On Supporting Legacy and RF Energy Harvesting Devices in Two-Tier OFDMA Heterogeneous Networks

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Abstract
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On Supporting Legacy and RF Energy Harvesting Devices in Two-Tier OFDMA Heterogeneous Networks

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ABSTRACT Future devices are likely to have the capability to harvest energy from radio-frequency (RF) signals. In this paper, we consider such energy harvesting (EH) devices operating in a two-tier orthogonal frequency-division multiple access-based heterogeneous network. Critically, we investigate how such EH devices can be supported alongside non-RF harvesting or legacy devices. Our aim is to minimize the downlink sum transmit power of both femto and macro base stations and ensure that legacy and EH devices receive a given data rate and amount of energy, respectively. Critically, we study sub-carrier and power allocation to both types of devices and investigate novel questions related to interference, which reduces network capacity but improves the amount of harvested energy by EH devices. To study these questions, we formulate a mixed-integer non-linear program (MINLP) and propose three linear approximations to the MINLP where devices are either assigned one or multiple sub-carriers. Numerical results show that EH devices will not affect network capacity if they can harvest sufficient energy from data transmissions to legacy devices. In addition, if multiple sub-carriers can be assigned to devices, our results show that the sum transmit power decreases by approximately 15% as compared with assigning a single sub-carrier to these devices.

INDEX TERMS Two-tier, resource allocation, sub-carrier, transmit power, macro base stations, femto base stations, OFDMA, heterogeneous networks.

I. INTRODUCTION

The realization of Wireless Power Transfer (WPT) has many notable implications. Future devices are likely to be batteryless. This means they will be more environmentally friendly as it reduces the number of disposed batteries [1]. WPT will be particularly critical to people with embedded medical devices as it saves them from undergoing repeated surgeries as these devices can be charged wirelessly [2]. Apart from that, RF charging is being increasingly used in Wireless Sensor Networks (WSNs); e.g., [3]. In particular, it is a key enabler of Internet of Things (IoTs) where sensing devices can be charged and programmed to sample their environment [4]. Advantageously, advances in WPT will enable the delivery of both information and energy over the wireless channel [5].

In this paper, we consider RF charging in an Orthogonal Frequency Division Multiple Access (OFDMA) based two-tier Heterogeneous Network (HetNet). Briefly, a HetNet consists of a macro cell with multiple underlay femto cells [6]. A Macro Base Station (MBS) covers a few kilometers while a Femto Base Station (FBS) serves an area with a radius of a few meters. Femto cells are deployed within a macrocell. The advantages of such FBSs include improvement in capacity and indoor coverage [7]. Another advantage is that these BSs can charge RF Energy Harvesting (EH) devices that are likely to exist at all tiers of a HetNet in the near future; e.g., they can be part of an IoTs system. Figure 1 illustrates an example. We see a MBS and two femto cells. Macro users are free to move within both coverage areas. An EH device is located in a femto cell. Data transmissions are shown by solid line arrows whereas energy transmissions are indicated by dotted line arrows. From this example, we see that a network operator has to support both types of User Equipments (UEs) whereby base stations need to satisfy respectively the energy and data rate requirement of EH nodes and data (legacy) users.
Managing interference is a key challenge in a two-tier OFDMA HetNet. There are two types of interferences: co-tier and cross-tier. Interference occurs among UEs that belong to the same tier and is called co-tier. Conversely, the interference between UEs that belong to different tiers is called cross-tier interference. One possible solution is to assign a distinct sub-carrier to each UE within a tier. Another possible solution is to reduce the sum transmit power of interfering UEs. In Figure 1, solid and dotted lines are used for data and energy transmissions respectively, which indicates both these transmissions must have distinct sub-carriers to avoid interference. On the other hand, interference benefits EH devices as it improves their RF energy harvesting rate [8].

In this work, we investigate the problem of downlink resource allocation to minimize the sum transmit power in a two-tier OFDMA based HetNet with both data UEs and EH nodes. In Figure 1, we see legacy and EH devices being served by different BSs. The problem is how BSs can support these devices that have a given data or energy requirement. In particular, unlike prior works, our aim is to allocate subcarriers, and set an an appropriate transmit power over each assigned subcarrier to support (a) so called legacy devices, which are incapable of RF energy harvesting but has a minimum data rate requirement, and (b) EH devices, which require a minimum amount of energy to operate; e.g., transmit/receive or sample the environment [4]. As it will be made clear in Section II, constraint (b) distinguishes our work from those that consider RF charging.

Indeed, the co-existence of these devices gives rise to the following novel research questions:

1) How are subcarriers assigned in a two-tier OFDMA HetNet with both data and EH UEs? This question is significant because future HetNets will have to support both data UEs and EH devices. The introduction of EH devices results in two types of charging: namely, ambient and dedicated. In the case of ambient RF charging, an EH device receives energy from data transmissions. In this respect, a MBS/FBS may intentionally increase its transmit power to be higher than the amount necessary to meet a given Signal-to-Interference-Plus-Noise Ratio (SINR) in order to deliver energy to EH devices. As for dedicated RF charging, a sub-carrier may be allocated to an EH node for charging purposes only. This, however, reduces the number of subcarriers that can be assigned for data transmissions; i.e., allocating subcarriers for charging reduces network capacity. In this respect, we are interested in determining how subcarriers are allocated among legacy and EH devices.

2) How is the transmit power of BSs controlled in a two-tier OFDMA network with EH devices? In past works, see Section II, transmit power control is critical for interference avoidance. In particular, a MBS/FBS must not cause excessive interference to data UEs when they are transmitting data or when charging EH devices. However, a high transmit power or interference benefits EH devices. Consequently, there is a trade-off between interference avoidance and energy delivery.

3) How are increasing number of femto-cells with EH nodes supported? We investigate the case where within the coverage of a MBS there are many femto-cells, each with a data and EH user. In particular, we determine whether EH devices are better served by the MBS, as opposed to their nearby FBS. The hypothesis is that as the MBS has a wider coverage and a higher transmission power, then it is an ideal energy source, especially if EH devices have a low energy requirement.

