Dual-Connectivity Enabled Traffic Offloading via Small Cells Powered by Energy-Harvesting

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Abstract—Dual-connectivity (DC), an emerging paradigm in the recent 3GPP specification, is envisioned as a promising solution to enhance mobile users’ (MUs’) traffic offloading by aggregating radio resources at both macro and small cells. In this paper, we investigate the energy-efficient DC-enabled traffic offloading through small cells which are powered by the on-grid power supply and harvesting renewable energy from nature. In spite of reducing the on-grid power consumption, powering traffic offloading by energy harvesting (EH) leads to the offloading outage due to the intermittency in EH-power-supply, which degrades the offloading throughput. Therefore, to reap both the advantages of DC and the EH-supply, we propose a joint traffic scheduling and power allocation scheme that aims at minimizing the total on-grid power consumption, while accounting for the offloading outage and guaranteeing the MU’s quality of service (QoS) requirement. In spite of the non-convexity nature of the joint optimization of traffic scheduling and power allocation, we propose an algorithm to efficiently compute the optimal offloading solution. Numerical results are provided to validate our proposed algorithm and the performance gain of the proposed DC-enabled traffic offloading scheme.

I. INTRODUCTION

Traffic offloading has been considered as an efficient approach to accommodate the tremendous traffic growth in nowadays cellular networks [1]. To enhance mobile users’ (MUs’) traffic offloading, the recent 3GPP specification has proposed the small-cell dual-connectivity (DC) that enables MUs to communicate with macrocell and simultaneously offload data through small cell. By aggregating radio resources at both macro and small cells and flexibly scheduling traffic towards macro and small cells, the DC-enabled traffic offloading facilitates the improvement of MUs’ throughput and efficiency in resource utilization [2], [3]. In particular, due to activating two radio interfaces simultaneously, the DC requires a proper resource-splitting between two radio interfaces [4]–[6]. In [4], Liu et al. proposed a scheme to split the MU’s power capacity for two radio interfaces to facilitate the MU’s uplink data offloading through DC. In [5], Wu et al. proposed a secrecy-oriented traffic scheduling and resource allocation scheme for the DC-enabled traffic offloading through unlicensed bands. A DC-enabled traffic offloading based on the emerging non-orthogonal multiple access (NOMA) was proposed in [6].

However, the densely deployed small cells for traffic offloading have consumed excessive power consumption, and there are many research works investigating energy efficiency of small cells [7]–[9]. Thanks to advanced energy technologies, it becomes viable to exploit renewable energy to power small cells, e.g., by actively harvesting solar/wind energy from nature [10]–[13]. Despite the advantage of reducing the on-grid power consumption, powering small cells by energy-harvesting (EH) suffers from volatility in EH-supply, which degrades users’ quality of service (QoS) experience. Therefore, it becomes a critical issue on how to effectively exploit EH to power macro/small cells and mobile devices while providing satisfactory QoS [14]–[21]. For instance, in [14], Zhang et al. proposed a joint optimization of user association, on-off control of base stations, and power control to minimize the overall power consumption of all cells. In [15], Gong et al. proposed a joint optimization of the base station on-off control, subcarrier allocation, and renewable energy allocation to satisfy the users’ QoS requirement. However, the aforementioned critical issue becomes even more complicated in the context of DC-enabled offloading, since the DC-enabled offloading requires macro and small cells to cooperatively allocate radio resources. For instance, due to the uncertain EH-supply of small cell, aggressively offloading too much traffic through small cells will result in severe offloading outage (i.e., when the EH-supply fails to meet the offloading need). Consequently, the macrocell needs to afford most of the MU’s traffic, which adversely consumes a large on-grid power consumption. In other words, the traffic scheduling between macro and small cells and the associated resource allocations enabled by the DC-feature necessitate a careful management, especially when we take into account the intermittent EH-supply at small cells.

