Flexible Functional Split in C-RAN with Renewable Energy Powered Remote Radio Units

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***Abstract*—Functional split is a promising technique to reduce the fronthaul rate requirement in cloud radio access networks (C-RAN). Different functional split schemes have different processing costs and fronthaul transmission rates. To maximize the throughput while satisfying the average fronthaul rate constraint in C-RAN with renewable powered Remote Radio Units (RRUs), we first explore the offline problem of selecting the optimal functional split scheme, jointly with the corresponding user data transmission duration and transmission power. We find that in each interval between successive energy arrivals, at most two functional split schemes should be selected, and the two schemes have the same transmission power. We further analyze the scenario with one instance of energy arrival and two candidate functional split schemes, and derive the closed-form expressions of the optimal transmission power and transmission duration for each scheme. Based on the analysis of the special case, a heuristic online algorithm is then proposed, which has similar performance with the optimal offline policy, as validated by simulations.**

I. Introduction

Cloud radio access network (C-RAN) [1], which centralizes the baseband functions at the baseband units (BBUs), can efficiently reduce the operation and deployment costs while at the same time increase the network capacity. In C-RAN, the fronthaul network transports the baseband signals between the BBUs and the remote radio units (RRUs). However, the fronthaul rate requirement is high, which poses a major design challenge on C-RAN. For example, in a single 20MHz LTE antenna-carrier system, 1Gbps fronthaul rate is required with the CPRI interface [2].

By placing some baseband and network functions at RRUs, functional split is a promising technique to reduce the fronthaul rate requirement [3], [4]. With certain functional split schemes, for example, scheme 3, scheme 4 and scheme 5 in Fig. 1(b), the fronthaul transmission rate depends on the traffic load, and thus exploiting the fronthaul statistical multiplexing gain can further reduce the fronthaul rate requirement [5], [6]. The fronthaul rate requirement and processing complexity requirement at the RRUs vary, under different functional split schemes. In general, with more baseband functions at the RRUs, the required fronthaul rate is smaller, but the processing complexity is higher [7], which also means more energy consumption at the RRUs.

By harvesting renewable energy from the environment, the RRUs are able to consume less or no energy from the power grid [8]–[10]. With the renewable energy, RRUs can be deployed at the places where the grid can not cover. However, reliable communication is challenging due to the randomness of renewable energy arrivals. Different from conventional "water-filling", the throughput-optimal "directional water-filling" power control policy is found in a fading energy harvesting channel [11]. If the processing energy consumption is considered, the throughput-optimal transmission policy should become bursts, a "glue pouring" power control policy is proved to be optimal in [12]. For energy harvesting system with processing cost, a "directional backward glue-pouring" algorithm is proposed in [13].

If only one functional split scheme is fixed in the energy harvesting communication system,"directional backward glue-pouring" algorithm [13] can be used to find the optimal power control policy. However, it is expensive and sometimes difficult to deploy fibers between the RRUs and the BBUs, and thus wireless fronthaul may be used as a low cost solution [14]. In this case, the fronthaul rate is limited, which means flexible functional split is necessary, and we also need to consider the overhead brought by wireless fronthaul. To this end, there are more than one candidate functional split schemes, with different processing costs, and thus existing schemes like "directional backward glue-pouring" algorithm no longer apply. This calls for new mechanisms that determine the optimal functional split with the joint consideration of fronthaul properties and renewable energy arrivals.

In this paper, we study the selection of the functional split schemes for C-RAN with energy harvesting RRUs. We first consider the offline problem, where the energy arrivals are non-causally known. The functional split is jointly determined with the corresponding user data transmission duration and transmission power, and the objective is to maximize the throughput, while satisfying the energy and the average fronthaul rate constraints. For the optimal offline policy, we find that in each interval between successive energy arrivals, at most two schemes are selected, and the corresponding transmission power of the schemes are the same. We further analyze the scenarios with only one instance of energy arrival and two alternative functional split schemes, and get the closed-from expression of the transmission power given the average fronthaul rate constraint. Based on the analysis, we propose a heuristic online policy, and numerical results show that the online policy has similar performance with the offline policy, which means that it has close-to-optimal performance.