The key contributions of our work are as follows:

- To answer the above questions, we formulate a novel Mixed-Integer Non-Linear Program (MINLP) with the objective to minimize the sum transmit power of both macro and femto BSs. Its key decision variables are sub-carrier and power allocation. Its main constraints ensure legacy data UEs have a minimum data rate and EH devices receive a minimum amount of energy.
- We propose three solutions to approximate the formulated MINLP; the resulting formulations can then be solved readily using a commercial Mixed Integer Linear Program (MILP) solver. We name our solutions Single Data Carrier (SDC), Multiple Data Carrier (MDC)-1 and MDC-2. Specifically, SDC assigns only one sub-carrier to a data UE. However, in both MDC versions, data UEs can be assigned multiple sub-carriers; each supporting one or more data rates. In all our solutions, one or more dedicated sub-carriers can be assigned to a EH device for charging purpose only.
- Using SDC, MDC-1 and MDC-2, we study the aforementioned research questions. We found that sub-carriers with better channel gains are assigned to legacy and EH devices. Consequently, the required sum
transmit power decreases. In addition, if data transmissions alone are insufficient to meet the energy requirement of EH devices then they will be allocated a dedicated sub-carrier by their FBS for charging purposes only. We also study increasing number of FBSs and their impact on the sum transmit power and sub-carriers allocation in the presence of EH devices. We find that as the MBS has a high transmit power, its transmission benefits all EH nodes within its coverage area. This suggests that the MBS plays an important role in supporting EH devices.

Next, in Section II, we motivate our research questions by reviewing prior works. After that, we present our system model and problem formulation in Section III. Then three approximations to our formulated MINLP are presented in Section IV. We outline and discuss our results in Section V. We then present our conclusions in Section VI.

II. RELATED WORKS
There are a number of works that have proposed Radio Resource Management (RRM) algorithms for one or multi-tier OFDMA based HetNets. Their aim is to maximize throughput or sum-rate of legacy or data devices. Recent works that consider RF charging do not consider the research questions listed in Section I. Their primary aim is to maximize the throughput of EH devices; in some works, they do so whilst protecting the data rate of legacy users. Our aim, however, is different as we seek to answer research questions in Section I. Moreover, we jointly assign subcarriers and transmit power across macro and femto cells in order to satisfy data and energy requirements; a quick comparison of our work and previous works can be in found in Table 1 and Figure 2.

![Figure 2. Comparison of prior works.](image)

**A. JOINT TRANSMIT POWER AND SUB-CARRIER ALLOCATION**
Joint transmission power and sub-channel allocation has been widely investigated for femto data UEs, see [9]–[11]. Mili et al. [9] optimize the total sum-rate and transmission power allocation of femto data UEs. They introduce a weighing coefficient to combine two conflicting objectives: sum-rate maximization and transmit power minimization. Zhang et al. [10] consider uplink and downlink transmissions in femto cells. They divide femto UEs into two groups: delay-sensitive and delay-tolerant UEs. Delay-sensitive UEs must receive their minimum data rate. The authors introduce an interference temperature limit to protect the minimum data rate requirement of delay-sensitive UEs in case of downlink transmissions. Reference [11] aims to maximize the number of small cell UEs that can be admitted subject to the protection of data rate of all macro UEs.

**B. INTERFERENCE MANAGEMENT VIA POWER CONTROL**
Another line of research is interference management via power control, see [12]–[17]. In [12], the problem is to determine the minimum transmit power over assigned sub-carriers in order to guarantee the QoS requirement of each user. This improves system capacity due to better spatial reuse of radio resources. Similarly, Hatoum et al. [13] aim to minimize the transmit power of all femto data UEs having different bandwidth requirements. Han et al. [14] propose a power control scheme that considers the case where FBSs do not allow any unauthorized users to access their resources. They derive a minimum allowable distance between FBS and MBS for co-channel deployment. Within the allowable distance, FBS can transmit with a higher power in order to increase the capacity of femto users whilst guaranteeing the QoS requirement of data devices. Similarly in [15], Shen and Lok study the problem of downlink cross-tier and inter-cell interference in a two-tier HetNet. They aim to maximize the sum-rate of femto UEs and optimize the transmit power of FBSs using a water-filling algorithm. In [16], Sharma et al. aim to maximize the throughput of all users whilst minimizing the FBS power budget in order to mitigate cross-tier interference. Similarly, Zhu et al. [17] introduce an interference temperature limit to protect the minimum data rate requirement of delay-sensitive UEs.

**C. INTERFERENCE AVOIDANCE WITH RF CHARGING**
A number of researchers have also considered RF charging in addition to interference avoidance, see [24], [25], [27]. In particular, they consider UEs with SWIPT [5]. Briefly, an UE can decode information and harvest energy using one of the following methods: time switching or power splitting. In [27], Zhou et al. aim to maximize the weighted sum-rate for all UEs with SWIPT. They consider both Time Division Multiple Access (TDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) for information transmission. For TDMA, they jointly optimize the time switching ratio at the receiver side. For OFDMA, they optimize the power-splitting ratio at the receiver side. The work in [24] considers joint uplink and downlink resource allocation in an OFDMA-based three-tier HetNet. Mobile users harvest energy from their respective BSs. Also, some data can be offloaded to access points. They aim to maximize the sum-rate of uplink transmissions from these users subject to a minimum downlink data rate requirement. Lohani et al. [25]
propose a RRM algorithm where Small Base Stations (SBSs) are deployed specifically to charge and deliver data to EH devices with SWIPT. They aim to maximize data and energy-harvesting rate of small cell UEs equipped with SWIPT. They found a rate-energy trade-off based on the interference tolerance level of macro UEs. Therefore, SBSs set their downlink transmit power differently depending on whether UEs use time switching or power-splitting.

We study the trade-off between interference management and energy delivery subject to meeting the data rate and energy requirements of legacy and EH devices. Critically, unlike [25], we aim to study scenarios whereby both the MBS and FBSs coordinate the assignment of their transmit power and sub-carrier allocation to better support both legacy/data and EH devices located in both macro and femto cells. To the best of our knowledge, this study is new.

### III. SYSTEM MODEL

We assume a two-tier OFDMA network. A MBS serves a geographical area with \(|K|\) FBSs, where \(K\) is the set of FBSs. The macro cell is one kilometer in range while a FBS serves an area with a radius of 10 meter. The macro cell is denoted by \(m\) and we index each femtocell by \(k \in \{1, 2, \ldots, |K|\}\). Let the set \(U \) and \(W\) record the set of data users for a FBS and MBS, respectively. Let \(V\) record the set of EH devices that are located in femto cells. Data users and EH devices managed by FBS \(k\) are recorded in the set \(U_k\) and \(V_k\), respectively. Note, \(U_k \subseteq U\) and \(V_k \subseteq V\). We will denote a link between node \(u\) and \(v\) as \((u, v)\). Femtocells are configured by the close access method where only authorized users in \(U\) and devices in \(V\) can be

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<td>This paper</td>
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connected to FBS \( k \). The OFDMA system has a bandwidth of \( B \), which is divided into \( N \) sub-carriers. We will index each sub-carrier as \( n \). The channel fading of each sub-carrier is assumed to be known. Each subcarrier has a different channel gain. We assume co-channel interference between femtocells is negligible. Let \( g_{FM}^{m,w} \) and \( g_{FM}^{M} \) be the channel gain over sub-carrier \( n \) from MBS \( m \) to a macro user \( w \), femto user \( u \) and EH device \( v \), respectively. We denote by \( g_{FM}^{m,w} \) the channel gain over sub-carrier \( n \) from FBS \( k \) to respectively the following users: femto user \( n \), macro user \( w \) and EH device \( v \).