In this paper, we investigate the DC-enabled traffic offloading through small cell which is powered by EH. We propose a joint traffic scheduling and power allocation for the DC-enabled traffic offloading that accounts for small cell’s intermittent EH-supply and guarantees user’s traffic demand (under the offloading-outage). Our objective is to minimize the total on-grid power consumption of macrocell and small cell. Despite the non-convexity of the joint resource allocation problem, we propose an efficient algorithm to compute the optimal offloading solution. Numerical results are provided to validate our proposed algorithm and the performance gain of

978-1-5090-5019-2/17/$31.00 ©2017 IEEE
the proposed offloading scheme.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model and Problem Formulation

In this paper, we focus on the DC-enabled downlink traffic offloading as shown in Figure 1. The mBS is solely powered by the on-grid power-supply, and the small-cell access point (sAP) is powered by both the on-grid supply and EH-supply. As a first step to investigate the DC-enabled traffic offloading powered by EH, we focus on investigating one DC-pair that includes one mBS and one sAP providing traffic to a targeted MU (our proposed model takes into account that the sAP may offload traffic for several MUs simultaneously)\(^1\). Specifically, with DC, the mBS provides part of MU’s traffic demand, and the sAP offloads the remaining part. We use \(p_B\) to denote the mBS’s transmit-power, and the downlink rate \(x_B\) from the mBS can be given by

\[
x_B = W_B \log_2 \left( 1 + \frac{p_B g_B}{n_B} \right),
\]

where \(W_B\) denotes the channel bandwidth from the mBS to the MU, and \(g_B\) denotes the channel power gain from the mBS to the MU. Parameter \(n_B\) denotes the power of the background noise at the MU from the mBS’s transmission. Parameter \(n_S\) denotes the power of the background noise at the MU from the sAP’s transmission. We consider that the BS and the sAP use different frequency channels, and thus no interference exists between the mBS-link and the sAP-link.

To investigate the DC-enabled traffic offloading, we consider an on-spot utilization of EH-supply in this paper, i.e., the sAP uses as much as its EH-supply to power traffic offloading (e.g., due to the heavy traffic demand). Moreover, we consider the long-term average on-grid power consumption and model the sAP’s EH-supply \(Q_S\) in each short scheduling period as an independent and uniform distribution within \([M_S^{low}, M_S^{upp}]\).

The use of uniform distribution is a general and widely approach to model the uncertain EH-supply in a short-term period, e.g., in [14], [19], [20].

Due to the randomness in \(Q_S\), the achievable offloading rate \(x_S\) from the sAP to the MU is random. To capture this effect, we introduce \(P_{out}(p_S, r_S)\) to denote the outage probability that the sAP’s achievable offloading rate \(x_S\) for the MU fails to meet the assigned offloading rate \(r_S\). In other words, it is possible that the sAP’s assigned offloading rate \(r_S\) cannot be reached, leading to the offloading outage as follows:

\[
P_{out}(p_S, r_S) = \text{Pr} \left\{ r_S \geq W_S \log_2 \left( 1 + \frac{(N_S p_S + Q_S) g_S}{N_S n_S} \right) \right\}
\]

\[
= \begin{cases} 
    N_S \left( \frac{r_S}{2 W_S} - 1 \right) \frac{p_{S}^{max}}{g_S} - M_S^{up}, & \text{if} \ (2 \frac{r_S}{W_S} - 1) \frac{p_S}{g_S} - M_S^{low} \leq p_S \leq (2 \frac{r_S}{W_S} - 1) \frac{p_S}{g_S} - M_S^{up} \\
    0, & \text{if} \ (2 \frac{r_S}{W_S} - 1) \frac{p_S}{g_S} - M_S^{low} < p_S \\
    1, & \text{otherwise}
\end{cases}
\]

With \(P_{out}(p_S, r_S)\), we formulate the following total On-Grid Power Consumption Minimization (OGPM) problem:

\[
\begin{align*}
\text{(OGPM)} \quad & \min \ p_B + p_S \\
\text{Subject to:} \quad & x_B + r_S \left( 1 - P_{out}(p_S, r_S) \right) = R^{eq}, \\
& 0 \leq p_B \leq p_{B}^{max}, \\
& 0 \leq p_S \leq p_{S}^{max},
\end{align*}
\]

In Problem (OGPM), we jointly optimize: i) the sAP’s assigned offloading rate \(r_S\) and the transmit-power \(p_S\), and ii) the mBS’s data rate \(x_B\) and the transmit-power \(p_B\). Our objective is to minimize the total on-grid power consumption \(p_B + p_S\). Constraint (3) means that the MU receives a total rate (which is successfully delivered) equal to its required rate \(R^{eq}\).