The paper is organized as follows. The system model is

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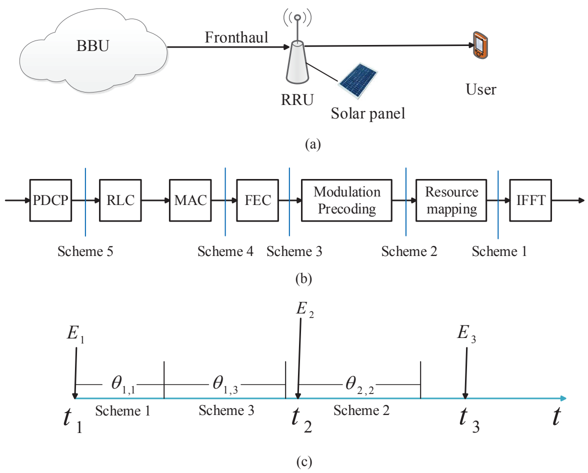

Fig. 1. Functional split in C-RAN with renewable energy powered RRU. (a) C-RAN system with renewable energy powered RRU. (b) Illustration of the functional split schemes. (c) Functional split selection and the power control policy.

described in Section II. The optimization problem is formulated and analyzed in Section III. The optimal power control policy with one energy arrival, two functional split schemes is derived in Section IV. A heuristic online policy is proposed in Section V. The numerical results are presented in Section VI. The paper is concluded in Section VII.

II. System Model

We consider downlink transmission from a particular RRU to its user, and the RRU is powered by renewable energy, as described in Fig. 1(a). The RRU can be configured with N candidate functional split schemes. Assume that the BBU has sufficient data to transmit to the user, we aim to maximize the throughput given the constraint of the average fronthaul rate D, by exploring the optimal power control policy, including the selection of the functional split scheme, and the corresponding user data transmission duration and the transmission power. We consider the offline problem in the interval from 0 to T. As illustrated in Fig. 1(c), the energy packets arrive at time instants $t_1, t_2, ..., t_M$, where $t_1 = 0$, $t_i < t_{i+1}$ and $t_M < T$. E_i units of energy arrives at time t_i. The arrived energy is stored in a battery with capacity $E_{\max}$ before it is used. Without loss of generality, we assume that $E_i \leq E_{\max}$, i.e., the amount of energy in each packet is at most $E_{\max}$. There is no initial energy in the battery, i.e., the battery is empty before time instant t_1. There are M epochs, the length of each epoch is the interval between the successive energy arrivals i.e., $L_i = t_{i+1} - t_i$, and $L_M = T - t_M$.

In each epoch, one or more functional split schemes can be selected, but at most one functional split scheme can be selected at any given time. In epoch i, the duration that scheme j is selected is denoted by $\theta_{i,j}$, as described in Fig. 1(c). Note that $\theta_{i,j} = 0$ means that scheme j is not selected in epoch i. The transmission power of scheme j in each epoch should be constant, denoted by $p_{i,j}$. During one epoch, the total transmission duration of the N schemes should satisfy

$$\sum_{j=1}^{N} \theta_{i,j} \leq L_i, \tag{1}$$

note that there is no data transmission when no scheme is selected. The processing power of scheme j is ε_j, the corresponding fronthaul rate is R_j. We assume that $\varepsilon_j > \varepsilon_{j-1}$ and $R_j < R_{j-1}$, i.e., with larger index j, more baseband functions are placed at the RRU, as illustrated in Fig. 1(b), and thus the processing power is larger, while the fronthaul rate is smaller. Note that, to simplify the analysis, we ignore the possible impact of the transmission power $p_{i,j}$ on the fronthaul rate R_j and the processing power ε_j [7].

The RRU only consumes energy when it is transmitting data to the user. We consider static channel with constant channel gain γ, or the channel fading is averaged out over the time scale of energy harvesting and functional split. In this case, $\theta_{i,j} \log(1 + \gamma p_{i,j})$ bits of data are transmitted to the user with energy consumption $\theta_{i,j}(p_{i,j} + \varepsilon_j)$ in epoch i with scheme j.

III. Maximizing the Throughput

Due to the causality constraints, the energy that has not arrived can not be used, we have

$$\sum_{i=1}^{m} \sum_{j=1}^{N} \theta_{i,j}(p_{i,j} + \varepsilon_j) \leq \sum_{i=1}^{m} E_i, \quad m = 1, 2, ..., M. \tag{2}$$

As the energy in the battery at any time can not exceed the battery capacity, when energy arrives at t_i, at which time the battery has the most energy in epoch i, there should be

$$\sum_{i=1}^{m+1} E_i - \sum_{i=1}^{m} \sum_{j=1}^{N} \theta_{i,j}(p_{i,j} + \varepsilon_j) \leq E_{\max}, \quad \forall m. \tag{3}$$

