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COOPERATIVE AF RELAYING WITH MULTIPLE ENERGY HARVESTING DATA SOURCES

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Abstract. *Conventional researches about radio frequency (RF) energy harvesting networks generally assume that the idle relay node is dedicated to forwarding the signals and harvesting energy from the source. In this paper, we investigate the RF energy harvesting problem in a new scenario that two data sources exist in the network. Each source utilizes the other one to forward its own signal and harvest the RF energy. To maximize the system throughput, we propose a cooperative amplify-and-forward (AF) transmission and energy harvesting protocol, and then theoretically analyze its achievable throughput under the Rayleigh fading channels. Simulation results show that the performance of the proposed protocol outperforms existing methods.*

Keywords: RF energy harvesting, Cooperative relaying, Multiple data sources

1. **Introduction.** With the capability of radio frequency (RF) energy harvesting, user terminals can scavenge energy from the transmitted radio signals. Therefore, it has been considered as a promising solution to prolong the lifetime of energy-constrained wireless network in future wireless systems [1].

Recently, a large amount of researches have been proposed to utilize RF energy harvesting techniques to enhance the performance of relay systems. Specifically, in [2], time switching-based relaying (TSR) protocol and power splitting-based relaying (PSR) protocol were proposed to enhance energy harvesting and information forwarding in an AF (Amplify-and-Forward) relaying network. In [3,4], the performances of the two protocols were analyzed under the Log-Normal fading and the Nakagami-m fading channels, respectively. In [5], the achievable throughput of the TSR protocol was derived for both AF and DF (Decode-and-Forward) systems. Note that these papers focus on the energy harvesting process at the relay node. In [6], a protocol was proposed to deal with energy harvesting at both the source and relay nodes. However, all the aforementioned work focuses on idle relay nodes which can only forward the signals from the source. In 5G systems, especially the networks with D2D communications, some active nodes can also be used as relays to assist the transmission of others. For those nodes, how to allocate resource among their own transmission, relaying and energy harvesting should be considered. Therefore, novel transmission and energy harvesting protocol for these systems is worth further exploring.

In this paper, we investigate RF energy harvesting problem in an AF based cooperative relaying network with active relay nodes. The source and the relay utilize each other to forward their own signals and harvest the RF energy. To maximize the system throughput, we propose a new cooperative transmission and energy harvesting protocol and then theoretically analyze the total achievable throughput under the Rayleigh fading channels. For the data sources and active relays, the optimal solution of time slots allocation for data transmission and RF energy harvesting can be obtained through the proposed protocol, which leads to better system performance compared to existing methods. Simulation results show the performance advantage of the proposed protocol compared with existing approaches.

The rest of the paper is organized as follows. In Section 2, we briefly describe the cooperative data transmission and RF energy harvesting model, and formulate the time slots allocation protocol for multiple data sources. In Section 3, the total achievable throughput of the proposed protocol under Rayleigh fading channels is analyzed. Simulation results are presented in Section 4 to describe the performance of the proposed protocol. Finally, Section 5 concludes the paper.

2. System Model and the Proposed Protocol.

We consider a scenario consisting of two transmission pairs as shown in Figure 1, where s_1 and s_2 denote the transmitters while d_1 and d_2 denote their corresponding receivers. For each transmission pair, there exists no direct link between the transmitter and the associate receiver, and the transmission can only be achieved with the help of the transmitter of the other pair. In addition, each transmitter operates in cooperative AF mode and can harvest energy from the transmitted signal. For example, when s_2 is forwarding the data from s_1 to d_1, s_1 can harvest RF energy from s_2. Although this is just a basic scenario with one active relay node, the results obtained under this scenario can also be applied to the cases of multiple active relay nodes using appropriate relay selection schemes.

