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Research Article

Multihop Capability Analysis in Wireless Information and Power Transfer Multirelay Cooperative Networks

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We study simultaneous wireless information and power transfer (SWIPT) in multihop wireless cooperative networks, where the multihop capability that denotes the largest number of transmission hops is investigated. By utilizing the broadcast nature of multihop wireless networks, we first propose a cooperative forwarding power (CFP) scheme. In CFP scheme, the multiple relays and receiver have distinctly different tasks. Specifically, multiple relays close to the transmitter harvest power from the transmitter first and then cooperatively forward the power (not the information) towards the receiver. The receiver receives the information (not the power) from the transmitter first, and then it harvests the power from the relays and is taken as the transmitter of the next hop. Furthermore, for performance comparison, we suggest two schemes: cooperative forwarding information and power (CFIP) and direct receiving information and power (DFIP). Also, we construct an analysis model to investigate the multihop capabilities of CFP, CFIP, and DFIP schemes under the given targeted throughput requirement. Finally, simulation results validate the analysis model and show that the multihop capability of CFP is better than CFIP and DFIP, and for improving the multihop capabilities, it is best effective to increase the average number of relay nodes in cooperative set.

1. Introduction

Among several wireless energy harvesting techniques, simultaneous wireless information and power transfer (SWIPT) has drawn great attention [1–3]. SWIPT was first proposed in [1, 2], where the transmitter sends one wireless signal, and the receiver harvests energy and decodes information from the signal at the same time. Owing to practical constraint, SWIPT cannot be performed on one circuit. Therefore, two practical architectures, called time switching and power splitting, have been proposed by permitting the receiver to have two circuits to carry out energy harvesting and information decoding separately [3].

On the other hand, cooperative communication has been shown to be a promising method to mitigate the wireless channel impairments by applying either amplify-and-forward (AF) or decode-and-forward (DF) relaying protocol [4] in relay nodes. However, a relay node needs to expend its energy for accomplishing the information forwarding, which can make the relay node reluctant to participate in the cooperation. Fortunately, by using energy harvesting node as relay, the cooperative excitement of relay node can be ignited and the network performance can be significantly improved.

The performance of SWIPT in cooperative relay networks has been analyzed in various studies (see Section 2), but these studies assume that they have at most two hops from source to destination with the signal forwarding by relays. For multihop (more than two hops) networks, because the energy harvesting efficiency cannot reach 100% (the range of 10%–80% is normal) [5], the difficulty is how to transmit energy and information simultaneously from source to destination, that is, solving the SWIPT issue in the multihop case. To solve this problem, we consider using cooperative multiple relays by fully utilizing the broadcast nature of multihop wireless networks. Unlike previous studies, Chen et al. [6] considered multihop scenarios and identified the largest number of transmission hops. However, the work in [6] did not consider multiple cooperative relays and failed to provide insights into the impact factors that affected the largest number of transmission hops.

Although the use of cooperative relays can reduce the loss of energy, it is not guaranteed that the information is transmitted to the destination with enough power. Then, what is the largest number of transmission hops under the given targeted throughput requirement? This problem is closely related to the initial energy of source node, the number of relay nodes, communication distance, and other parameters, which sparks our research motivation. In this paper, we first propose a cooperative forwarding power (CFP) scheme, and then, for performance comparison, we suggest two schemes: cooperative forwarding information and power (CFIP) and direct receiving information and power (DFIP). Furthermore, we construct analysis model to investigate the multihop capabilities of CFP, CFIP, and DFIP schemes under the given targeted throughput requirement from application layer. Finally, simulation results validate the analysis model and show that the multihop capability of CFP is better than CFIP and DFIP, and for improving the multihop capabilities, it is best effective to increase the average number of relay nodes in a cooperative set. Therefore, through our study in this paper, the appropriate values of related parameters can be set to achieve the given transmission hops from source to destination.

The remainder of this paper is organized as follows. First, the related works are described in Section 2. Next, system models and network scenario are given in Section 3, and in Section 4, we present CFP, CFIP, and DFIP schemes. Afterwards, Section 5 presents analytical models for evaluating the performance of the three schemes, and simulation results are given to validate the analytical model and obtain some important insights in Section 6. Finally, conclusions are given in Section 7.

2. Related Works

According to the difference in information transmission ways, communication systems adopted by existing literature can be categorized into point-to-point SWIPT systems and cooperative relay SWIPT systems. In the following, we present an overview of existing literature in the above two SWIPT systems.