The throughput maximization problem is then formulated as

$$\max_{\theta_{i,j}, p_{i,j}} \sum_{i=1}^{M} \sum_{j=1}^{N} \theta_{i,j} \log(1 + \gamma p_{i,j}) \tag{4}$$

$$\text{s.t.} \frac{1}{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \theta_{i,j} R_j \leq D \tag{5}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{N} \theta_{i,j}(p_{i,j} + \varepsilon_j) \leq \sum_{i=1}^{m} E_i, \quad \forall m \tag{6}$$

$$\sum_{i=1}^{m+1} E_i - \sum_{i=1}^{m} \sum_{j=1}^{N} \theta_{i,j}(p_{i,j} + \varepsilon_j) \leq E_{\max}, \quad \forall m \tag{7}$$

$$\sum_{j=1}^{N} \theta_{i,j} \leq L_i, \quad \forall i \tag{8}$$

$$p_{i,j} \geq 0, \theta_{i,j} \geq 0, \quad \forall i, j \tag{9}$$

where (5) is the constraint of the average fronthaul rate.

Note that as constraints (6) and (7) are not convex, this is not a convex optimization problem. Similar to the analysis in [12], denoted by $\alpha_{i,j} = \theta_{i,j} p_{i,j}$, which is the energy consumed by the radio transmission in epoch i with scheme j, the optimization problem can be reformulated as

$$\max_{\theta_{i,j},\alpha_{i,j}} \sum_{i=1}^{M}\sum_{j=1}^{N} \theta_{i,j}\log(1+\gamma\frac{\alpha_{i,j}}{\theta_{i,j}}) \quad (10)$$

$$\text{s.t.} \sum_{i=1}^{m}\sum_{j=1}^{N}(\alpha_{i,j}+\varepsilon_j\theta_{i,j}) \le \sum_{i=1}^{m} E_i, \quad \forall m \quad (11)$$

$$\sum_{i=1}^{m+1} E_i - \sum_{i=1}^{m}\sum_{j=1}^{N}(\alpha_{i,j}+\varepsilon_j\theta_{i,j}) \le E_{\max}, \quad \forall m \quad (12)$$

$$\alpha_{i,j} \ge 0, \theta_{i,j} \ge 0, \quad \forall i,j \quad (13)$$

$$(5),(8). \quad (14)$$

As (10) is convex, and the constraints are linear, this is a convex problem. With Lagrangian multiplier method, we can get the following structure of the optimal solution.

Proposition 1. *At most two functional split schemes are selected in each epoch, and the corresponding transmission power of the selected schemes are the same.*

Proof: The Lagrangian with $\lambda \ge 0$, $\mu_m \ge 0$, $\nu_m \ge 0$, $\tau_i \ge 0$ $\eta_{i,j} \ge 0$ and $\xi_{i,j} \ge 0$ can be written as

$$\begin{aligned}\mathcal{L} =& \sum_{i=1}^{M}\sum_{j=1}^{N} \theta_{i,j}\log(1+\gamma\frac{\alpha_{i,j}}{\theta_{i,j}}) - \lambda\left(\sum_{i=1}^{M}\sum_{j=1}^{N}\theta_{i,j}R_j - DT\right) \\ &- \sum_{m=1}^{M}\mu_m\left[\sum_{i=1}^{m}\sum_{j=1}^{N}(\alpha_{i,j}+\varepsilon_j\theta_{i,j}) - \sum_{i=1}^{m}E_i\right] \\ &- \sum_{m=1}^{M-1}\nu_m\left[\sum_{i=1}^{m+1}E_i - \sum_{i=1}^{m}\sum_{j=1}^{N}(\alpha_{i,j}+\varepsilon_j\theta_{i,j}) - E_{\max}\right] \\ &- \sum_{i=1}^{M}\tau_i\left(\sum_{j=1}^{N}\theta_{i,j} - L_i\right) \\ &+ \sum_{i=1}^{M}\sum_{j=1}^{N}\eta_{i,j}\alpha_{i,j} + \sum_{i=1}^{M}\sum_{j=1}^{N}\xi_{i,j}\theta_{i,j} \quad (15)\end{aligned}$$