We will use the binary variable \( a_{k,u}^{(m,w,v)} \) to denote the allocation of sub-carrier \( n \) to link \((k,u)\), where \( k \) is a FBS and \( u \) is a femto user; specifically, we have \( a_{k,u}^{(m,w,v)} = 1 \) if sub-carrier \( n \) is allocated to FBS user \( u \) in femtocell \( k \) and it is zero otherwise. Similarly, the binary variable \( a_{m,w}^{(m,v)} \) indicates whether sub-carrier \( n \) has been allocated to link \((m,w)\). Here, \( m \) is the MBS, and \( w \) is a macro user. We also consider sub-carriers that are dedicated for charging. In this regard, the binary variable \( a_{k,v}^{(m,w,v)} \) is set to one if sub-carrier \( n \) is used by FBS \( k \) to charge energy harvesting device \( v \). Similarly the binary variable \( a_{m,v}^{(m,v)} \) indicates that sub-carrier \( n \) is used by MBS \( m \) to charge EH device \( v \).

Let \( p_{m,w}^{M} \) and \( p_{m}^{M} \) denote the transmit power of MBS \( m \) over sub-carrier \( n \) to the macro user \( w \) and EH device \( v \), respectively. We denote \( p_{m,w}^{F} \) and \( p_{m,v}^{F} \) to be the transmit power of FBS \( k \) over sub-carrier \( n \) to femto user \( u \) and EH device \( v \), respectively. The maximal transmit power over all sub-carriers is \( P_{max} \), whereas the maximal transmit power over each sub-carrier assigned to FBS or MBS is \( P_{max}^{F} \) and \( P_{max}^{M} \), respectively.

In a given femto-cell managed by FBS \( k \), the received SINR at user \( u \) on sub-carrier \( n \) is \( (1) \), as shown at the bottom of the next page, where \( \sigma^2 \) is the additive white Gaussian noise (AWGN) power. Note that the denominator represents the interference caused by the MBS, which include its transmission to a macro user \( w \) and EH device \( v \). Similar to \( (10) \), we do not consider intra-tier interference because of severe wall attenuation and sparse femto cells deployment. We also note that EH devices has a high energy sensitivity level; e.g., for the platforms in \([28]\), the received input power must be higher than \(-22 \text{ dBm} \) before RF harvesting begins. Consequently, transmissions from neighboring Femto Base Stations (FBSs) are unlikely to contribute to the energy harvested by EH devices, especially when FBSs reduce their transmission power to avoid interference.

From the SINR, we can the compute the capacity (bit/s/Hz) at user \( u \) as

\[
C_{k,u}^{F} = \log_2 (1 + \gamma_{k,u}^{F}) \tag{2}
\]

As for the capacity of a macro user \( w \), its received SINR over the \( n \)-th sub-carrier is given by \( (3) \), as shown at the bottom of the next page.

The capacity (bit/s/Hz) of a macro user \( w \) is then given by

\[
C_{m,w}^{M} = \log_2 (1 + \gamma_{m,w}^{M}) \tag{4}
\]

The EH device has a broadband antenna capable of harvesting across all frequencies \([29]\). The energy harvesting rate of EH node \( v \) located in femtocell \( k \) is given by

\[
E_{v}^{k} = \eta_{v} \left[ \sum_{n=1}^{[K]} \sum_{u=1}^{[U]} a_{k,u}^{(m,w,v)} p_{k,u}^{F} s_{k,u}^{F} + \sum_{w=1}^{[W]} \sum_{n=1}^{[M]} \sum_{v=1}^{[V]} a_{m,w}^{(m,v)} p_{m,w}^{M} s_{m,w}^{M} + \sum_{n=1}^{[N]} \sum_{v=1}^{[V]} a_{k,v}^{(m,w,v)} p_{k,v}^{F} s_{k,v}^{F} + \sum_{n=1}^{[N]} \sum_{v=1}^{[V]} a_{m,v}^{(m,v)} p_{m,v}^{M} s_{m,v}^{M} \right] \tag{5}
\]

where \( \eta_{v} \) is the energy conversion efficiency. An EH node \( v \) has two sources of energy. First, it is able to harvest energy from its FBS \( k \) whenever it transmits to users in \( U^{k} \) and whenever MBS \( m \) transmits to a macro user \( w \); the resulting energy harvesting rate is represented by the first two summations of \( (5) \). Second, both MBSs and FBSs may dedicate one or more sub-carriers for the purpose of charging energy harvesting devices; the last two terms compute the energy harvesting rate obtained from these sub-carriers.

Table 2 summarizes some key notations.

### A. MINLP

Our target is to minimize the sum of transmit power over each sub-carrier under co-tier interference, cross-tier interference and QoS constraints for legacy and EH devices. The decision variables are (i) \( a_{k,u}^{(m,w,v)} \), \( a_{m,w}^{(m,v)} \), \( a_{k,v}^{(m,w,v)} \) and \( a_{m,v}^{(m,v)} \) – these are binary link selection variables that determine whether a given link is assigned a sub-carrier \( n \), and (ii) \( p_{k,u}^{F} \), \( p_{k,v}^{F} \), \( p_{m,v}^{M} \) – these correspond to the transmit power over each assigned subcarrier from the FBS and MBS, respectively.