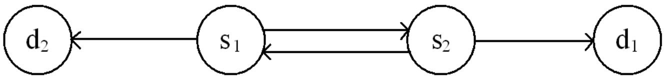

FIGURE 1. System model for two data sources in cooperative AF networks with RF energy harvesting

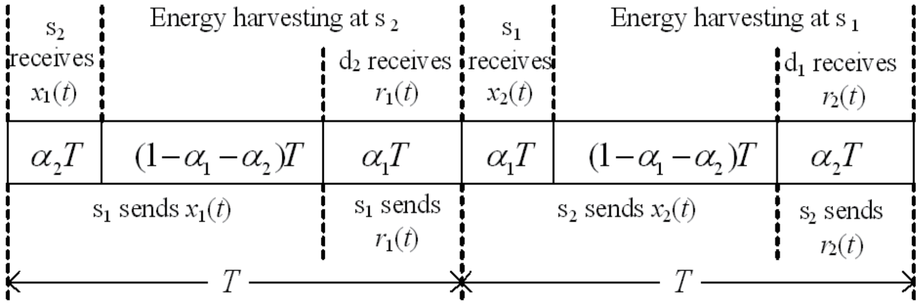

FIGURE 2. Illustration of the proposed protocol for data transmission and energy harvesting

The proposed data transmission and energy harvesting protocol is illustrated in Figure 2. Specially, α_1 and α_2 denote the fraction of a time slot that s_1 and s_2 work as relays, respectively, and T denotes the duration of one time slot. The left $(1-\alpha_1)T$ and $(1-\alpha_2)T$ of s_1 and s_2 are used for transmitting their own signals. The received signals to be relayed at s_1 and s_2 are

$$r_1(t) = \frac{1}{\sqrt{\ell^m_{\mathrm{s}_1\mathrm{s}_2}}}\sqrt{P_{\mathrm{s}_2} g_{\mathrm{s}_1\mathrm{s}_2}} x_2(t) + n_{\mathrm{s}_1\mathrm{s}_2}(t) \tag{1}$$

$$r_2(t) = \frac{1}{\sqrt{\ell^m_{\mathrm{s}_1\mathrm{s}_2}}}\sqrt{P_{\mathrm{s}_1} g_{\mathrm{s}_1\mathrm{s}_2}} x_1(t) + n_{\mathrm{s}_1\mathrm{s}_2}(t) \tag{2}$$

where $\ell_{\mathrm{s}_1\mathrm{s}_2}$ is the distance between s_1 and s_2, and m is the path loss exponent. P_{s_1} and P_{s_2} are the transmission powers of s_1 and s_2, respectively. $g_{\mathrm{s}_1\mathrm{s}_2}$ is the Rayleigh fading channel gain between s_1 and s_2. $x_1(t)$ and $x_2(t)$ are the transmitted signals of s_1 and s_2 with unit power. $n_{\mathrm{s}_1\mathrm{s}_2}(t)$ is the additive white Gaussian noise with zero mean and variance $\sigma^2_{\mathrm{s}_1\mathrm{s}_2}$.

The received signals at d_1 and d_2 are

$$y_1(t) = \frac{1}{\sqrt{\ell^m_{\mathrm{s}_2\mathrm{d}_1}}}\sqrt{P_{\mathrm{s}_2} g_{\mathrm{s}_2\mathrm{d}_1}} b_2 r_2(t) + n_{\mathrm{s}_2\mathrm{d}_1}(t) \tag{3}$$

$$y_2(t) = \frac{1}{\sqrt{\ell^m_{\mathrm{s}_1\mathrm{d}_2}}}\sqrt{P_{\mathrm{s}_1} g_{\mathrm{s}_1\mathrm{d}_2}} b_1 r_1(t) + n_{\mathrm{s}_1\mathrm{d}_2}(t) \tag{4}$$

where b_1 and b_2 are the coefficients to normalize the powers of the relayed signals, and can be defined as

$$b_1 = \left(\frac{P_{\mathrm{s}_2} g_{\mathrm{s}_1\mathrm{s}_2}}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}} + \sigma^2_{\mathrm{s}_1\mathrm{s}_2}\right)^{-\frac{1}{2}} \qquad b_2 = \left(\frac{P_{\mathrm{s}_1} g_{\mathrm{s}_1\mathrm{s}_2}}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}} + \sigma^2_{\mathrm{s}_1\mathrm{s}_2}\right)^{-\frac{1}{2}}$$