Taking derivatives with respect to $\alpha_{i,j}$ and $p_{i,j}$, we have

$$\frac{\partial\mathcal{L}}{\partial\alpha_{i,j}} = \frac{\gamma\theta_{i,j}}{\theta_{i,j}+\gamma\alpha_{i,j}} - \sum_{m=i}^{M}\mu_m + \sum_{m=i}^{M-1}\nu_m + \eta_{i,j}, \quad (16)$$

$$\begin{aligned}\frac{\partial\mathcal{L}}{\partial\theta_{i,j}} =& \log(1+\gamma\frac{\alpha_{i,j}}{\theta_{i,j}}) - \frac{\gamma\alpha_{i,j}}{\theta_{i,j}+\gamma\alpha_{i,j}} - \lambda R_j \\ &- \sum_{m=i}^{M}\mu_m\varepsilon_j + \sum_{m=i}^{M-1}\nu_m\varepsilon_j - \tau_i + \xi_{i,j} \quad (17)\end{aligned}$$

If scheme j is selected in epoch i, we have $\alpha_{i,j} > 0$, with the complementary slackness condition $\eta_{i,j}\alpha_{i,j} = 0$, $\eta_{i,j} = 0$. According to (16), let $\frac{\partial\mathcal{L}}{\partial\alpha_{i,j}} = 0$, we have $\frac{\gamma\theta_{i,j}}{\theta_{i,j}+\gamma\alpha_{i,j}} = \sum_{m=i}^{M}\mu_m - \sum_{m=i}^{M-1}\nu_m$, i.e., the values of $\frac{\alpha_{i,j}}{\theta_{i,j}}$ for $\forall j$ in epoch i are the same, i.e., different schemes have

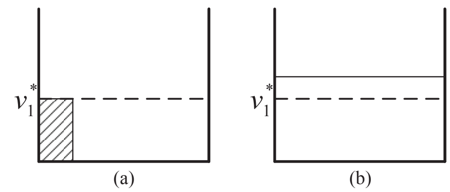

Fig. 2. The optimal power control policy when $D \ge R_1$, where θ_1 and p_1 are represented by the width and height of the black block with up diagonal respectively: (a) $E < (v_1^* + \varepsilon_1)L$; (b) $E \ge (v_1^* + \varepsilon_1)L$.

the same transmission power.

If scheme j is selected in epoch i, we have $\theta_{i,j} > 0$, with the complementary slackness condition $\xi_{i,j}\theta_{i,j} = 0$, $\xi_{i,j} = 0$. Since the values of $\frac{\alpha_{i,j}}{\theta_{i,j}}$ of different j are the same, according to (17), to guarantee that the equations formed by $\frac{\partial\mathcal{L}}{\partial\theta_{i,j}} = 0$ have solution, at most two values of $\xi_{i,j}$ can be the same given i, i.e., at most two schemes satisfy that $\xi_{i,j} = 0$, and thus at most two schemes can be selected in epoch i. ■

IV. Single Energy Arrival, Two Split Schemes

To gain some insights, we will give some intuitive results when there is only one instance of energy arrival, and two candidate functional split schemes, i.e., $M = 1$, $N = 2$. For brevity, we will use θ_1, θ_2, p_1, p_2 instead of $\theta_{1,1}$, $\theta_{1,2}$, $p_{1,1}$ and $p_{1,2}$, the amount of energy arrived at t_1 is denoted by E, the epoch length is denoted by L.

If only one scheme is selected, denoted as scheme j, the optimal power control policy can be obtained by glue pouring. Given the processing power ε_j and channel gain γ, and without maximum transmission duration constraint, the optimal transmission power v_j^* satisfies:

$$(1+\gamma v_j^*)\log(1+\gamma v_j^*) - \gamma v_j^* = \gamma\varepsilon_j. \quad (18)$$

Note that the expression on the left side of the equality is an increasing function of v_j^*, the equation has an unique solution, and v_j^* increases with ε_j. Due to the constraints of epoch length and average fronthaul rate, the transmission duration is limited. Denoted by $l_j = \min\{\frac{DL}{R_j}, L\}$, which is the maximum transmission duration when only scheme j is selected. When $E < l_j(v_j^* + \varepsilon_j)$, the optimal power control policy is $p_j = v_j^*$, $\theta_j = \frac{E}{v_j^*+\varepsilon_j}$. When $E \ge l_j(v_j^* + \varepsilon_j)$, the optimal power control policy is $p_j = \frac{E}{l_j} - \varepsilon_j$, $\theta_j = l_j$.

Due to the fronthaul rate constraint, the average fronthaul rate D will affect the power control policy. We will derive the optimal power control policy with different D in the following part of this section.