Parameter \(p_{B}^{max}\) denotes the mBS’s on-grid power capacity for each MU, and \(p_{S}^{max}\) denotes the sAP’s on-grid power capacity for each MU. Solving Problem (OGPM) is difficult, since it

\(^1\)For different MUs, the mBS’s and the sAP’s power allocations are different. However, since we focus on one targeted MU as a concrete example, we skip the MU index for the notation simplicity.
corresponds to a nonconvex optimization. We will exploit the unique properties of Problem (OGPM) to solve it.

Remark 1: (A Trivial Case of Full Offloading-Outage) A trivial case is the full offloading-outage with \( P_{ou}(p_S, r_S) = 1 \).

In this case, only the mBS can provide throughput for the MU, and no rate is provided by the sAP. Correspondingly, the solution of Problem (OGPM) is: \( x_S^* = R_{req} \), and \( p_B^* = (2^{\frac{r_s}{\nu_S}} - 1) \frac{n_B}{g_S} \) (supposing that \( p_B^* \leq p_B^{max} \)), and \( p_S^* = 0 \). Due to the triviality, we consider that the full offloading-outage will not happen at the optimum of Problem (OGPM).

B. Layered Structure of Problem (OGPM) in General Case

We exploit the unique properties of Problem (OGPM) to efficiently solve it. In the general case of \( P_{ou}(p_S, r_S) \in [0, 1] \), we can equivalently transform Problem (OGPM) as follows (here, “G” denotes “General”):

\[
\text{(OGPM-G): \quad \min \quad p_B + p_S} \\
\text{subject to:} \quad W_B \log_2 \left( 1 + \frac{p_B g_B}{n_B} \right) + \frac{r_S - M_S^{up} + N_S p_S - N_S (2^{\frac{r_S}{\nu_S}} - 1) \frac{n_S}{g_S}}{M_S^{up} - M_S^{low}} = R_{req} \quad (6)
\]

\[
(2^{\frac{r_S}{\nu_S}} - 1) \frac{n_S}{g_S} - \frac{M_S^{up}}{N_S} \leq p_S \leq (2^{\frac{r_S}{\nu_S}} - 1) \frac{n_S}{g_S} - \frac{M_S^{low}}{N_S} \quad (7)
\]

Variables: \((r_S, p_S)\) and \(p_B\).

Constraints (6) and (7) together yield a nonconvex feasible region, resulting in that Problem (OGPM-G) is a nonconvex optimization problem which is difficult to solve in general. To tackle this difficulty, we exploit the layered structure of Problem (OGPM-G) to turn it into three subproblems (two subproblems in the bottom-layer and one top-problem on the top-layer) which are easy to solve. Specifically, we first introduce an auxiliary variable \( \rho \in [0, 1] \) as follows:

\[
\rho = \frac{M_S^{up} + N_S p_S - N_S (2^{\frac{r_S}{\nu_S}} - 1) \frac{n_S}{g_S}}{M_S^{up} - M_S^{low}}. \quad (8)
\]

Variable \( \rho \) denotes the portion of the MU’s traffic successfully offloaded through the sAP. Introducing \( \rho \) facilitates the following layer decomposition. Supposing that \( \rho \) is fixed, we can equivalently transform Problem (OGPM-G) into two subproblems in the bottom-layer. The first subproblem is to compute the smallest required \( p_B \) as follows:

\[
\text{(Sub-mBS): \quad \hat{p}_B(\rho) = \arg \min \quad p_B} \\
\text{subject to:} \quad W_B \log_2 \left( 1 + \frac{p_B g_B}{n_B} \right) = (1 - \rho) R_{req} \quad (9)
\]

and constraint (4)

Variable: \( p_B \).

Here, we use \( \hat{p}_B(\rho) \) to denote the optimal output of Problem (Sub-mBS) which is a function of \( \rho \).