Since s_2 transmits its own signal for $(1-\alpha_2)T$ and s_1 only takes $\alpha_1 T$ for relaying the signal, s_1 can harvest energy in the other $(1-\alpha_2-\alpha_1)T$. In addition, when s_2 is relaying the signal $r_2(t)$ to d_1, s_1 can also harvest energy from s_2. Thus, in one time slot T, the energy harvested by s_1 from s_2 is

$$E_{\mathrm{eh1}} = \alpha_2 T\eta \frac{P_{\mathrm{s}_2} g_{\mathrm{s}_1\mathrm{s}_2} b_2^2}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}} \cdot \frac{P_{\mathrm{s}_1} g_{\mathrm{s}_1\mathrm{s}_2}}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}} + (1-\alpha_2-\alpha_1)T\eta \frac{P_{\mathrm{s}_2} g_{\mathrm{s}_1\mathrm{s}_2}}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}} \tag{5}$$

$$E_{\mathrm{eh2}} = \alpha_1 T\eta \frac{P_{\mathrm{s}_1} g_{\mathrm{s}_1\mathrm{s}_2} b_1^2}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}} \cdot \frac{P_{\mathrm{s}_2} g_{\mathrm{s}_1\mathrm{s}_2}}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}} + (1-\alpha_1-\alpha_2)T\eta \frac{P_{\mathrm{s}_1} g_{\mathrm{s}_1\mathrm{s}_2}}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}} \tag{6}$$

Note that since the relaying time of s_1 and s_2 should be no more than the transmission time of the source signal from the partner, we have $\alpha_1 \leq 1-\alpha_2$ and $\alpha_2 \leq 1-\alpha_1$. In addition, users in cooperative system always selfishly take less time for relaying than transmitting their own signals. Consequently, the condition $\alpha_1+\alpha_2 \leq 1$ is achieved.

3. **Total Achievable Throughput Analysis.** For the AF transmission scheme, the end-to-end SNR at d_1 and d_2 are, respectively,

$$\gamma_1 = \frac{\frac{P_{\mathrm{s}_2} g_{\mathrm{s}_2\mathrm{d}_1}}{\ell^m_{\mathrm{s}_2\mathrm{d}_1}} \cdot b_2^2 \cdot \frac{P_{\mathrm{s}_1} g_{\mathrm{s}_1\mathrm{s}_2}}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}}}{\frac{P_{\mathrm{s}_2} g_{\mathrm{s}_2\mathrm{d}_1}}{\ell^m_{\mathrm{s}_2\mathrm{d}_1}} b_2^2 \sigma^2_{\mathrm{s}_1\mathrm{s}_2} + \sigma^2_{\mathrm{s}_2\mathrm{d}_1}} \qquad \gamma_2 = \frac{\frac{P_{\mathrm{s}_1} g_{\mathrm{s}_1\mathrm{d}_2}}{\ell^m_{\mathrm{s}_1\mathrm{d}_2}} \cdot b_1^2 \cdot \frac{P_{\mathrm{s}_2} g_{\mathrm{s}_1\mathrm{s}_2}}{\ell^m_{\mathrm{s}_1\mathrm{s}_2}}}{\frac{P_{\mathrm{s}_1} g_{\mathrm{s}_1\mathrm{d}_2}}{\ell^m_{\mathrm{s}_1\mathrm{d}_2}} b_1^2 \sigma^2_{\mathrm{s}_1\mathrm{s}_2} + \sigma^2_{\mathrm{s}_1\mathrm{d}_2}}$$

Assume that E_1 and E_2 are the initial energy of s_1 and s_2. The transmission process terminates when s_1 or s_2 exhausts all its energy. According to (5) and (6), the total number of transmission of s_1 and s_2 can be calculated as: $K_1 = (E_1 + K_1 E_{\mathrm{eh1}})/P_{\mathrm{s}_1}T$, $K_2 = (E_2 + K_2 E_{\mathrm{eh2}})/P_{\mathrm{s}_2}T$. The transmission number of the whole system is $K = \min\left(\lfloor K_1 \rfloor, \lfloor K_2 \rfloor\right)$, where $\lfloor . \rfloor$ is the floor function. Thus, the total achievable throughput of the system is

$$C_{\mathrm{total}} = C_{\mathrm{s}_1} + C_{\mathrm{s}_2} = K\alpha_2 \log_2(1+\gamma_1) + K\alpha_1 \log_2(1+\gamma_2) \tag{7}$$