A. $D \ge R_1$

When $D \ge R_1$, as $R_1 > R_2$, the average fronthaul rate constraint can always be satisfied, and thus only scheme 1, which has smaller processing power, is selected. When $E <$

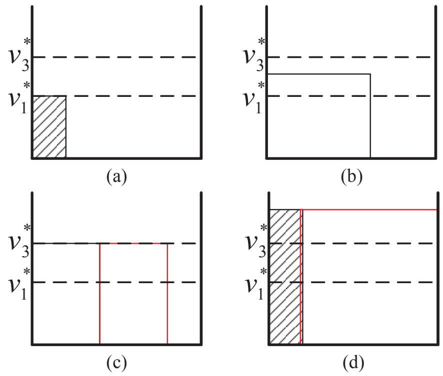

Fig. 3. The optimal power control policy when $R_2 < D < R_1$, θ_1 and p_1 are represented by the width and height of the black block with up diagonal, respectively, θ_2 and p_2 are represented by the width and height of the red block with down diagonal, respectively: (a) $E \leq \frac{DL(v_1^*+\varepsilon_1)}{R_1}$; (b) $\frac{DL(v_1^*+\varepsilon_1)}{R_1} < E \leq \frac{DL(v_3^*+\varepsilon_1)}{R_1}$; (c) $\frac{DL(v_3^*+\varepsilon_1)}{R_1} < E \leq Lv_3^* + \frac{DL(\varepsilon_1-\varepsilon_2)+(R_1\varepsilon_2-R_2\varepsilon_1)L}{R_1-R_2}$; (d) $E > Lv_3^* + \frac{DL(\varepsilon_1-\varepsilon_2)+(R_1\varepsilon_2-R_2\varepsilon_1)L}{R_1-R_2}$.

$(v_1^*+\varepsilon_1)L$, the optimal power control policy is

$$\theta_1 = \frac{E}{v_1^*+\varepsilon_1}, p_1 = v_1^*, \theta_2 = 0, p_2 = 0, \quad (19)$$

as described in Fig. 2(a). When $E \geq (v_1^*+\varepsilon_1)L$, the optimal power control policy is

$$\theta_1 = L, p_1 = \frac{E}{L} - \varepsilon_1, \theta_2 = 0, p_2 = 0, \quad (20)$$

as described in Fig. 2(b).

B. $R_2 < D < R_1$

When $E \leq \frac{DL(v_1^*+\varepsilon_1)}{R_1}$, according to glue pouring, the optimal transmission power v_1^* can be achieved. Only functional split scheme 1 is selected, and thus the optimal power control policy is

$$\theta_1 = \frac{E}{v_1^*+\varepsilon_1}, p_1 = v_1^*, \theta_2 = 0, p_2 = 0, \quad (21)$$

as described in Fig. 3(a).

If $\theta_1 R_1 + \theta_2 R_2 < DL$, functional split scheme 2, which has larger processing power, should not be selected. When $D < R_1$, and $E \geq \frac{DL(v_1^*+\varepsilon_1)}{R_1}$, if only functional split scheme 1 is selected, $\theta_1 = \frac{DL}{R_1}$, we have $\theta_1 R_1 + \theta_2 R_2 = DL$. We can draw the conclusion that when $E \geq \frac{DL(v_1^*+\varepsilon_1)}{R_1}$, we have $\theta_1 R_1 + \theta_2 R_2 = DL$.

As the transmission power of the two schemes are the same, denoted by p, we have $\theta_1(p+\varepsilon_1) + \theta_2(p+\varepsilon_2) = E$, the transmission duration can be expressed as

$$\theta_1 = \frac{(p+\varepsilon_2)DL - R_2E}{R_1(p+\varepsilon_2) - R_2(p+\varepsilon_1)}, \quad (22)$$

$$\theta_2 = \frac{R_1E - (p+\varepsilon_1)DL}{R_1(p+\varepsilon_2) - R_2(p+\varepsilon_1)}. \quad (23)$$

The throughput is

$$H = \frac{(R_1-R_2)E + (\varepsilon_2-\varepsilon_1)DL}{R_1(p+\varepsilon_2) - R_2(p+\varepsilon_1)} \log(1+\gamma p). \quad (24)$$

Taking the derivative of H with respect to p, we have

$$\frac{\partial H}{\partial p} = \frac{(R_1-R_2)\left[(R_1-R_2)E + (\varepsilon_2-\varepsilon_1)DL\right]}{\left[(R_1-R_2)p + R_1\varepsilon_2 - R_2\varepsilon_1\right]^2} \times \left[\frac{\gamma(p+\varepsilon_2+\frac{R_2(\varepsilon_2-\varepsilon_1)}{R_1-R_2})}{1+\gamma p} - \log(1+\gamma p)\right] \quad (25)$$