To aid exposition, we now define a few key quantities. The following four quantities represent the sum transmit power. First, from all FBSs \( K \) to femto data \( U \) over all assigned sub-carriers \( n \), we have,

\[
A = \sum_{k=1}^{[K]} \sum_{u=1}^{[U]} \sum_{n=1}^{[N]} a_{k,u}^{(m,w,v)} p_{k,u}^{F} \tag{6}
\]

The sum of transmit power from all FBSs \( K \) to EH devices in \( V \) over all assigned sub-carriers \( n \) is,

\[
B = \sum_{k=1}^{[K]} \sum_{v=1}^{[V]} \sum_{n=1}^{[N]} a_{k,v}^{(m,w,v)} p_{k,v}^{F} \tag{7}
\]

The sum of transmit power from MBS \( m \) to users \( w \) in \( W \) over all assigned sub-carriers \( n \) is,

\[
C = \sum_{w=1}^{[W]} \sum_{n=1}^{[N]} a_{m,w}^{(m,v)} p_{m,w}^{M} \tag{8}
\]
Lastly, the sum of transmit powers \( \gamma_{(m,v),n}^{MF} \) from MBS \( m \) to EH devices in \( V \) over all assigned sub-carriers \( n \) is,

\[
\gamma = \sum_{n=1}^{V} a_{(m,v),n}^{MF} \text{P}(m,v,n)
\]

For convenience, we also define two sets containing decision variables: (i) \( \zeta_1 = \{ a_{(k,u),n}, a_{(k,v),n}, a_{(m,w),n}, a_{(m,v),n} \} \), and (ii) \( \zeta_2 = \{ p_{(k,u),n}^F, p_{(k,v),n}^F, p_{(m,w),n}^M, p_{(m,v),n}^M \} \).

We are now ready to define our mathematical model. Formally,

\[
\begin{align*}
\text{minimize} & \quad A + B + C + D \\
\text{s.t.} & \quad C1: \sum_{n=1}^{V} a_{(k,u),n}^{MF} \leq \text{P}_{\text{max}}^F, \forall u \in U^k, \forall k \in K, \\
& \quad C2: \sum_{n=1}^{V} a_{(m,w),n}^{MF} \leq \text{P}_{\text{max}}, \forall w \in W, \\
& \quad C3: \sum_{n=1}^{V} a_{(k,u),n}^{C^F} \geq \text{R}_{\text{min}}, \forall u \in U^k, \forall k \in K, \\
& \quad C4: \sum_{n=1}^{V} a_{(m,w),n}^{C^M} \geq \text{R}_{\text{min}}, \forall w \in W, \\
& \quad C5: a_{(m,w),n} \leq 1, \forall m \in M, a_{(m,v),n} \leq 1, \forall v \in V^k, \forall k \in K, \\
& \quad C6: \sum_{n=1}^{V} a_{(m,w),n} + \sum_{n=1}^{V} a_{(m,v),n} \leq 1, \forall n \in N, \forall k \in K, \\
& \quad C7: p_{(k,u),n}^F \geq 0, \forall u \in U^k, \forall k \in K, \\
& \quad C8: p_{(m,w),n}^M \geq 0, \forall w \in W, \\
& \quad C9: \sum_{k=1}^{K} E_{k}^v \geq E_{\text{min}}, \forall v \in V^k
\end{align*}
\]

where constraint C1 and C2 limit the total transmission power used by FBS and MBS over all assigned sub-carriers to no more than \( \text{P}_{\text{max}}^F \) and \( \text{P}_{\text{max}}^M \), respectively. Constraints C3 and C4 ensure that each femto user \( u \) and macro user \( w \) receive a minimum data rate of \( \text{R}_{\text{min}} \). Constraint C5 ensures that sub-carriers for data and EH devices within a femto cell \( k \) must be different to avoid co-channel interference. Similarly, constraint C6 ensures that sub-carriers for data and EH devices for MBS must be different. Constraints C7 and C8 ensure that the transmit power over sub-carrier \( n \) is non-negative. Constraint C9 ensures that the total harvesting
energy rate of device $v$ exceeds its required threshold. Table 3 summarizes our key constraints.

**TABLE 3. A brief description of constraints.**

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Maximum transmit power of a PBS</td>
</tr>
<tr>
<td>C2</td>
<td>Maximum transmit power of the MBS</td>
</tr>
<tr>
<td>C3</td>
<td>Data rate requirement of a femto user $u$.</td>
</tr>
<tr>
<td>C4</td>
<td>Data rate requirement of a macro user $w$.</td>
</tr>
<tr>
<td>C5</td>
<td>C-to-T interference avoidance between legacy and EH devices</td>
</tr>
<tr>
<td>C6</td>
<td>M-to-M interference avoidance between MBS and femto data UE’s</td>
</tr>
<tr>
<td>C7</td>
<td>Transmission power of PBSs must be non-negative.</td>
</tr>
<tr>
<td>C8</td>
<td>Transmission power of the MBS must be non-negative.</td>
</tr>
<tr>
<td>C9</td>
<td>Energy harvesting rate requirement of an EH device.</td>
</tr>
</tbody>
</table>

The main challenges to solving our MINLP are that constraint C3 and C4 are non-linear and its combinatoric nature due to the binary decision variables in $\zeta$. In fact, MINLPs are NP-hard in general [30]. In the next section, we outline three alternative linear approximations to constraint C3 and C4. They thus allow us to approximate our MINLP as a Mixed Integer Linear Program (MILP). Although the resulting MILP remains difficult to solve, we were able to solve sufficiently large problem instances in order to shed some light on the research questions posed in Section I.

We conclude this section by analyzing the number of constraints and decision variables for our MINLP; both of which have an impact on the computation time.

**Proposition 1:** Our MINLP has $3|U|^k|K| + 3|W| + |N||(K) + 1| + |V|^k|K|$ constraints and $2|K||U|^k||N| + 2|W||N| + 2|K||V|^k||N| + 2|V|^k||N|$ decision variables.

**Proof:** In terms of constraints, namely C1 to C9, we have respectively the following number of constraints:

(i) $|U|^k|K|$, (ii) $|W|$, (iii) $|U|^k|K|$, (iv) $|W|$, (v) $|N||K|$, (vi) $|N|$, (vii) $|U|^k|K|$, (viii) $|W|$, (ix) $|V|^k$. In total, we thus have $3|U|^k|K| + 3|W| + |N||(K) + 1| + |V|^k$. As for the number of decision variables, we have $|K||U|^k||N|$ of type $a_{(k,u),n}$, $|K||V|^k||N|$ of type $a_{(k,v),n}$, $|W||N|$ of type $a_{(w,v),n}$ and $|V|^k||N|$ of type $a_{(w,v),n}$. There are also decision variables related to transmission power. In particular, we have $|K||U|^k||N|$ of type $p^F_{(k,u),n}$, $|K||V|^k||N|$ of type $p^M_{(k,v),n}$, $|W||N|$ of type $p^M_{(w,v),n}$ and $|V|^k||N|$ of type $p^M_{(w,v),n}$. Adding these decision variables together, we have the desired result.