The second subproblem is to compute the smallest required \( p_S \) as follows:

\[
\text{(Sub-sAP): \quad \hat{p}_S(\rho, \hat{r}_S(\rho)) = \arg \min \quad p_S} \\
\text{subject to:} \quad p_S = \frac{(M_S^{up} - M_S^{low}) \rho R_{req}}{N_S R_S} + \frac{(2^{\frac{r_S}{\nu_S}} - 1) \frac{n_S}{g_S} - M_S^{up}}{N_S} \quad (10)
\]

and constraints (7) and (5)

Variables: \( p_S \) and \( r_S \).

Constraint (10) stems from (8). We use \( \hat{p}_B(\rho) \) and \( \hat{r}_S(\rho) \) to denote the optimal output of Problem (Sub-sAP).

After solving Problem (Sub-mBS) and Problem (Sub-sAP) for each given \( \rho \), we then solve the top-problem to minimize the total on-grid power consumption, i.e., finding the optimal \( \rho^* \in [0, 1] \) as follows:

\[
\text{(OGPM-G-Top): \quad \rho^* = \arg \min_{0 \leq \rho \leq 1} \hat{p}_B(\rho) + \hat{p}_S(\rho)}.
\]

Using \( \hat{p}_S(\rho) \), the optimal solution of Problem (OGPM-G) is

\[
(p_B^*, p_S^*, r_S^*) = (\hat{p}_B(\rho^*), \hat{p}_S(\rho^*), \hat{r}_S(\rho^*)).
\]

Meanwhile, \( x_B^* = W_B \log_2 (1 + \frac{p_B^* g_B}{n_B}) \).

With the above layered structure, we can solve Problem (OGPM-G) as follows. For each \( \rho \), we first solve Problem (Sub-mBS) and Problem (Sub-sAP) to evaluate \( \hat{p}_B(\rho) \) and \( \hat{p}_S(\rho) \), respectively. With \( \hat{p}_B(\rho) \) and \( \hat{p}_S(\rho) \), we execute a linear-search of \( \rho \in [0, 1] \) to solve Problem (OGPM-G-Top), which thus solves the whole Problem (OGPM-G). We show the detailed procedures in the next section.

III. Algorithm to Solve Problem (OGPM-G)

In this section, we solve Problem (Sub-mBS), Problem (Sub-sAP), and Problem (OGPM-G-Top), and finally propose an algorithm to compute the optimal offloading solution for Problem (OGPM-G).

(Solving Problem (Sub-mBS)) The optimal solution of Problem (Sub-mBS) can be easily derived. By taking into account \( p_B^{max} \), the viable interval of \( \rho \), which can ensure that Problem (Sub-mBS) is feasible, is \( \rho \in [\max\{0, \rho^{low}\}, 1] \) with \( \rho^{low} = 1 - \frac{W_B \log_2 \left( 1 + \frac{p_B^{max} g_B}{n_B} \right)}{R_{req}} \). For each \( \rho \) in this viable interval, we can derive the optimal solution of Problem (Sub-mBS) and the corresponding optimal throughput from the mBS as follows:

\[
\hat{p}_B(\rho) = (2^{\frac{r_B^{max}(1-\rho)}{\nu_B}} - 1) \frac{n_B}{g_B}, \quad \hat{x}_B(\rho) = (1 - \rho) R_{req}. \quad (12)
\]

(Solving Problem (Sub-sAP)) Problem (Sub-sAP) is difficult to solve due to the non-convexity of (9). To tackle this difficulty, we transform Problem (Sub-sAP) into the following one which only uses \( r_S \) as the decision variable:

\[
\text{(Sub-sAP-E): \quad \hat{p}_S(\rho, \hat{r}_S(\rho)) = \min_{r_S} \frac{(M_S^{up} - M_S^{low}) \rho R_{req}}{N_S R_S} + \frac{(2^{\frac{r_S}{\nu_S}} - 1) \frac{n_S}{g_S} - M_S^{up}}{N_S} \quad (13)
\]

subject to: \( r_S \geq \rho R_{req} \).
The first “≤” part of (7) can be directly satisfied by using (10) to replace \( p_S \), and the second “≤” part of (7) translates to (13). Compared with Problem (Sub-sAP), we temporarily do not consider constraint (5) in Problem (Sub-sAP-E). This choice makes Problem (Sub-sAP-E) a convex optimization (i.e., Proposition 1 below). Before that, we discuss about the connections between Problems (Sub-sAP) and (Sub-sAP-E).