Denoted by v_3^* satisfies $\frac{\partial H}{\partial p} = 0$, we have

$$\frac{\gamma(v_3^*+\varepsilon_2+\frac{R_2(\varepsilon_2-\varepsilon_1)}{R_1-R_2})}{1+\gamma v_3^*} - \log(1+\gamma v_3^*) = 0, \quad (26)$$

this equation is equivalent to (18), which obtains the optimal transmission power in glue pouring. Since $\frac{R_2(\varepsilon_2-\varepsilon_1)}{R_1-R_2} > 0$ and $\varepsilon_2 > \varepsilon_1$, we have $v_3^* > v_1^*$.

When $p < v_3^*$, $\frac{\partial H}{\partial p} > 0$, the throughput increases with p, so that the transmission power p should be as large as possible, while satisfies that $\theta_1 \geq 0$ and $\theta_2 \geq 0$. When $\frac{DL(v_1^*+\varepsilon_1)}{R_1} < E \leq \frac{DL(v_3^*+\varepsilon_1)}{R_1}$, the maximum $p = \frac{ER_1}{DL} - \varepsilon_1$ is achieved when $\theta_1 = \frac{DL}{R_1}$ and $\theta_2 = 0$, i.e., the optimal power control policy is

$$\theta_1 = \frac{DL}{R_1}, p_1 = \frac{ER_1}{DL} - \varepsilon_1, \theta_2 = 0, p_2 = 0, \quad (27)$$

i.e., only functional split scheme 1 is selected, the transmission power increases with E, while the transmission duration remains unchanged, as described in Fig. 3(b).

When $p > v_3^*$, $\frac{\partial H}{\partial p} < 0$, the throughput decreases with p. If $\frac{DL(v_3^*+\varepsilon_1)}{R_1} < E \leq Lv_3^* + \frac{DL(\varepsilon_1-\varepsilon_2)+(R_1\varepsilon_2-R_2\varepsilon_1)L}{R_1-R_2}$, the transmission power can be v_3^*, and the transmission duration can be obtained by solving the following equations:

$$\theta_1 R_1 + \theta_2 R_2 = DL, \ \theta_1(v_3^*+\varepsilon_1) + \theta_2(v_3^*+\varepsilon_2) = E. \quad (28)$$

The optimal power control policy is

$$\theta_1 = \frac{(v_3^*+\varepsilon_2)DL - R_2E}{R_1(v_3^*+\varepsilon_2) - R_2(v_3^*+\varepsilon_1)}, p_1 = v_3^*,$$
$$\theta_2 = \frac{R_1E - (v_3^*+\varepsilon_1)DL}{R_1(v_3^*+\varepsilon_2) - R_2(v_3^*+\varepsilon_1)}, p_2 = v_3^*, \quad (29)$$

as described in Fig. 3(c). With the increasing of E, the transmission power remains unchanged, the transmission duration of functional split scheme 1 decreases while the transmission duration of functional split scheme 2 increases. Note that when $E = Lv_3^* + \frac{DL(\varepsilon_1-\varepsilon_2)+(R_1\varepsilon_2-R_2\varepsilon_1)L}{R_1-R_2}$, the total transmission duration is equal to the epoch length, i.e., $\theta_1 + \theta_2 = L$.

When $E > Lv_3^* + \frac{DL(\varepsilon_1-\varepsilon_2)+(R_1\varepsilon_2-R_2\varepsilon_1)L}{R_1-R_2}$, due to the epoch length constraint, we have $p > v_3^*$, and the transmission durations of the two functional split schemes should satisfy

$$\theta_1 + \theta_2 = L, \ \theta_1 R_1 + \theta_2 R_2 = DL, \quad (30)$$

i.e., $\theta_1 = \frac{DL-R_2L}{R_1-R_2}$, $\theta_2 = \frac{R_1L-DL}{R_1-R_2}$. As there is no energy waste, we have $\theta_1(p+\varepsilon_1) + \theta_2(p+\varepsilon_2) = E$, i.e., $p =$