**IV. LINEAR APPROXIMATIONS**

In the first approximation, for a given data user, we remove the requirement that the sum rate of all its assigned sub-carriers must exceed $R_{min}$. Instead, we only require one assigned sub-carrier to have the capacity $R_{min}$. This forces a MILP solver such as Gurobi or CPLEX to pick the best sub-carrier that can afford $R_{min}$ to a data user that yield the minimal transmission power. In the second approximation, there are multiple data rates per-subcarrier. For each data user, we determine the data rate that can be attained for each subcarrier. Each user is then assigned one or more subcarriers as long as the sum total of the corresponding data rate on these subcarriers exceed $R_{min}$.

In our last approximation, multiple subcarriers can also be assigned to a user. However, each subcarrier only has one data rate and a subcarrier is assigned to a user only if its SINR exceeds the required threshold for the said data rate.

**A. SINGLE DATA CARRIER (SDC) SOLUTION**

We proceed to replace constraints C3 and C4 as follows. First, we determine the transmission power required to achieve $R_{min}$ over a given sub-carrier. From (2) for a femto user $u$ over a sub-carrier $n$, we have,

$$\log_2(1 + \gamma^F_{(k,u),n}) \geq R_{min}$$

Re-arranging, we have

$$\gamma^F_{(k,u),n} \geq 2^{R_{min} - 1}$$

Using the definition of $\gamma^F_{(k,u),n}$, we get (7). Rearranging, we obtain (8). Expression (8) gives the required transmit power required to overcome both noise and interference in order to attain $R_{min}$ over sub-carrier $n$. Observe that for each user, and each sub-carrier $n$, we have constraint (8).

In SDC, we require that each data or legacy UE is assigned one sub-carrier that yields $R_{min}$. This means for subcarriers that are not assigned to user $u$ by femto BS $k$, then (8) is non-binding. To model this fact, we include the term $-(1 - a_{(k,u),n})\mathcal{M}$ into (8), where $\mathcal{M}$ is a suitable large number; e.g., $\mathcal{M} = p^F_{\max}|U|$. We thus have expression (9). Notice that when sub-carrier $n$ is not assigned to user $u$, i.e., $a_{(k,u),n} = 0$, then the corresponding constraint (8) is not binding or disabled.

The next constraint ensures each data user is assigned only one sub-carrier. Formally, we have,

$$\sum_{k=1}^{|K|} a_{(k,u),n} = 1, \quad \forall u \in U^k, \quad \forall k \in K.$$  \hspace{1cm} (15)

and

$$\sum_{k=1}^{|K|} a_{(m,w),n} = 1, \quad \forall w \in W.$$  \hspace{1cm} (16)

Similarly, for a macro user $w$ over sub-carrier $n$, expression (10) gives the transmit power required to overcome both noise and interference in order to attain $R_{min}$ over sub-carrier $n$. We also include the term $-(1 - a_{(m,w),n})\mathcal{M}$ into (10) to enable or disable a constraint.

We now comment on the number of constraints and decision variables. Instead of $|U|^k|K|$ C3 constraints, we have $|U|^k|K||N|$ constraints plus $|U|^k|K|$ constraints of type (15). For macro users, C4 is now replaced with $|W||N|$ constraints plus $|W|$ constraints of type (16).

**B. MULTIPLE DATA CARRIER (MDC)-1**

In this approach, the key idea is that for a given subcarrier, we create multiple intervals corresponding to different SINR
multiple subcarriers such that the sum data rate of these said subcarrier. Lastly, unlike SDC, a user can be assigned multiple subcarriers such that the sum data rate of these subcarriers exceeds $R_{\min}$. 

Assume there are $|J|$ given data rates for each sub-carrier. We denote them as $R^1, R^2, \ldots, R^{|J|}$ and their corresponding SINR threshold is $\Psi^1, \Psi^2, \ldots, \Psi^{|J|}$, respectively. For each SINR threshold, where $j \in \{1, 2, \ldots, |J|\}$, we have inequality (12). Rearranging, we obtain,

$$p_{(k,u),n}^F, nS_{(k,u),n}^F - \Psi^j \left[ \sum_{w=1}^{\left|W\right|} a_{(m,w),n}p_{(m,w),n}^M, nS_{(m,w),n}^M + \sum_{v=1}^{\left|V\right|} a_{(m,v),n}p_{(m,v),n}^M, nS_{(m,v),n}^M + \sigma^2 \right] \geq 0 \quad (17)$$

To ensure only one SINR threshold or constraint (17) is active, we include the term $-(\Phi_{(k,u),n}^j - 1)\mathcal{M}$, where $\mathcal{M}$ is a suitable large number. Let $\Phi_{(k,u),n}^1, \Phi_{(k,u),n}^2, \ldots, \Phi_{(k,u),n}^{|J|}$ be binary decision variables corresponding to said data rates or thresholds. We have for each data rate or threshold $j \in J$,

$$p_{(k,u),n}^F, nS_{(k,u),n}^F - \Psi^j \left[ \sum_{w=1}^{\left|W\right|} a_{(m,w),n}p_{(m,w),n}^M, nS_{(m,w),n}^M + \sum_{v=1}^{\left|V\right|} a_{(m,v),n}p_{(m,v),n}^M, nS_{(m,v),n}^M + \sigma^2 \right] \geq (\Phi_{(k,u),n}^j - 1)\mathcal{M} \quad (18)$$

Notice that if $\Phi_{(k,u),n}^j = 1$ in (18), then the data rate corresponding to SINR threshold $j$ is used for subcarrier $n$.

For each subcarrier $n$ that is assigned to a link $(k, u)$, at most one data rate can be chosen. Formally, we have,

$$\sum_{j=1}^{\left|J\right|} \Phi_{(k,u),n}^j \leq 1 \quad (19)$$

We are now ready to rewrite constraint C3. Specifically, for a given data user $u$, the total data rate of subcarriers assigned to it must exceed $R_{\min}$. Formally, for each user $u \in U^k$, where $k \in K$, we have,

$$\sum_{n=1}^{\left|N\right|} \sum_{j=1}^{\left|J\right|} \Phi_{(k,u),n}^j \geq R_{\min} \quad (20)$$

For a macro user $w$, we also have a similar expression to (18), (19), and (20). Specifically, we replace constraint C4 with,

$$p_{(m,w),n}^M, nS_{(m,w),n}^M - \Psi^j \left[ \sum_{k=1}^{\left|K\right|} \sum_{v=1}^{\left|V\right|} a_{(k,v),n}p_{(k,v),n}^F, nS_{(k,w),n}^F + \sum_{k=1}^{\left|K\right|} \sum_{v=1}^{\left|V\right|} a_{(k,v),n}p_{(k,v),n}^F, nS_{(k,w),n}^F + \sigma^2 \right] \geq (\Phi_{(m,w),n}^j - 1)\mathcal{M} \quad (21)$$