Remark 2: (Connections between Problem (Sub-sAP) and Problem (Sub-sAP-E)) Problem (Sub-sAP-E) is equivalent to Problem (Sub-sAP), except that we do not include (5). As a result, there will be three possible outcomes after we solve Problem (Sub-sAP-E). First, if the optimal output of Problem (Sub-sAP-E) (i.e., \( \hat{p}_S(\rho) \)) satisfies \( 0 \leq \hat{p}_S(\rho) \leq p_{S_{\text{max}}}^{\text{pp}} \), then \( \hat{p}_S(\rho) \) suffices to be the optimal solution of Problem (Sub-sAP). Second, if \( \hat{p}_S(\rho) > p_{S_{\text{max}}}^{\text{pp}} \), then Problem (Sub-sAP) is infeasible under the currently given \( \rho \). Third, if \( \hat{p}_S(\rho) < 0 \), then it means that the sAP’s \( r_S \) can be supported by its EH-supply, and there is no need for the sAP to use a positive on-grid power. In this case, additional operations are required such that we can find the right \( \hat{p}_S(\rho) = 0 \). Our proposed GSol-Algorithm will show the detailed operations.

To solve Problem (Sub-sAP-E), we identify the following important property.

**Proposition 1:** (Convexity of Problem (Sub-sAP-E)) Problem (Sub-sAP-E) is a convex optimization problem.

**Proof:** Let \( F(r_S) \) denote the first-order derivative of the objective function of Problem (Sub-sAP-E). We have

\[
F(r_S) = \frac{\ln 2n_S}{W_S g_S} \frac{r_S}{r_S} + M_{S_{\text{pp}}}^{\text{upp}} - M_{S_{\text{low}}}^{\text{upp}} \rho^{\text{req}} \frac{r_S}{N_S}, \tag{14}
\]

which is monotonically increasing in \( r_S \). Moreover, the feasible interval of Problem (Sub-sAP-E) is affine. Thus, Problem (Sub-sAP-E) is a convex optimization problem according to the theory of convex optimization [22].

Proposition 1 enables us to use the Karush-Kuhn-Tucker (KKT) conditions [22] to compute the optimal solution of Problem (Sub-sAP-E). Specifically, we use \( r_S^{\text{opt, temp}} \) to denote the optimal solution of Problem (Sub-sAP-E), which depends on the given \( \rho \). To find \( r_S^{\text{opt, temp}}(\rho) \), we propose GSol-Algorithm in the following. The key of GSol-Algorithm is to exploit the increasing property of \( F(r_S) \) (according to the proof of Proposition 1) and use the bisection search to find the critical value (denoted by \( r_S^{\text{opt, temp}} \)) such that \( F(r_S^{\text{opt, temp}}) = 0 \). The WHILE-Loop (from Step 7 to Step 17) shows the bisectional operations. On the other hand, since \( r_S \) is lower bounded by \( \rho_S^{\text{req}} \) according to (13), we directly set \( r_S^{\text{opt, temp}} = \rho_S^{\text{req}} \) if \( F(\rho_S^{\text{req}}) > 0 \), i.e., Steps 4-5 in GSol-Algorithm. Finally, GSol-Algorithm outputs \( \hat{r}_S(\rho) = r_S^{\text{opt, temp}} \).