(A) Point-to-Point SWIPT Systems. After the pioneering works of Varshney [1] and Grover and Sahai [2], the performance of practical SWIPT systems is investigated in several studies. Zhang and Ho [3] considered two scenarios, where the information receiver and energy receiver are separated or colocated. More importantly, the work in [3] used rate-energy region to characterize the tradeoff between information rate and energy transfer and proposed two practical receiver designs, namely, time switching and power splitting, for colocated receivers. Later in [7–9], sophisticated architectures for improving the rate-energy region were further proposed. Moreover, multiuser scheduling in SWIPT system was studied for achieving the maximum sum throughput in [10] and tradeoff between the average per user harvested energy and ergodic achievable rate in [11]. Unlike the above works, Zhong et al. [12] considered a novel network architecture, where the source is powered by a dedicated power beacon (PB), and gave the average throughput analysis for two different transmission modes, namely, delay tolerant and delay intolerant. Recently, for reutilizing interferences to avoid a great waste of energy, Zhao et al. [13, 14] proposed a novel SWIPT scheme based on opportunistic communications in interference alignment (IA) networks and analyzed the performance of SWIPT in IA networks, respectively.

(B) Cooperative Relay SWIPT Systems. Considering that there is no direct point-to-point link between the source and destination, it is necessary to make use of relay for forwarding information to destination, where the relay node is energy-constrained and needs to harvest energy from the source. Nasir et al. [15] proposed time switching-based relaying (TSR) and power splitting-based relaying (PSR) protocols and derived the throughput for both TSR and PSR under delay-limited and delay-tolerant transmission modes. Afterwards, Do [16] considered that both relay and destination are mobile node and analyzed the optimal throughput performance for the proposed time power switching-based relaying (TPSR) protocol. Unlike the previous studies, Zhang and Chen [17] considered that the relay can harvest energy from source, destination, or joint source and destination and investigated the maximal throughputs of three wireless power transfer (WPT) schemes, respectively. Furthermore, to overcome the loss of spectral efficiency induced by one-way relaying and half-duplex relaying, two-way relaying [18–20] and full-duplex relaying [21–23] were introduced into SWIPT system, respectively. Instead of considering one relay-assisted SWIPT cooperative system in the aforementioned works, the works of [24–26] investigated multirelay-assisted case and analyzed the outage probability and end-to-end rate, respectively. Unlike the existing prominent works, we investigate SWIPT in a multihop scenario and analyze the multihop capability of SWIPT system with multirelay-assisted cooperative transmission.

3. System Model

We consider a network scenario shown in Figure 1, where the source node (S) wants to transmit data packets to the destination node (D). We assume that a path $R\{S, p_1, p_2, \ldots, p_i, \ldots, p_k, D\}$ has been selected by virtue of a routing algorithm and all nodes are equipped with a single omnidirectional antenna and work in half-duplex mode. For cooperative transmission, we also assume that each node in a routing path R is surrounded by a number of relays. In addition, for facilitating the analysis, we suggest the relay and channel models as follows.

(A) Relay Model. We assume that S is considered as an energy-unconstrained node with a maximum transmit power P_s, while other relay nodes are energy-constrained and have not energy to complete the forwarding operation, but they can harvest energy from the received signal by power

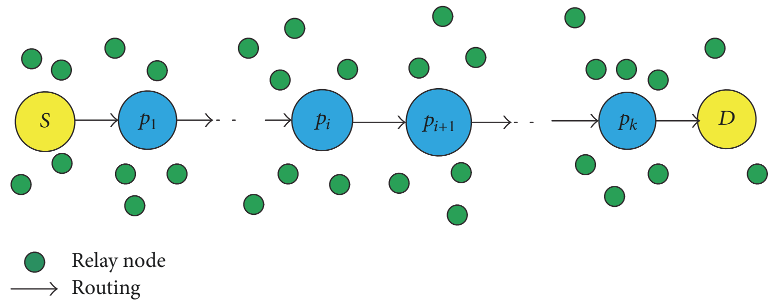

Figure 1: Network scenario.

splitting. More specifically, each relay i splits a portion of the received signal energy α_i for information decoding and the remaining part $1 - \alpha_i$ for energy harvesting. Since the processing power consumed by the receive circuitry at the relay nodes is assumed to be negligible as compared to the power used for signal forwarding [15], we assume that all nodes have the energy to receive signal. In this paper, all relays form a cooperative set and simultaneously forward the signals to the receiver by using distributed space-time codes (DSTC) [27].