Let $\gamma_{\mathrm{s}_2\mathrm{d}_1} = g_{\mathrm{s}_2\mathrm{d}_1}/\ell^m_{\mathrm{s}_2\mathrm{d}_1}$, $\gamma_{\mathrm{s}_1 s_2} = g_{\mathrm{s}_1\mathrm{s}_2}/\ell^m_{\mathrm{s}_1\mathrm{s}_2}$ and $\gamma_{\mathrm{s}_1\mathrm{d}_2} = g_{\mathrm{s}_1\mathrm{d}_2}/\ell^m_{\mathrm{s}_1\mathrm{d}_2}$. For Rayleigh fading channels, $g_{\mathrm{s}_2\mathrm{d}_1}$, $g_{\mathrm{s}_1\mathrm{s}_2}$ and $g_{\mathrm{s}_1\mathrm{d}_2}$ follow exponential distribution. Thus, $\gamma_{\mathrm{s}_2\mathrm{d}_1}$, $\gamma_{\mathrm{s}_1 s_2}$ and $\gamma_{\mathrm{s}_1\mathrm{d}_2}$ are exponential variables with parameters $\lambda_1 = 1/\ell^m_{\mathrm{s}_2\mathrm{d}_1}$, $\lambda_2 = 1/\ell^m_{\mathrm{s}_1\mathrm{s}_2}$ and $\lambda_3 = 1/\ell^m_{\mathrm{s}_1\mathrm{d}_2}$. The average total throughput of s_1 can be expressed as

$$\overline{C}_{\mathrm{s}_1} = \int_0^\infty \int_0^\infty \frac{1}{\lambda_1}\frac{1}{\lambda_2} C_{\mathrm{s}_1} e^{-\frac{\gamma_{\mathrm{s}_2\mathrm{d}_1}}{\lambda_1}} e^{-\frac{\gamma_{\mathrm{s}_1\mathrm{s}_2}}{\lambda_2}} d\gamma_{\mathrm{s}_2\mathrm{d}_1} d\gamma_{\mathrm{s}_1\mathrm{s}_2} \tag{8}$$

According to (7), C_{s_1} is given by

$$\begin{aligned} C_{\mathrm{s}_1} &= K\alpha_2 \log_2 \left(1 + \frac{P_{\mathrm{s}_2} P_{\mathrm{s}_1} \gamma_{\mathrm{s}_2\mathrm{d}_1} \gamma_{\mathrm{s}_1 s_2}}{P_{\mathrm{s}_2} \gamma_{\mathrm{s}_2\mathrm{d}_1} \sigma^2_{\mathrm{s}_1\mathrm{s}_2} + P_{\mathrm{s}_1} \gamma_{\mathrm{s}_1 s_2} \sigma^2_{\mathrm{s}_2\mathrm{d}_1} + \sigma^2_{\mathrm{s}_1\mathrm{s}_2} \sigma^2_{\mathrm{s}_2\mathrm{d}_1}} \right) \\ &= \frac{1}{\ln 2} K\alpha_2 \big[\ln \left(P_{\mathrm{s}_2} P_{\mathrm{s}_1} \gamma_{\mathrm{s}_2\mathrm{d}_1} \gamma_{\mathrm{s}_1 s_2} + P_{\mathrm{s}_2} \gamma_{\mathrm{s}_2\mathrm{d}_1} \sigma^2_{\mathrm{s}_1\mathrm{s}_2} + P_{\mathrm{s}_1} \gamma_{\mathrm{s}_1 s_2} \sigma^2_{\mathrm{s}_2\mathrm{d}_1} + \sigma^2_{\mathrm{s}_1\mathrm{s}_2} \sigma^2_{\mathrm{s}_2\mathrm{d}_1} \right) \\ &\quad - \ln \left(P_{\mathrm{s}_2} \gamma_{\mathrm{s}_2\mathrm{d}_1} \sigma^2_{\mathrm{s}_1\mathrm{s}_2} + P_{\mathrm{s}_1} \gamma_{\mathrm{s}_1 s_2} \sigma^2_{\mathrm{s}_2\mathrm{d}_1} + \sigma^2_{\mathrm{s}_1\mathrm{s}_2} \sigma^2_{\mathrm{s}_2\mathrm{d}_1} \right) \big] \end{aligned} \tag{9}$$