Using \( \hat{r}_S(\rho) \) output by GSol-Algorithm, we can derive the smallest transmit-power required by the sAP, i.e., the optimal objective function value of Problem (Sub-sAP-E), as

\[
\hat{p}_S(\rho) = \frac{(M_{S_{\text{pp}}}^{\text{upp}} - M_{S_{\text{low}}}^{\text{upp}}) \rho^{\text{req}}}{N_S g_S} + \left( \frac{r_S^{\text{opt, temp}}}{W_S} - 1 \right) \frac{n_S}{g_S} - M_{S_{\text{pp}}}^{\text{upp}}. \tag{15}
\]

We illustrate the viability of GSol-Algorithm to solve Problem (Sub-sAP) by addressing the three cases in Remark 2. First, \( (\hat{p}_S(\rho), \hat{r}_S(\rho)) \) (i.e., the output of GSol-Algorithm) corresponds to the optimal solution of Problem (Sub-sAP), if \( \hat{p}_S(\rho) \) satisfies \( 0 \leq \hat{p}_S(\rho) \leq p_{S_{\text{max}}}^{\text{pp}} \). Second, Problem (Sub-sAP) is infeasible (under the given \( \rho \)), if \( \hat{p}_S(\rho) > p_{S_{\text{max}}}^{\text{pp}} \). Third, if \( \hat{p}_S(\rho) < 0 \), it means that there is no need for the sAP to spend any positive on-grid power. In this case, we need additional operations to find the right \( r_S^{\text{opt, temp}} \) that yields \( \hat{p}_S^{\text{opt, temp}} = 0 \). To this end, we design additional Steps 20-31 in GSol-Algorithm. We exploit the property that \( (M_{S_{\text{pp}}}^{\text{upp}} - M_{S_{\text{low}}}^{\text{upp}}) \rho^{\text{req}} + (2 \frac{r_S^{\text{opt, temp}}}{W_S} - 1) \frac{n_S}{g_S} - M_{S_{\text{pp}}}^{\text{upp}} \) is increasing for \( r_S \in [r_S^{\text{thre}}, \infty] \) (here, \( r_S^{\text{thre}} \) is equal to \( r_S^{\text{opt, temp}} \) obtained in Step 9 of GSol-Algorithm). Hence, we use the bisection search to find the new \( r_S^{\text{opt, temp}} \) that yields \( \hat{p}_S^{\text{opt, temp}} = 0 \).

**Solving Problem (OGPM-G-Top)** After solving Problems (sub-mBS) and (Sub-sAP), we further solve Problem (OGPM-G-Top). In spite of its simple form, it is difficult to solve Problem (OGPM-G-Top), since we still cannot analytically derive \( \hat{p}_B(\rho) + \hat{p}_S(\rho) \). Fortunately, Problem (OGPM-G-Top) only involves a single variable \( \rho \) within a fixed interval \([0, 1]\). Using this property, we propose the following LS-Algorithm (shown on the next page) that performs a Linear-Search of \( \rho \) to solve Problem (OGPM-G-Top) and outputs the globally
optimal solution \( (r_S^*, p_S^*, x_B^*, p_B^*) \) of Problem (OGPM).

**LS-Algorithm:** output the optimal solution \( (r_S^*, p_S^*, x_B^*, p_B^*) \) of Problem (OGPM-G)

1. Initialization: Set \( \rho = 0 \) and \( \Delta \) as a sufficiently small number (\( \Delta = 10^{-5} \)). The MU sets CBV = \( \infty \) and CBS = \( \emptyset \).
2. while \( \rho \leq 1 \) do
3. if Problem (sub-sAP) is feasible, the MU uses GSol-Algorithm to compute \( (\hat{r}_S(\rho), \hat{p}_S(\rho)) \). Otherwise, start the next iteration.
4. if Problem (sub-mBS) is feasible, MU i uses (12) to compute \( \hat{x}_B(\rho) \) and \( \hat{p}_B(\rho) \). Otherwise, start the next iteration.
5. if \( (\hat{p}_S(\rho) + \hat{p}_B(\rho)) < \text{CBV} \) then
6. The MU updates CBV = \( \hat{p}_S(\rho) + \hat{p}_B(\rho) \).
7. The MU sets CBS = \( (\hat{r}_S(\rho), \hat{p}_S(\rho), \hat{x}_B(\rho), \hat{p}_B(\rho)) \) according to (11).
8. end if
9. Update \( \rho = \rho + \Delta \).
10. end while
11. Output: \( (r_S^*, p_S^*, x_B^*, p_B^*) = \text{CBS} \).