(B) Channel Model. We assume that the additive white Gaussian noises (AWGN) at all nodes are independent circular symmetric complex Gaussian random variables with zero mean and unit variance. The channel fading is modeled by large-scale path loss and statistically independent small-scale Rayleigh fading. It is also assumed that the fading channel gains are assumed to be constant during one block time $T_{t,v}$ in which the information is transmitted from the transmitter to receiver, and independent and identical distribution (i.i.d.) is used from one transmission to the next. Also, we assume that perfect channel state information (CSI) is available at the receiver side through channel estimation and $h_{i,j}$ denotes the channel gain between node i and node j, which are circular symmetric complex Gaussian random variables with zero mean and unit variance [5, 15, 18].

4. Proposed Scheme

To investigate the multihop capability in SWIPT multihop cooperative networks, we give the following three transmission schemes. We first propose *cooperative forwarding power (CFP) scheme*. In CFP scheme, the relays and receiver have distinctly different tasks. Specifically, multiple relays close to the transmitter harvest power from the transmitter first and then cooperatively forward the power (not the information) towards the receiver. The receiver receives the information (not the power) from the transmitter first, and then it harvests the power from the relays and is taken as the transmitter of the next hop. Furthermore, we use the following two schemes as comparison.

(A) Cooperative Forwarding Information and Power (CFIP) Scheme. In this scheme, it is assumed that there is no direct link between the transmitter and receiver of a path (this assumption is adopted by most of the previous studies [5, 15–26]), such as p_i and p_{i+1} in Figure 1. Multiple relays harvest power and decode the information from the transmitter first and then cooperatively forward the information and power to the receiver. Then, the receiver harvests the power and decodes the information from the relays and is taken as the transmitter of the next hop to transmit the information and power. Note that, at present, CFIP is often used in at most two-hop scenarios by most of the previous works to analyze system performance. So, we extend this scheme to multihop scenario for comparing and analyzing the multihop capability in SWIPT cooperative networks.

(B) Direct Receiving Information and Power (DFIP) Scheme. This scheme does not consider cooperative transmission, which means that the receiver harvests power and decodes the information from the transmitter directly (this assumption is adopted by most of the previous studies [3, 7–14]). Then, the receiver is taken as the transmitter of the next hop to transmit the information and power. The purpose of proposing this scheme is to investigate whether cooperative transmission can bring more performance improvement than direct transmission in SWIPT networks.

It should be pointed out that our schemes are independent of the specific routing protocol and only require an existing path from source to destination. In fact, the analysis results of multihop capability can be used to design a new routing protocol in SWIPT networks. Also, our schemes are indifferent to the specific method of relay selection, because the analysis results of multihop capability are related to the number of relays instead of which node becomes a relay.

5. Analytical Model

5.1. For CFP Scheme. In CFP scheme, one transmission is divided into two phases. In the first phase, the transmitter (source or p_i) transmits the signal to the receiver (p_i or destination), and thus, the relays overhear the signal and harvest the power from the signal, and at the same time, the receiver decodes the information from the signal. In the second phase, the relays form a cooperative set according to the DSTC to forward the harvested power by transmitting the special signal to the receiver cooperatively, and then the receiver harvests the power from the special signal and is taken as the transmitter in the next hop with the harvested power. Note here that the special signal is different from the signal from the transmitter to receiver and does not include the useful information that needs to be decoded by the receiver. Therefore, for the special signal, we let the relays transmit a PTS (power ready to send) frame cooperatively in which the frame format is extended to the RTS and CTS control frames in IEEE 802.11 protocol [28].

First of all, let us consider that the signal is transmitted from the source to receiver node p_1 in Figure 1. Let $y_{r,i}$ denote the received signal at relay i around the source node in the first phase; we can derive

$$y_{r,i} = \frac{1}{\sqrt{d_{s,i}^m}}\sqrt{P_s}h_{s,i}x_s + n_{r,i}, \quad (1)$$

where $h_{s,i}$ is the source to relay i channel gain, $d_{s,i}$ is the distance from S to relay i, m is the path loss exponent, $n_{r,i}$ is the additive white Gaussian noise at relay i with zero mean and $\sigma_{n,r}^2$ variance, and x_s is the normalized information signal from the source. Because the relays do not decode the signal from the transmitter to receiver, we can let $\alpha_i = 0$. According to (1), the harvested energy $E_{r,i}$ at relay i during energy harvesting time $T_{t,v}$ is given by

$$E_{r,i} = \frac{\eta P_s \left|h_{s,i}\right|^2 T_{t,v}}{d_{s,i}^m}, \quad (2)$$

where η is the energy harvesting efficiency coefficient and $T_{t,v}$ is the transmission time for the signal. Note that we do not consider multirate network scenarios, which means that $T_{t,v}$ is equal for any one hop in the routing path. In (2), we ignore the impact of noise since the noise power is normally very small and below the sensitivity of the energy receiver [29].