And for each user $u \in U^k$, we have,

$$\sum_{n=1}^{\left|N\right|} \Phi_{(m,w),n}^j \leq 1 \quad (22)$$
\[
\sum_{n=1}^{\left| N \right|} \sum_{j=1}^{\left| J \right|} \Phi_{(m,w),n}^j R_n^j \geq R_{\min} \tag{23}
\]

To conclude this section, we analyze the number of new constraints and decision variables. In terms of femto users, as each subcarrier now has \(J\) data rates, we have \(U^k ||K||N||J\) constraints of type (18). Also we have \(U^k ||K||N\) constraints of type (19). Lastly, there are \(U^k ||K\) constraints (20). For macro users, the corresponding number of constraints are respectively \(|W||N||J|, |W||N\) and \(|W|\). In terms of \(\Phi_{(k,u),n}^j\), we have \(|K||U^k||J||N\) decision variables, and for \(\Phi_{(m,w),n}^j\) there are \(|J||W||N\) decision variables.

C. MULTIPLE DATA CARRIER (MDC)-2

A key problem with MDC-1 is that for each subcarrier, there are \(|J|\) constraints of type (18) and decision variables \(\Phi_{(k,u),n}^j\). In MDC-2, we used a fixed or one data rate for all subcarriers. Let this data rate be \(R^0\); its SINR threshold is denoted as \(\Psi^0\). Also, for a given femto BS \(k\) and user \(u\), we have the binary variable \(\Phi_{(k,u),n}^j\). Then, we replace constraint C3 with two new inequalities. First, for each user \(u\) in \(U^k\) and each subcarrier \(n\), we have

\[
\gamma_{(k,u),n}^F \geq \Psi^0 - (1 - \Phi_{(k,u),n}) M
\]

In (24), we have \(\Phi_{(k,u),n}^j = 1\) when the condition \(\gamma_{(k,u),n}^F \geq \Psi^0\) is true. Otherwise, the inequality is non-binding or inactive. Secondly, to ensure that the total data rate of all subcarriers assigned to user \(u \in U^k\) in femto BS-k exceeds \(R_{\min}\), we have,

\[
\sum_{n=1}^{\left| N \right|} \Phi_{(k,u),n}^j R_n^j \geq R_{\min} \tag{25}
\]

Similarly, for macro users, we replace constraint C4 with,

\[
\gamma_{(m,w),n}^M \geq \Psi^0 - (1 - \Phi_{(m,w),n}) M \tag{26}
\]

\[
\sum_{n=1}^{\left| N \right|} \Phi_{(m,w),n}^j R_n^j \geq R_{\min} \tag{27}
\]

Here, \(\Phi_{(m,w),n}^j\) is a binary decision variable that is set to one if \(\gamma_{(m,w),n}^M \geq \Psi^0\) is true. Also note that constraint (26) exists for each user \(w \in W\) and each subcarrier \(n \in N\) and inequality (27) exists for each macro user \(w \in W\).

As a concluding remark, instead of \(|U^k||K|\) C3 constraints, we now have \(|U^k||K||N||J|\) constraints of type (24) plus \(|U^k||K|\) constraints of type (25). Similarly, instead of \(|W|\) C4 constraints, we now have \(|N||W|\) constraints of type (26) plus \(|W|\) constraints of type (27). Moreover, we now have additional \(|K||U^k||J||N|\) decision variables of type \(\Phi_{(k,u),n}^j\), and \(|J||W||N|\) of type \(\Phi_{(m,w),n}^j\).

V. EVALUATION

In our experiments, there is an MBS and initially, only one FBS; multiple FBSs are considered in Section V-E. We place the MBS at the origin (0, 0) of a two dimensional plane. An FBS is placed at coordinate (100,100); however, in Section V-E, we place one or more FBSs uniformly at a radius of 100 meter around the MBS. The MBS and FBS have a coverage area of 200 and 20 meters, respectively. Macro and femto data UEs and EH devices are then placed uniformly within the coverage area of the MBS or FBS. Their position is changed after each experiment. The maximum transmit power of the MBS and the FBS is 24W and 12W, respectively. These values are chosen to distinguish the transmit power between MBS and FBS. The bandwidth of each sub-carrier is 1 MHz. Unless stated otherwise, there are 20 sub-carriers. The thermal noise power is assumed to be \(-90\ dBm/Hz\). The received power is calculated as per the Friis path loss formula using the Euclidean distance between a FBS or MBS and a user. We use a path loss exponent of 2.7 and 2.2, which corresponds to fading within a suburban area, and line-of-sight in indoor environments, respectively [31]. The energy harvesting efficiency \(\eta_v\) is set to 50% [28]. For MDC-1, we set four data rates per sub-carrier. These data rates are 1, 1.58, 2 and 2.32 bps/Hz with a SNR threshold of 1, 2, 3 and 4, respectively. For MDC-2, all subcarriers have the same data rate of \(R^0 = 1\) bps/Hz. We use the commercial MILP solver from Gurobi\(^1\) for all our simulations. All results are an average of ten simulation runs. In the sequel, we will use \(P_{\text{min}}\) to denote the total transmit power; i.e., the objective value of our MILP/MINLP. Table 4 presents our simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K)</td>
<td>1</td>
</tr>
<tr>
<td>Coverage radius of a FBS</td>
<td>20 meter</td>
</tr>
<tr>
<td>Coverage radius of a MBS</td>
<td>200 meter</td>
</tr>
<tr>
<td>(U^k)</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>(N)</td>
<td>1</td>
</tr>
<tr>
<td>(W)</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>(B)</td>
<td>1 MHz</td>
</tr>
<tr>
<td>(P_{\text{max}})</td>
<td>24 W</td>
</tr>
<tr>
<td>(P_{\text{max}})</td>
<td>12 W</td>
</tr>
<tr>
<td>(\eta_v)</td>
<td>50%</td>
</tr>
<tr>
<td>For MDC-1, (\Psi_{(k,u),n}^j), (\Psi_{(m,w),n}^j)</td>
<td>1, 2, 3 and 4 dB</td>
</tr>
<tr>
<td>(R^j, j \in {1, 2, 3, 4})</td>
<td>1, 1.58, 2 and 2.32 bps/Hz</td>
</tr>
</tbody>
</table>

A. IMPACT OF \(R_{\min}\)

We first analyze the impact of energy harvesting rate when we increase \(R_{\min}\). We also analyze the sum transmit power. There is one EH device, and we place either two, four or six data UEs in the femto cell.

