesting Phase

We consider UEs with large energy storages such that enough harvest energy can support for stable transmit power. Moreover, for wireless EH, all RF signals are interpreted as energy. Therefore, in the massive MIMO MCell, we adopt the simplest linear MRT beamforming to direct RF signal twoard intended UEs. During $\tau$ fraction of each time slot, which is devoted to

\footnote{Note that for the UL transmission, the UEs can only associate with the FD SBSs.}
the EH phase, the total harvested energy at a typical UE that 
is associated with the MBS is given by
\[
E_{M,0} = \eta \sum_{S,i} P_M h_{M,0} \| X_{M,0} \|^{-\alpha_M} \tau T + \eta (I_{M,1} + I_{S,1}) \tau T,
\]
where \( E_{M,0} \) is the energy from the directed WPT from MBS, \( E_{S,0} \) is the energy from the ambient RF. Here \( 0 < \eta < 1 \) is the RF-to-DC conversion efficiency, \( h_{M,0} \sim \Gamma(N,1) \) is the small-scale fading channel power gain between MBS, \( X_{M,0} \), and typical UE, and \( X_{M,0} \) denotes the distance between MBS \( X_{M,0} \) and typical UE. In addition,
\[
I_{M,1} = \sum_{S,i} P_M h_{M,i} \| X_{M,i} \|^{-\alpha_M},
\]
is the sum of interference from the interfering MBSs, where \( h_{M,i} \sim \Gamma(1,1) \) and \( X_{M,i} \) denote, respectively, the small-scale fading channel power gain and the distance between a typical user and other MBS, and
\[
I_{S,1} = \sum_{S,i} P_S h_{S,i} \| X_{S,i} \|^{-\alpha_s},
\]
is the sum of interference from the SBSs, where \( h_{S,i} \sim \exp(1) \) and \( X_{S,i} \) are, respectively, the small-scale fading interfering channel power gain and the distance between a typical user and its associated SBS, and 
\[
I_{M,2} = \sum_{X_{M,i} \in \Phi_M} P_M h_{M,i} \| X_{M,i} \|^{-\alpha_M},
\]
\[
I_{S,2} = \sum_{X_{S,i} \in \Phi_S / X_{S,0}} P_S h_{S,i} \| X_{S,i} \|^{-\alpha_s}.
\]

1) Uplink/Downlink Information Transmission Phase: After 
EH, during the remaining \((1 - \tau)\) fraction of each time slot, each 
MBS transmit \( S \) data streams to associated DL UEs using linear 
zero-forcing beamforming (ZFBF) with the equal transmit power 
allocation [8], thus the uncorrelated intra-cell interference is 
suppressed. The signal-to-interference-plus-noise ratio (SINR) 
for a typical DL MCell UE located at the origin can be written as
\[
\text{SINR}_{U_0}^\text{dl} = \frac{P_M h_{M,0} \| X_{M,0} \|^{-\alpha_M}}{I_{M,1}^\text{dl} + I_{S,1}^\text{dl} + I_{U}^\text{dl} + \epsilon P_{RS1} + N_0},
\]
where \( h_{M,0} \sim \Gamma(N - S + 1,1) \) is the small-scale fading channel 
power gain between the typical DL UE and its serving MBS 
and \( \beta \) is the frequency dependent constant value. \( \epsilon \in [0,1] \) 
is the self-interference factor for FD UEs \( \epsilon = 1 \) else \( \epsilon = 0 \),
\( P_{RS1} \) is the residual SI power after performing 
cancellation, where \( h_{RS1}^\text{dl} \sim \exp(1) \) is the residual SI 
channel of the typical UEs. Moreover, \( I_{M,1}^\text{dl}, I_{S,1}^\text{dl}, \) and \( I_{U}^\text{dl} \) 
are the interferences from the other MBSs, the SBSs, and the other 
FD SCell UEs given as
\[
I_{M,1}^\text{dl} = \sum_{X_{M,i} \in \Phi_M / X_{M,0}} \frac{P_M}{S} h_{M,i} \| X_{M,i} \|^{-\alpha_M},
\]
\[
I_{S,1}^\text{dl} = \sum_{X_{S,i} \in \Phi_S} P_S h_{S,i} \| X_{S,i} \|^{-\alpha_s},
\]
and
\[
I_{U}^\text{dl} = \sum_{U_j \in \Phi_u / 0} \text{E} \{ P_{U_j} \} g_j \| U_j \|^{-\alpha_s},
\]
respectively. In (9), (10), and (11), \( h_{M,1} \sim \Gamma(S,1) \), \( h_{S,i} \sim \exp(1) \), and \( g_j \sim \exp(1) \) denote the small-scale fading channel 
power gains from the interfering MBSs to the typical MCell 
DL UE, and from the SBSs to the typical MCell DL UE, and 
the FD SCell UEs to the typical MCell DL UE, respectively,
and their corresponding distances are denoted as \( X_{M,i}, X_{S,i}, \) 
and \( U_j \), respectively. Moreover \( P_{U_j} \) denotes the transmit power of 
FD UEs which upload packets to SBSs.