**IV. Numerical Results**

We validate our analytical results and the proposed algorithm in this section. We consider a scenario in which the mBS is located at the origin (0m,0m), the sAP is located at (250m,0m), and the MU is located at (220m,0m). We set the channel power gain \( g_B \) according to the path-loss model, i.e., \( g_B = \lambda d_B^\kappa \), in which parameter \( d_B \) denotes the distance between the mBS and the MU, \( \kappa \) denotes the scaling-parameter (we use \( \kappa = 2.5 \)), and \( \lambda \) follows an exponential distribution with unit mean for capturing the impact of channel fading. The channel power gain \( g_S \) is generated in a similar way. With this setting, the randomly generated channel power gains are \( g_B = 6.383 \times 10^{-7} \) and \( g_S = 8.620 \times 10^{-5} \), which are used in the following Figures 2 to 4. In addition, we set \( p_B^{\text{max}} = 1 \)W and \( p_S^{\text{max}} = 0.4 \)W, and set the bandwidths \( W_B = 10 \)MHz and \( W_S = 5 \)MHz. We set the power density of the background noise as \( n_0 = 10^{-14} \)W.

Figure 2 illustrates the optimal solution of Problem (OGPM) versus different traffic demand. The top-subplot of Figure 2 plots the sAP’s optimal on-grid transmit-power, the mBS’s optimal transmit-power, and the corresponding minimum total on-grid power consumption. As shown in the top-subplot of Figure 2, when the MU’s traffic demand is low, the minimum total on-grid power consumption is zero. This is because that we can completely rely on the sAP’s EH-supply to power the offloading in order to meet the MU’s traffic demand. However, when the MU’s traffic demand increases, the sAP’s EH-supply alone cannot satisfy the MU’s demand. Thus, the sAP needs to spend a non-zero on-grid power to afford the MU’s demand, which corresponds to the increase in the sAP’s optimal on-grid power. Moreover, when the MU’s traffic demand further increases, traffic offloading through the sAP will consume a large on-grid power. As a result, the mBS needs to spend a non-zero on-grid power to afford part of MU’s traffic demand, which corresponds to the increase in the mBS’s optimal on-grid power consumption. In this situation, the corresponding optimal offloading-ratio (i.e., the value of \( 1 - x_B^*/(R^{\text{req}}) \)) starts to decrease, as shown in the bottom-subplot of Figure 2. In particular, the bottom-subplot of Figure 2 also shows that the successful offloading probability (i.e., the value of \( 1 - P_{\text{out}}(r_S^*, p_S^*) \)) gradually increases to one, when the MU’s traffic demand increases. The reason is that the throughput offloaded through the sAP increases, when the MU’s traffic demand increases. As a result, the sAP needs to be more conservative in relying on EH-supply, but using more on-grid power to support traffic offloading. This is essentially because that a larger offloading outage-probability will lead to a larger waste of the sAP’s on-grid power consumption.

Figure 3 further shows the advantage of the proposed optimal offloading scheme in reducing the total on-grid power consumption. For the purpose of comparison, we also consider the heuristic offloading scheme in which the MU offloads a fixed portion of its traffic demand to the sAP (we set such a portion as 70%, 80%, 90%, and 100% in Figure 3). The results show that the proposed optimal offloading scheme always yields the smallest total on-grid power consumption. Specifically, although offloading through the sAP can help reduce the on-grid power consumption, the optimal offloading rate to minimize the total on-grid power consumption needs to be carefully designed according to the detailed conditions.
(such as the MU’s traffic demand and the sAP’s EH-supply). For instance, as shown in Figure 3, aggressively offloading the MU’s entire (i.e., 100%) traffic demand to the sAP will lead to a quick increase in the total on-grid power consumption when the MU’s traffic demand increases, which is due to the fact the sAP’s EH-supply cannot support such a large traffic rate, and thus significant on-grid power is consumed to avoid very large offloading-outage. As a result, such a full-offloading (i.e., 100% of the MU’s demand is offloaded through the sAP) quickly becomes infeasible when the traffic demand increases.

Our future work is to further consider the scenario of multiple small cells and investigate how the small cells properly select different MUs to provide the DC-enabled traffic offloading (with the macrocell) to minimize the overall on-grid power consumption of all small and macro cells.

**REFERENCES**