Figure 3 shows the minimum sum transmit power required to satisfy a given \(R_{\min}\) value using SDC. We consider the case when the EH device needs an harvesting rate of \(E_{\text{min}} = 1\) mW. As \(R_{\min}\) increases or when data UEs require better SINR, the sum transmit power increases. For example, for two data

\(^1\)http://www.gurobi.com
users, the sum transmit power increases from 0.094 to 6.92 W when $R_{\min}$ increases from 0.5 to 4 bps/Hz. We note that the sum transmit power increases in proportion to $R_{\min}$ and the number of data UEs. For example, for four data users, the sum transmit power increases from 0.1423 W to 18.786 W; this is approximately three times the value when there are only two data users. Similarly, for six data users, the sum transmit power increases from 0.2554 W to 21.245 W for the same value of $R_{\min}$. As expected, the increase in sum transmit power is due to higher $R_{\min}$ values or the number of data UEs.

Figure 4 shows the same trend when using MDC-1. The transmit power obtained by MDC-1 decreases from approximately 60% as compared to SDC when $R_{\min}$ increases from 1.5 to 4 bps/Hz. This is because MDC-1 can assign more than one sub-carrier per user, whereas SDC can only assign one sub-carrier per user. In the case of MDC-1, multiple sub-carriers can be used to satisfy the required data rate. As an example, consider $R_{\min} = 2$ bps/Hz and assume the channel gain over each channel is 0.0007. When using SDC, the SNR value that yields $R_{\min}$ is $\Psi = 2R_{\min} - 1 = 3$ dB. The transmit power required for a femto user $u$ over sub-carrier $n$ to achieve the required SNR of $\Psi$ is given by $p_F^{F(u,n)}g_{F(u,n)}^{F(u,n)}/\sigma^2 = \Psi$, where $g_{F(u,n)}^{F(u,n)}$ is the channel gain and $\sigma^2$ is the thermal noise power. As SDC allocates one sub-carrier to the user, the transmit power over the allocated sub-carrier in order to achieve the required $R_{\min}$ is calculated as 4.28 mW. On the other hand, MDC-1 can assign more than one sub-carrier per user to achieve the required $R_{\min}$; advantageously, it requires a lower transmit power. Consider two data rates per sub-carrier where $R^1 = 1$ and $R^2 = 1.58$ bps/Hz with a respective SNR threshold of 1 and 2 dB. Assume the channel gain over each channel is 0.0007. Therefore, the transmit power required to achieve $R^1$ and $R^2$ is calculated as 1.42 mW and 2.85 mW, respectively. To achieve $R_{\min}$, we have to assign at least two sub-carriers with similar or different data rates. The minimum transmit power can be achieved by assigning two similar sub-carriers with data rate $R^1 = 1$ bps/Hz. As a result, the sum transmit power allocated over two sub-carriers with data rate $R^1 = 1$ bps/Hz to achieve $R_{\min}$ is 2.84 mW. Therefore, the transmit power obtained by MDC-1 decreases by approximately 33% as compared to SDC. Another reason MDC-1 has a lower transmit power is because the link capacity grows linearly for lower values of SNRs and logarithmically for higher values of SNRs. This means at lower SNR values, a small increase in transmit power results in a large increase in capacity. MDC-1 takes advantage of this property whereby it assigns data carriers with a low rate in order to achieve $R_{\min}$. As the SNR threshold for these data carriers is low, a BS uses a lower transmit power in order to achieve the required $R_{\min}$.

Figure 5 shows a similar trend when using MDC-2. We set the data rate requirement of each data UE to 1 bps/Hz.

B. IMPACT OF $E_{\min}$

In this experiment we analyze the impact of $E_{\min}$ on the sum transmit power when using SDC, MDC-1 and MDC-2. The minimum transmit power can be achieved by assigning two similar sub-carriers with data rate $R^1 = 1$ bps/Hz. As a result, the sum transmit power allocated over two sub-carriers with data rate $R^1 = 1$ bps/Hz to achieve $R_{\min}$ is 2.84 mW. Therefore, the transmit power obtained by MDC-1 decreases by approximately 33% as compared to SDC. Another reason MDC-1 has a lower transmit power is because the link capacity grows linearly for lower values of SNRs and logarithmically for higher values of SNRs. This means at lower SNR values, a small increase in transmit power results in a large increase in capacity. MDC-1 takes advantage of this property whereby it assigns data carriers with a low rate in order to achieve $R_{\min}$. As the SNR threshold for these data carriers is low, a BS uses a lower transmit power in order to achieve the required $R_{\min}$.

Figure 5 shows a similar trend when using MDC-2.
satisfy a given $E_{\text{min}}$ value using SDC, MDC-1 and MDC-2 for two data UEs. We see that the transmit power for SDC increases from 0.157 W to 2.8218 W when $E_{\text{min}}$ increases from 1 to 8 mW. This is because the FBS assigns one or more dedicated sub-carriers to the EH device, especially since the FBS is near the EH device. Moreover, the transmit power over assigned sub-carriers increases as $E_{\text{min}}$ increases. Similarly for MDC-1 and MDC-2, the transmit power increases from 0.2824 W to 1.425 W, and 0.432 W to 2.953 W respectively, when $E_{\text{min}}$ increases from 1 mW to 8 mW. Figure 7 shows the minimum sum transmit power required for four and six data UEs in order to satisfy a given $E_{\text{min}}$ value using SDC, MDC-1 and MDC-2. For four data UEs, the transmit power for SDC increases from 0.327 to 1.414 W when $E_{\text{min}}$ increases from 1 mW to 4 mW. This is because the EH device does not require a dedicated sub-carrier for charging. In other words, the EH device has sufficient energy harvesting rate. However, when the EH device requires an energy harvesting rate of at least 4 mW, one or more sub-carriers are assigned to the EH device. This increases the total transmit power, especially with increasing $E_{\text{min}}$. Furthermore, for six data UEs, the transmit power for SDC, increases from 0.856 to 2.464 W when $E_{\text{min}}$ increases from 1 mW to 8 mW. This is because additional number of data transmissions means the EH device is able to receive $E_{\text{min}}$ mW worth of energy without requiring dedicated sub-carriers that are assigned for charging. Figure 7 shows a similar trend for MDC-1 and MDC-2 for four and six data users, respectively.