Moreover, the SINR for a typical DL SCell UE located at 
the origin can be written as
\[
\text{SINR}_{U_0}^\text{ul} = \frac{P_S h_{S,0} \| X_{S,0} \|^{-\alpha_s}}{I_{M,1}^\text{ul} + I_{S,1}^\text{ul} + I_{U}^\text{ul} + \epsilon P_{RS1} + N_0},
\]
where \( h_{S,0} \sim \exp(1) \) and \( X_{S,0} \) are the small-scale fading channel 
power gain and the distance between the typical DL 
SCell UE and its serving SBS and \( \alpha_s \) is the path loss exponent 
for the SCell channel. Moreover, \( I_{M,1}^\text{ul}, I_{S,1}^\text{ul}, \) and \( I_{U}^\text{ul} \) 
are the interference from the MBSs, the other SBSs, the other FD SCell 
UEs, given as
\[
I_{M,1}^\text{ul} = \sum_{X_{M,i} \in \Phi_M} \frac{P_M}{S} h_{M,i} \| X_{M,i} \|^{-\alpha_M},
\]
\[
I_{S,1}^\text{ul} = \sum_{X_{S,i} \in \Phi_S / X_{S,0}} P_S h_{S,i} \| X_{S,i} \|^{-\alpha_s},
\]
and
\[
I_{U}^\text{ul} = \sum_{U_j \in \Phi_u / 0} \text{E} \{ P_{U_j} \} g_j \| U_j \|^{-\alpha_s},
\]
In (13), (14), and (15) \( h_{M,1} \sim \Gamma(S,1), h_{S,1} \sim \exp(1), \) 
and \( g_j \sim \exp(1) \) denote the small scale fading channel power gain to 
the DL SCell UE from the MBSs, the SBSs, the FD SCell 
UEs, respectively, and their corresponding distances are denoted as 
\( X_{M,i}, X_{S,i}, \) and \( U_j \), respectively. The UL SINR for a typical 
SBS located at the origin can be written as
\[
\text{SINR}_{S}^\text{ul} = \frac{E \{ P_{U_0} \} g_0 \| U_0 \|^{-\alpha_s}}{I_{M,1}^\text{ul} + I_{S,1}^\text{ul} + I_{U}^\text{ul} + \epsilon P_{RS1} + N_0},
\]
where \( g_0 \sim \exp(1) \) is the small-scale fading channel power.
gain between typical FD SCell UE, uploading its packet and SBS \( X_{S,o} \). \( U_0 \) is the distance between typical FD SCell UE and its serving SBS and \( P_{RSI}^S = P_S |h_{RSI}^S|^2 \) is the residual SI power after performing cancellation, where \( h_{RSI}^S \sim \exp(1) \) is the residual SI channel of the typical SBS. Moreover, \( I^{ul}_{M,i} \), \( I^{ul}_{S,i} \), and \( I^{ul}_{U} \) are the interference from the MBS, the other SBSs, and the typical FD SCell UE, respectively.