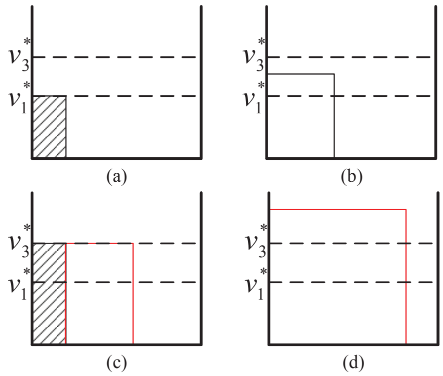

Fig. 4. The optimal power control policy when $D \leq R_2$, θ_1 and p_1 are represented by the width and height of the black block with up diagonal, respectively, θ_2 and p_2 are represented by the width and height of the red block with down diagonal, respectively: (a) $E \leq \frac{DL(v_1^*+\varepsilon_1)}{R_1}$; (b) $\frac{DL(v_1^*+\varepsilon_1)}{R_1} < E \leq \frac{DL(v_3^*+\varepsilon_1)}{R_1}$; (c) $\frac{DL(v_3^*+\varepsilon_1)}{R_1} < E \leq \frac{DL(v_3^*+\varepsilon_2)}{R_2}$; (d) $E > \frac{DL(v_3^*+\varepsilon_2)}{R_2}$.

$\frac{E}{L} - \frac{D(\varepsilon_1-\varepsilon_2)}{R_1-R_2} - \frac{R_1\varepsilon_2-R_2\varepsilon_1}{R_1-R_2}$. The optimal power control policy is as described in Fig. 3(d). With the increasing of E, the transmission durations of both functional split schemes stay unchanged, while the transmission power increases.

C. $D \leq R_2$

When $D \leq R_2$, the derivation of the optimal transmission power control policy is similar to the analysis in Section IV-B.

When $E < \frac{DL(v_1^*+\varepsilon_1)}{R_1}$, the optimal power control policy is

$$\theta_1 = \frac{E}{v_1^*+\varepsilon_1}, p_1 = v_1^*, \theta_2 = 0, p_2 = 0, \tag{31}$$

as described in Fig. 4(a).

When $\frac{DL(v_1^*+\varepsilon_1)}{R_1} < E \leq \frac{DL(v_3^*+\varepsilon_1)}{R_1}$, the optimal power control policy is

$$\theta_1 = \frac{DL}{R_1}, p_1 = \frac{ER_1}{DL} - \varepsilon_1, \theta_2 = 0, p_2 = 0, \tag{32}$$

as described in Fig. 4(b).

When $\frac{DL(v_3^*+\varepsilon_1)}{R_1} < E \leq \frac{DL(v_3^*+\varepsilon_2)}{R_2}$, the optimal transmission power v_3^* can be achieved, and the optimal power control policy is

$$\begin{aligned}\theta_1 &= \frac{(v_3^*+\varepsilon_2)DL - R_2E}{R_1(v_3^*+\varepsilon_2) - R_2(v_3^*+\varepsilon_1)}, p_1 = v_3^*,\\ \theta_2 &= \frac{R_1E - (v_3^*+\varepsilon_1)DL}{R_1(v_3^*+\varepsilon_2) - R_2(v_3^*+\varepsilon_1)}, p_2 = v_3^*,\end{aligned} \tag{33}$$

as described in Fig. 4(c).

When $E > \frac{DL(v_3^*+\varepsilon_2)}{R_2}$, due to the average fronthaul rate constraint, the transmission duration is limited, we have $p > v_3^*$. As the throughput H decreases with p, the transmission power p should be as small as possible. Functional split scheme 2, which has smaller fronthaul rate requirement is selected, and the optimal power control policy is

$$\theta_1 = 0, p_1 = 0, \theta_2 = \frac{DL}{R_2}, p_2 = \frac{ER_2}{DL} - \varepsilon_2, \tag{34}$$

as described in Fig. 4(d).

V. Heuristic Online Policy

According to Proposition 1, at most two functional split schemes should be selected in each epoch for the optimal offline policy. We have obtained the optimal power control policy with one instance of energy arrival and two candidate functional split schemes in Section IV. If there is one instance of energy arrival, and more than two candidate functional split schemes, i.e., $M = 1$, $N > 2$, we can first calculate the throughput when any two of the functional split schemes are selected (there are totally $\frac{N(N-1)}{2}$ possible scenarios), and obtain the optimal power control policy by comparing the throughput of all the possible scenarios. Based on the power control policy with one instance of energy arrival, we propose a heuristic online algorithm.

We assume that the energy arrives in time follows Poisson counting process with rate λ_e. Since the RRU does not know the future energy arrivals, the online policy evaluates the functional split schemes selection, and the corresponding transmission duration and transmission power, at time t_i based on the amount of energy in the battery, denoted by e_i.