Let $\beta_1 = P_{\mathrm{s}_1} \gamma_{\mathrm{s}_1 s_2} \sigma^2_{\mathrm{s}_2\mathrm{d}_1} + \sigma^2_{\mathrm{s}_1\mathrm{s}_2} \sigma^2_{\mathrm{s}_2\mathrm{d}_1}$, $\mu_1 = 1/\left[\lambda_1 \left(P_{\mathrm{s}_2} P_{\mathrm{s}_1} \gamma_{\mathrm{s}_1 s_2} + P_{\mathrm{s}_2} \sigma^2_{\mathrm{s}_1\mathrm{s}_2}\right)\right]$, and $\mu_2 = 1/\big(\lambda_1 P_{\mathrm{s}_2} \sigma^2_{\mathrm{s}_1\mathrm{s}_2}\big)$. Since K is only related to $\gamma_{\mathrm{s}_1\mathrm{s}_2}$, according to [7, eq. (4.337.1)], $\overline{C}_{\mathrm{s}_1}$ can be derived as

$$\overline{C}_{\mathrm{s}_1} = \frac{\alpha_2}{\lambda_2 \ln 2} \int_0^\infty K e^{-\frac{\gamma_{\mathrm{s}_1\mathrm{s}_2}}{\lambda_2}} \left[e^{\mu_2\beta_1} \mathrm{Ei}(-\beta_1\mu_2) - e^{\mu_1\beta_1} \mathrm{Ei}(-\beta_1\mu_1) \right] d\gamma_{\mathrm{s}_1\mathrm{s}_2} \tag{10}$$

where the "Ei" function is defined in [7, eq. (8.211.1)]. Similar to (8)-(10), $\overline{C}_{\mathrm{s}_2}$ can be obtained as

$$\overline{C}_{\mathrm{s}_2} = \frac{\alpha_1}{\lambda_2 \ln 2} \int_0^\infty K e^{-\frac{\gamma_{\mathrm{s}_1\mathrm{s}_2}}{\lambda_2}} \left[e^{\mu_4\beta_2} \mathrm{Ei}(-\beta_2\mu_4) - e^{\mu_3\beta_2} \mathrm{Ei}(-\beta_2\mu_3) \right] d\gamma_{\mathrm{s}_1\mathrm{s}_2} \tag{11}$$

where $\beta_2 = P_{\mathrm{s}_2} \gamma_{\mathrm{s}_1\mathrm{s}_2} \sigma^2_{\mathrm{s}_1\mathrm{d}_2} + \sigma^2_{\mathrm{s}_1\mathrm{s}_2} \sigma^2_{\mathrm{s}_1\mathrm{d}_2}$, $\mu_3 = 1/\left[\lambda_3 \left(P_{\mathrm{s}_2} P_{\mathrm{s}_1} \gamma_{\mathrm{s}_1\mathrm{s}_2} + P_{\mathrm{s}_1} \sigma^2_{\mathrm{s}_1\mathrm{s}_2}\right)\right]$, $\mu_4 = 1/\big(\lambda_3 P_{\mathrm{s}_1} \sigma^2_{\mathrm{s}_1\mathrm{s}_2}\big)$. Thus, from (10) and (11), the average total achievable throughput of the whole system is

$$\overline{C}_{\mathrm{total}} = \overline{C}_{\mathrm{s}_1} + \overline{C}_{\mathrm{s}_2} \tag{12}$$

4. **Simulation Results.** In this section, simulation results are presented to verify the effectiveness of the proposed protocol. The simulation parameters are set as the following table.

Table 1. Simulation parameters

Parameter	**Value**
Transmission power of s_1 and s_2	1 W
Distance between s_1 and s_2	10 m
Distance between s_1 and d_2	3 m
Distance between s_2 and d_1	5 m
Time slot length	1 s
Initial energy of s_1	90 J
Initial energy of s_2	100 J
Pathloss exponent	2.7
Noise power	0.01 W

In Figure 3, Monte Carlo method is provided to verify the analytical results of the total system throughput for different energy conversion efficiencies η when $\alpha_1 = \alpha_2 = 0.5$. The system throughput increases with the increase of η. This is because more energy can be harvested with a higher value of η to support more transmissions. For the analytical total throughput, we omit the rounding down process of K for convenience. Thus, the analytical values are a little higher than the simulation results. However, the increment is very small compared to the total throughput. However, the increment is very small. For example, when $\eta = 0.3$, the throughput of the analytical method is 414, which is 0.5% higher than that of the Monte Carlo method. Therefore, we can conclude that the analytical result can be a tight upper bound of the real value.