\[
I^{ul}_{M,i} = \sum_{X_{M,i} \in \Phi_{M}} \frac{P_M}{S} h_{M,i} \beta ||X_{M,i}||^{-\alpha_M}, \quad (17)
\]

\[
I^{ul}_{S,i} = \sum_{X_{S,i} \in \Phi_{S}} P_S h_{S,i} \beta ||X_{S,i}||^{-\alpha_S}, \quad (18)
\]

\[
I^{ul}_{U} = \sum_{U_j \in \Phi_{U}} \mathbb{E}\{ P_{U_j} \} g_j \beta ||U_j||^{-\alpha_S}, \quad (19)
\]

In (17), (18), and (19) \( h_{M,i} \sim \Gamma(S, 1) \), \( h_{S,i} \sim \exp(1) \), and \( g_j \sim \exp(1) \) denote the small scale fading channel gain power to the SBS from the MBSs, the SBSs, the FD SCell UEs, respectively, and their corresponding distances are denoted as \( X_{M,i} \), \( X_{S,i} \), and \( U_j \), respectively.

### III. PERFORMANCE ANALYSIS

#### A. Analysis Of Average Uplink Power Transfer

To determine the UL transmit power of a typical UE in the \( m \)th tier, \( m \in \{M, S\} \), we derive the average received power at the typical UE with the MMPA user association in the following Lemmas.

**Lemma 1:** For the MMPA user association, the average received power at the typical UE associated with the MBS, is given by

\[
\mathbb{E}\{ P_{U_0} \}^{\text{MMPA}}_{\text{MBS}} = \eta \left( 2\pi \lambda_M P_M \left( \frac{N}{S} \Xi_1 + \Xi_2 \right) + 2\pi \lambda_s P_S \Xi_3 \right),
\]

where

\[
\Xi_1 = \frac{1}{\Lambda_{M}^{\text{MMPA}}} \int_0^{\infty} x^{1-\alpha_M} \exp \left( -\pi \lambda_s \left( \frac{SP_S}{P_M} \right) \frac{x^{2\alpha_M}}{x^{2\alpha_M}} \right) dx,
\]

\[
\Xi_2 = \frac{2\pi \lambda_M}{\Lambda_{M}^{\text{MMPA}}} \int_0^\infty x^{1-\alpha_S} \exp \left( -\pi \lambda_s \left( \frac{SP_S}{P_M} \right) \frac{x^{2\alpha_S}}{x^{2\alpha_M}} \right) dx,
\]

\[
\Xi_3 = \frac{2\pi \lambda_s}{\Lambda_{M}^{\text{MMPA}}} \int_{\rho_M(x)}^\infty x^{1-\alpha_S} \exp \left( -\pi \lambda_M \left( \frac{P_M}{SP_S} \right) \frac{x^{2\alpha_M}}{x^{2\alpha_M}} \right) dx,
\]

and \( \rho_M(x) = \frac{SP_S}{P_M} \frac{x^{2\alpha_M}}{x^{2\alpha_M}} \) is the distance between the closest interfering SBS of the second tier and the typical MCell UE.

**Proof:** The proof is omitted here for the sake of space.

#### B. Coverage Probability

In this section, we study the coverage probability of two-tier HetNet with FD SCell, which is a metric that represents the average fraction of the cell area that is in coverage at any time. We define the coverage probability \( C \) as the probability that the instantaneous SINR of a randomly located user is larger than a SINR threshold.