When determining the online policy at t_i, we set an expected epoch length $L = \frac{1}{\lambda_e}$, and maximize the throughput in the interval between t_i and $t_i + L$. This is a problem with only one instance of energy arrival, which has been solved in the previous analysis, and we can use the derived power control policy. The RRU will transmit with this power control policy until an energy arrives, or the battery depletes. When an energy arrives at t_{i+1}, the power control policy is updated according to the amount of energy in the battery e_{i+1}, and the RRU begins to transmit with the new power control policy in the next $\frac{1}{\lambda_e}$ epoch.

VI. Numerical Results

In this section, we explore the effect of the average fronthaul rate on the throughput with numerical results. We consider an energy harvesting C-RAN system, the bandwidth is 20MHz. Three candidate functional split schemes are considered, the processing power and required fronthaul rates of the three functional split schemes are $\varepsilon_1 = 1$W, $\varepsilon_2 = 2.5$W, $\varepsilon_3 = 4$W, $R_1 = 980$Mbps, $R_2 = 460$Mbps and $R_3 = 86$Mbps, respectively. The channel gain is $\gamma = 0.025$/W.

We first study the offline throughput maximization problem. We consider three epochs with lengths [0.5, 0.8, 0.6]s, and the amounts of energy arrived at the beginning of each epoch are [24, 18, 8]J. The battery capacity is $E_{\max} = 40$J. The relationship between the throughput and the average fronthaul rate is presented in Fig. 5. We can see that the throughput grows rapidly with the average fronthaul rate when the fronthaul rate is small, and the growth slows down when the fronthaul rate gets large. To explain the reasons, we also present the total

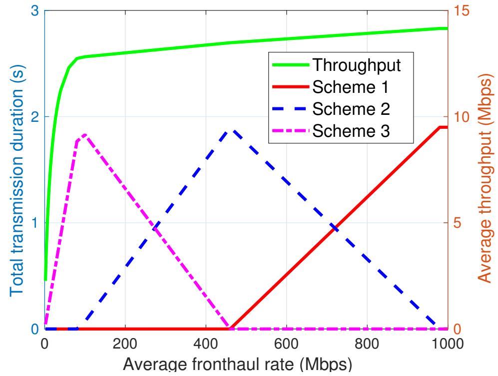

Fig. 5. The throughput and the total transmission duration of each scheme versus the average fronthaul rate.

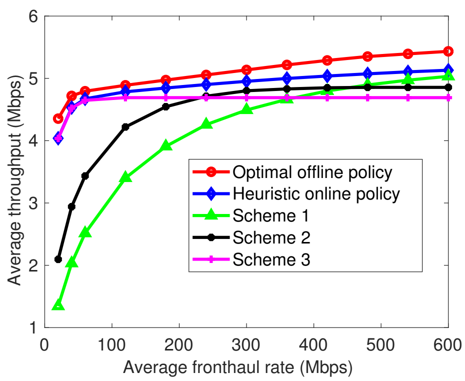

Fig. 6. The throughput versus the average fronthaul rate with online and offline policies.

transmission duration of each scheme in Fig. 5. We can see that when the average fronthaul rate is small, the functional split schemes with smaller fronthaul rate requirements are selected, the sum transmission duration of the selected functional split schemes increases with the average fronthaul rate rapidly. When the average fronthaul rate gets large, the functional split schemes with smaller processing power are selected.

We will next illustrate the online throughput maximization problem. We assume that the energy arrival rate is $\lambda_e = 1$/sec, and the packet size of each energy arrival follows uniform distribution from 0 to 20J. The deadline is $T = 10$s. The performance of the heuristic online power control policy is presented in Fig. 6, compared with the optimal offline policy. We find that the heuristic online policy has similar performance with the optimal offline policy. The policies with only one candidate functional split scheme are adopted as baselines. We can see that, the heuristic online policy has better performance under any average fronthaul rate constraint compared with the baselines.

VII. Conclusions

In this paper, we have explored the selection of the optimal functional split schemes, and the corresponding transmission duration and transmission power of each scheme, to maximize the throughput given the average fronthaul rate in C-RAN with renewable energy powered RRUs. The offline problem is formulated as a convex optimization formulation, and the optimal offline policy has the property that at most two schemes should be selected in each epoch, and the transmission power of the selected schemes are the same. We further analyze the scenario with one instance of energy arrival and two candidate functional split schemes, and derive the closed-form expression of the optimal power control policy. We then propose a heuristic online algorithm, and numerical results show that the proposed online policy has similar performance with the offline policy.

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