Figure 4 compares the performance of the protocol in [6] with that of our proposed protocol for different η. Since the protocol in [6] only considers one data source, we apply it in the same scenario of this article with a switching method defined as follows: 1) s_1 sends

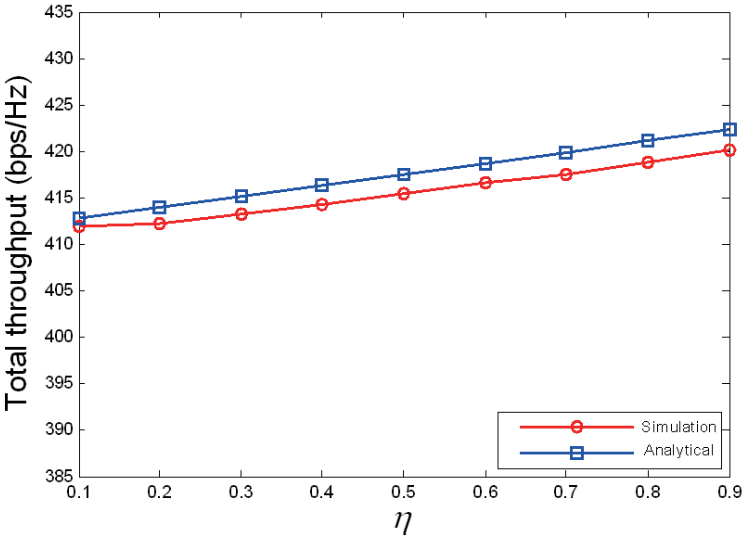

FIGURE 3. The analytical and simulated total throughput with different η

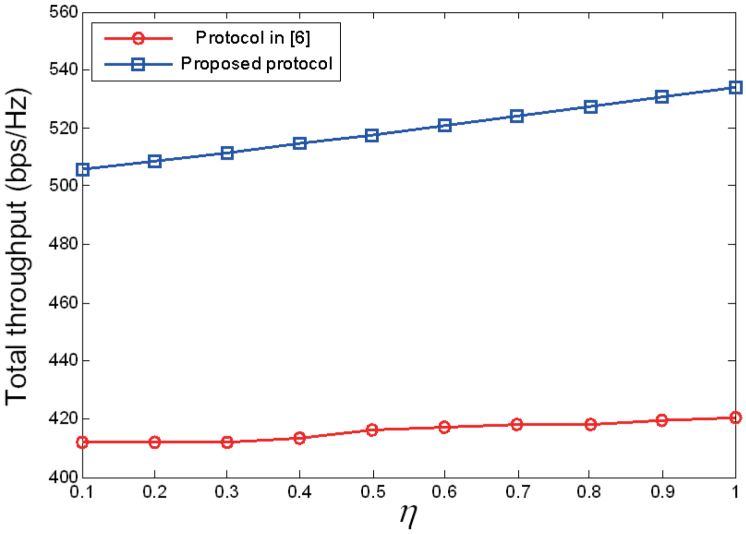

FIGURE 4. The total system throughput of the proposed protocol versus the protocol in [6]

$x_1(t)$ to s_2, and s_2 receives $r_2(t)$; 2) s_2 relays $r_2(t)$ to d_1, and s_1 harvests energy from s_2; 3) s_2 sends $x_2(t)$ to s_1, and s_1 receives $r_1(t)$; 4) s_1 relays $r_1(t)$ to d_2, and s_2 harvests energy from s_1. α_1 and α_2 of the proposed protocol are obtained by numerically searching for the best values that maximize the total throughput. Simulations show that the proposed protocol achieves higher throughput than that of the protocol in [6]. The reason is that the best values of α_1 and α_2 of the proposed protocol can be adjusted according to the practical scenario factors, such as channel conditions, transmission powers, and initial energies. Therefore, with the proposed protocol, the data source with high quality transmission links and more initial energy obtains more transmission time to send its own signal, which leads to a higher total throughput.

5. **Conclusions.** In this paper, we investigated the time slots allocation problem for multiple RF energy harvesting-enabled data sources, and proposed a cooperative AF transmission and energy harvesting protocol. In this protocol, the time slots allocation for

the data transmission and RF energy harvesting processes between multiple data sources were considered. The total achievable system throughput of the proposed protocol was analyzed. Simulation results show that, the proposed protocol achieved higher system throughput compared with existing approaches. The calculation of the optimal values of α_1 and α_2 that maximize the system throughput or the benefits of each user may be considered for extended research.

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