1) **Downlink:** The DL coverage probability of a DL UE in the two-tier HetNet is given by

\[
C_{DL} (R_{DL}) = \sum_{m \in \{M, S\}} \Lambda_m C_{m}^{DL} (R_{DL}),
\]

where \( \Lambda_m \) is the per-tier association probability and \( C_{m}^{DL} \) is the coverage probability of a typical user associated with \( m \)th tier BSs. For a SINR threshold \( \gamma_{DL}^{th} \) and a typical user SINR at a distance \( x \) from its associated BS, the coverage probability is given by

\[
C_{m}^{DL} (R_{DL}) = \mathbb{E}_x \{ \text{Pr} \left( SINR_m (x) \geq \gamma_{DL}^{th} | x \right) \},
\]

where \( \gamma_{DL}^{th} = 2 R_{DL} - 1 \) and \( R_{DL} \) is the DL rate threshold.

**Lemma 3:** The DL coverage probability of a typical UE associated with the MBS based on MMPA user association is derived as

\[
C_M (R_{DL}) = \frac{2\pi \lambda_M}{\Lambda_{M}^{\text{MMPA}}} \int_0^\infty x^{\frac{1}{2}} \left( \exp \left( -\pi \lambda_M x^2 - \pi \lambda_s \left( \frac{SP_S}{P_M} \right) \frac{x^{2\alpha_M}}{x^{2\alpha_M}} \right) \right) dx
\]

\[
- \frac{1}{\pi} \int_0^\infty \text{Im} \left[ \exp \left( -\Omega_1 (x, w) - \pi \lambda_M \Omega_2 (x, w) - 2\pi \lambda_s \right) \right] \left( \Omega_3 (x, w) + \Omega_4 (x, w) \right) \left( 1 + \epsilon (-j w) \mathbb{E}\{ P_{U_j} \} \right)^{-1} \frac{dw}{w} dx,
\]

where

\[
\Omega_1 = \left( \frac{SP_S}{P_M} \right) \frac{x^{2\alpha_M}}{x^{2\alpha_M}},
\]

\[
\Omega_2 = \left( \frac{SP_S}{P_M} \right) \frac{x^{2\alpha_M}}{x^{2\alpha_M}},
\]

\[
\Omega_3 = (1 + \epsilon (-j w) \mathbb{E}\{ P_{U_j} \}^{-1} \left( \frac{dw}{w} \right) dx,
\]

\[
\Omega_4 = \pi \lambda_M \Omega_2 (x, w) - 2\pi \lambda_s.
\]
where
\[ \Omega_1 (x, w) = jw \left( \frac{\beta P_M}{\gamma_{\text{MMPA}} x^{\alpha_s} - N_0} \right), \]  
\[ \Omega_2 (x, w) = \Gamma \left( 1 - \frac{2}{\alpha_s} \right) + \frac{2}{\alpha_s} \Gamma \left( \frac{-jwP_M}{x^{\alpha_s} - N_0} \right), \]  
\[ \Omega_3 (x, w) = \left( -jw \right) \beta P_S \left( \frac{2}{\alpha_s} x^{\alpha_s - 1} \right), \]
\[ \times 2F_1 \left( 1, 1 - \frac{2}{\alpha_s}; 2 - \frac{2}{\alpha_s}; \left( \frac{jw}{ \xi_{\text{MMPA}}} \right) \right), \]  
\[ \Omega_4 (x, w) = \frac{1}{2} \Gamma \left( 1 + \frac{2}{\alpha_s} \right) \Gamma \left( 1 - \frac{2}{\alpha_s} \right) \left( \frac{\beta P_M}{\gamma_{\text{MMPA}} x^{\alpha_s}} - jw \right)^{-1} \]
\[ \times \mathbb{E} \left\{ P_{U_0} \right\} \frac{\gamma_{\text{MMPA}}}{\gamma_{\text{MMPA}}}, \]
\[ \left( -jw \mathbb{E} \left\{ P_{U_0} \right\} \right)^{-1} \left( 1 + \epsilon \left( -jw \right) \mathbb{E} \left\{ P_{U_0} \right\} \right) \left( -\frac{dw}{w} \right) dx, \]
\[ \text{where} \]
\[ \Theta_1 (x, w) = \Gamma \left( 1 - \frac{2}{\alpha_s} \right) + \frac{2}{\alpha_s} \Gamma \left( \frac{-jwP_M}{x^{\alpha_s} - N_0} \right) - \left( \rho_M (x) \right)^2. \]
\[ \Theta_2 (x, w) = \left( -jw \right) \beta P_S \frac{R^{\alpha_s}}{x^{-\alpha_s}}, \]\n\[ \times 2F_1 \left( 1, 1 - \frac{2}{\alpha_s}; 2 - \frac{2}{\alpha_s}; \left( \frac{jw}{ \xi_{\text{MMPA}}} \right) \right), \]  
\[ \Theta_3 (x, w) = \frac{1}{2} \Gamma \left( 1 + \frac{2}{\alpha_s} \right) \Gamma \left( 1 - \frac{2}{\alpha_s} \right) \left( \frac{\beta P_M}{\gamma_{\text{MMPA}} x^{\alpha_s}} - jw \right)^{-1} \]
\[ \times \mathbb{E} \left\{ P_{U_0} \right\} \frac{\gamma_{\text{MMPA}}}{\gamma_{\text{MMPA}}}, \]
\[ \left( -jw \mathbb{E} \left\{ P_{U_0} \right\} \right)^{-1} \left( 1 + \epsilon \left( -jw \right) \mathbb{E} \left\{ P_{U_0} \right\} \right) \left( -\frac{dw}{w} \right) dx. \]