C. IMPACT OF DATA UEs

We now analyze how the number of data UEs impacts the total transmit power and EH devices. The data rate requirement of each data UE is fixed at 1 bps/Hz. Referring to Figure 8, we see that when $E_{\text{min}}$ is set to 1 mW, the transmit power increases from 0.157 W to 1.719 W when the number of data UEs increases from 2 to 10. This is because for higher values of $E_{\text{min}}$, one or more dedicated sub-carriers are assigned to meet the $E_{\text{min}}$ requirement of EH devices. However, when the number of data UEs increases, data transmissions alone are sufficient to yield an energy harvesting rate of $E_{\text{min}}$. Similarly, when $E_{\text{min}}$ is set to 5 mW, the transmit power increases from 2.0341 W to 2.985 W when the number of data UEs increases from 2 to 10. We see that the slope of the curves decreases from 0.19 to 0.11 when $E_{\text{min}}$ increases from 1 mW to 5 mW. This is because for a few data UEs, data transmissions alone are insufficient to meet the high $E_{\text{min}}$ of the EH device. Therefore, one or more sub-carriers are assigned for dedicated charging. However, with increasing number of data users, dedicated charging is no longer required as data transmissions become sufficient to satisfy a high energy harvesting rate.

D. IMPACT OF DATA CARRIERS

In this experiment, we consider one or multiple data carriers and how they impact the total transmit power. We fix $E_{\text{min}}$ to 1 mW. In Figure 9, we observe that the transmit power for SDC increases between 0.157 to 17.44 W when $R_{\text{min}}$ increases.
from 1 to 5 bps/Hz. However, when we use SDC, the system model becomes infeasible when $R_{\text{min}}$ exceeds 5 bps/Hz. This is because despite transmitting at the maximum power, both MBS and FBS are unable to satisfy the $R_{\text{min}}$ requirement of data UEs, and SDC can achieve $R_{\text{min}}$ of only 5 bps/Hz. On the other hand, both MDC-1 and MDC-2 achieve data rates higher than 5 bps/Hz by assigning multiple sub-carriers.

As an example, from Figure 9, we see that MDC-1 is able to achieve a data rate of 10 bps/Hz. Another observation is that at $R_{\text{min}} = 10$ bps/Hz, the transmit power decreases approximately by 15% from 6.27 to 5.33 W when the number of data carriers per sub-carrier increases from two to four. This is because the maximum data rate per sub-carrier increases from 1.58 and 2.32 bps/Hz for two and four data carriers, respectively. Therefore, for higher $R_{\text{min}}$ values, the number of assigned sub-carriers decreases when we increase the available data rates per sub-carrier. Referring to Figure 10, the assigned number of sub-carriers decreases from 9 to 6 when the number of data carriers increases from two to four. This is because the selection of sub-carriers with a higher data rate decreases the sum transmit power. In particular, the solver chooses those sub-carriers with better data rates, which help reduce the sum transmit power.

Figure 11 shows the selected data rate for each sub-carrier. For each $R_{\text{min}}$, the first bar shows the assigned number of sub-carriers for MDC-1 with two data rates, whereas the second bar shows the assigned number of sub-carriers for MDC-1 with four data rates. We see that for values of $R_{\text{min}}$ between 3 to 10 bps/Hz, the solver chooses those sub-carriers with better data rates. For example, when we have $R_{\text{min}} = 10$ bps/Hz, MDC-1 with two data rates assigns four and nine sub-carriers with a data rate of $R_1$ and $R_2$, respectively. However, when MDC-1 has four data rates, it assigns one, two, and one sub-carrier with a data rate of $R_1$, $R_2$, $R_3$ and $R_4$, respectively. Therefore, the selection of sub-carriers with a higher data rate reduces the number of sub-carriers and the resulting sum transmit power.

E. INCREASING FEMTO CELLS

We now increase the number of femto cells that underlay a macro cell; from one to eight. Each FBS is placed at a radius of 100 m from MBS. Each femto cell consists of a data UE and an EH device. We set $R_{\text{min}} = 2$ bps and $E_{\text{min}} = 1$ mJ. Figure 12 illustrates the sum transmit power contributed by each BS versus $|K|$ femto cells. Recall that $p(k,u,n)$ and $p(k,v,n)$ correspond to the transmit power from FBS to femto data UEs and EH devices, respectively, whereas $p(m,w,n)$ and $p(m,v,n)$ correspond to the transmit power from the MBS to macro data UEs and EH devices, respectively. For each number of femto cells, the three bars show the sum transmit power for SDC, MDC-1 with two data rates and MDC-2, respectively. As expected, the sum transmit power increases linearly as we add more femto cells. This is reasonable as there are more FBSs, each with legacy UEs and an EH device. As $E_{\text{min}}$ is low, EH devices are able to harvest sufficient energy from data transmissions alone. Critically, as $E_{\text{min}}$ is low, the MBS, due to its wider coverage area, plays an important role in charging these EH devices. We see that FBSs allocate the minimum transmit power necessary to support its associated data UE. Furthermore, FBSs allocate the minimum radio resources
to EH devices. However, for each solution, a high transmit power is allocated over the subcarrier(s) assigned to a macro user or one of the EH devices. This high power transmission from the MBS benefits all EH devices in the macro cell.

Figure 13 illustrates the transmit power contributed by each BS versus $|K|$ femto cells for $E_{\text{min}} = 5$ mW. The sum transmit power increases from 1.6 to 13 mW, where the number of femto cells increases from one to eight. As $E_{\text{min}}$ is high, the FBS plays an important role in supporting EH devices due to its smaller coverage area and path loss. We see that for high values of $E_{\text{min}} = 5$ mW, the MBS allocates the minimum transmit power necessary to support its associated data UE. Furthermore, MBS do not allocate radio resources to EH devices. However, for each solution, a high transmit power is allocated over the subcarrier(s) assigned to a femto user or the EH device.

VI. CONCLUSION

This paper has investigated a number of issues that arise when future HetNets have both legacy and EH devices. In particular, it studies a joint sub-carrier and power allocation problem in an OFDMA-based two tier HetNet. We find that the sum transmit power increases in proportion to the data rate requirement of legacy devices and the number of EH users. Moreover, if the said data rate requirement is high, the transmit power allocated for data transmissions alone is sufficient for EH devices to meet their energy harvesting rate requirement. Consequently, EH devices will not affect network capacity. However, if the total energy harvesting rate from data transmissions is insufficient, then a dedicated sub-carrier is assigned for the sole purpose of charging EH devices. In addition, the MBS plays a vital role in supporting EH devices due to its high transmit power and coverage area. Consequently, data transmissions from the MBS benefit all EH devices. As a future work, we plan to study the same set of research questions in ultra-dense networks, where inter-cell interference is non-negligible.

REFERENCES


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