Proof: The proof is omitted here for the sake of space.

Lemma 4: The DL coverage probability of a typical UE associated with the SBS based on MMPA user association is derived as
\[ C_{S\text{M}} (R^{\text{DL}}) = \]
\[ 2 \pi \lambda_M \left\{ \int_0^\infty \left[ \frac{1}{2} \left( \exp \left( -\pi \lambda_M \left( \frac{P_M}{\gamma_{\text{MMPA}}} \right)^{\alpha_s} x^{\alpha_s} - \pi \lambda_s x^2 \right) \right) \right] \right\} dx \]
\[ \left( 1 \right) \left( 1 + \epsilon \left( -jw \right) \mathbb{E} \left\{ P_{U_0} \right\} \right) \left( -\frac{dw}{w} \right) dx, \]
\[ \text{where} \]
\[ \pi \lambda_M \left( \frac{P_M}{\gamma_{\text{MMPA}}} \right)^{\alpha_s} x^{\alpha_s} - \pi \lambda_s x^2 \]) \]
\[ \times \mathbb{E} \left\{ P_{U_0} \right\} \frac{\gamma_{\text{MMPA}}}{\gamma_{\text{MMPA}}}, \]
\[ \left( -jw \mathbb{E} \left\{ P_{U_0} \right\} \right)^{-1} \left( 1 + \epsilon \left( -jw \right) \mathbb{E} \left\{ P_{U_0} \right\} \right) \left( -\frac{dw}{w} \right) dx. \]

Proof: The proof is omitted here for the sake of space.

2) Uplink: The coverage probability that a typical UE is associated with SBS, \( C_{S\text{ul}} (R^{\text{UL}}) \) is the UL coverage probability between a typical UE and its serving SBS defined as
\[ C_{S\text{ul}} (R^{\text{UL}}) = \mathbb{E} \left\{ \mathbb{P} \left( \left| \text{SINR}_{S,0} \right| \right) \right\}, \]
\[ \text{where} \]
\[ \text{SINR}_{S,0} \text{is given in (16), } \gamma_{\text{ul}} = 2R^{\text{UL}} - 1 \text{ and } R^{\text{UL}} \text{ is the UL rate threshold.} \]

Lemma 5: The UL coverage probability of a typical UE associated with SBS based on NBA is given by
\[ C_{S\text{ul}} (R^{\text{UL}}) = \]
\[ 2 \pi \lambda_s \left\{ \int_0^\infty \left[ \frac{1}{2} \left( \exp \left( -\pi \lambda_s x^2 \right) \right) \right] \right\} dx \]
\[ \pi \lambda_M \left( \frac{P_M}{\gamma_{\text{MMPA}}} \right)^{\alpha_s} x^{\alpha_s} - \pi \lambda_s x^2 \]) \]
\times \mathbb{E} \left\{ P_{U_0} \right\} \frac{\gamma_{\text{MMPA}}}{\gamma_{\text{MMPA}}}, \]
\[ \left( -jw \mathbb{E} \left\{ P_{U_0} \right\} \right)^{-1} \left( 1 + \epsilon \left( -jw \right) \mathbb{E} \left\{ P_{U_0} \right\} \right) \left( -\frac{dw}{w} \right) dx, \]
\[ \text{where} \]
\[ \gamma_{\text{ul}} = \gamma_{\text{ul}} \frac{1}{\gamma_{\text{MMPA}}} \]
\[ \text{and } \gamma_{\text{ul}} = \gamma_{\text{ul}} \frac{1}{\gamma_{\text{MMPA}}}, \]
\[ \left( -jw \mathbb{E} \left\{ P_{U_0} \right\} \right)^{-1} \left( 1 + \epsilon \left( -jw \right) \mathbb{E} \left\{ P_{U_0} \right\} \right) \left( -\frac{dw}{w} \right) dx. \]

Proof: The proof is omitted here for the sake of space.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, simulation results are presented to quantify the effect of system performance. In the DL and the UL in terms of the coverage probability. The system is modeled as a random process. The system's parameters are set to \( P_M = 40 \text{ W}, P_S = 33 \text{ W}, \lambda_M = 10^{-3}, \alpha_M = 3.5, \alpha_S = 4, \eta = 0.6, \beta = 0.9, S = 5, N_0 = -100 \text{ dBm}, R^{\text{DL}} = 0.5 \text{ bps/Hz}, \) and \( R^{\text{UL}} = 0.5 \text{ bps/Hz}. \)

Fig. 1 shows the DL coverage probability \( C_M \) and \( C_{S\text{ul}} \) versus \( \lambda_s \) for two values of \( P_S \) and \( N \). Analytical results were plotted using (27) and (29). It can be readily observed that, the analytical results are in exact agreement with the Monte Carlo simulation results. The increase in \( \lambda_s \) at first improves the DL coverage probability at both tires, which is due to the fact that increasing in \( \lambda_s \) decreases the distance between the typical UE and its serving SBS. However, increasing \( \lambda_s \) to some extent, reduces coverage probability because it increases interference from interferer SBSs and interference from UL UEs, as the harvested power at UEs is increased when \( \lambda_s \) is increased. Moreover, the increase in \( N \) improves the DL coverage probability. This can be explained by the fact that the amount of harvested power from MBS is increased, which accordingly increases interference from other MBSs and UL UEs. Furthermore, we observe that, in both tiers with the increase of \( P_M \), DL coverage probability is improved at higher values of \( \lambda_s \).

Fig. 2 presents the UL coverage probability versus \( \lambda_s \) for different values of \( P_S \) and \( N \). It can be observed that by
have shown that for different system setup there is an optimum value for the SBS density at which both DL and UL coverage probabilities are maximized.

REFERENCES


In this paper, we developed an analytical framework to investigate the performance of DUDe in FD wireless-powered HetNets. In particular, we analyzed the UL MPPA and the DL NBA user association scheme and derived closed-form expressions of the UL and DL coverage probabilities, which provide an efficient means to evaluate the impact of the MBS density, SBS density, and corresponding transmit powers on the UL and DL coverage of the considered system. Our results have shown that for different system setup there is an optimum