In the second phase, each relay i uses the transmission power $P_{r,i} = E_{r,i}/T_{c,v}$ and forms a cooperative set with other relays to transmit the PTS frame towards the receiver p_1, simultaneously. Consequently, p_1 does not decode the PTS frame but only harvests the energy that can be expressed by $E_{p,1}$ as

$$E_{p,1} = \eta\sum_{i=1}^{N_r}\frac{P_{r,i}\left|h_{i,p_1}\right|^2}{d_{i,p_1}^m}T_{c,v} = \eta^2 P_s T_{t,v}\sum_{i=1}^{N_r}\frac{\left|h_{s,i}\right|^2\left|h_{i,p_1}\right|^2}{d_{s,i}^m d_{i,p_1}^m}, \quad (3)$$

where h_{i,p_1} is channel gain from the relay i to receiver p_1, $T_{c,v}$ is the transmission time for the PTS, N_r is the average number of relay nodes in cooperative set, and d_{i,p_1} is the distance from the relay i to receiver p_1. So, we can derive the transmission power $P_{p,1}$ from p_1 to receiver node p_2 in the second hop as follows:

$$P_{p,1} = \frac{E_{p,1}}{T_{t,v}} = \eta^2 P_s\sum_{i=1}^{N_r}\frac{\left|h_{s,i}\right|^2\left|h_{i,p_1}\right|^2}{d_{s,i}^m d_{i,p_1}^m}. \quad (4)$$

According to the abovementioned analysis, let $P_{p,j-1}$ denote jth ($j \geq 2$) hop transmission power, where the signal is transmitted from p_{j-1} to p_j node (p_0 is the source node); we can obtain

$$P_{p,j-1} = \eta^{2(j-1)}P_s\prod_{k=2}^{j}\left(\sum_{i=1}^{N_r}\frac{\left|h_{p_{k-2},i}\right|^2\left|h_{i,p_{k-1}}\right|^2}{d_{p_{k-2},i}^m d_{i,p_{k-1}}^m}\right), \quad (5)$$

where $|h_{p_{k-2},i}|$, $|h_{i,p_{k-1}}|$ denote the channel gains from p_{k-2} to its relay i and from its relay i to p_{k-1}, respectively, and $d_{p_{k-2},i}^m, d_{i,p_{k-1}}^m$ denote the distance from p_{k-2} to its relay i and from its relay i to p_{k-1}, respectively. So, we can obtain the signal-to-noise ratio (SNR) γ_j at the receiver node p_j as follows: $\gamma_j = P_{p,j-1}|h_{p_{j-1},p_j}|^2/(\sigma_{p_{j-1},p_j}^2 d_{p_{j-1},p_j}^m)$, where σ_{p_{j-1},p_j}^2 denotes the variance of additive white Gaussian noise at receiver p_j. Given a targeted throughput R_0, if we find the maximum value of l for that $\log_2(1+\gamma_l) \geq R_0$ holds, we can derive that the value of l is the largest number of hops supported by the CFP scheme. Therefore, we can derive

$$\begin{aligned} &2(l-1)\log_2\eta \\ &+\sum_{k=2}^{l}\log_2\left(\sum_{i=1}^{N_r}\frac{\left|h_{p_{k-2},i}\right|^2\left|h_{i,p_{k-1}}\right|^2}{d_{p_{k-2},i}^m d_{i,p_{k-1}}^m}\right) + \log_2\frac{\left|h_{p_{l-1},p_l}\right|^2}{d_{p_{l-1},p_l}^m\sigma_{p_{l-1},p_l}^2} \\ &\geq \log_2\frac{2^{R_0}-1}{P_s}. \end{aligned} \quad (6)$$

In formula (6), for calculability, we replace the exponential random variables $|h_{p_{k-2},i}|^2$, $|h_{i,p_{k-1}}|^2$, and $|h_{p_{l-1},p_l}|^2$with their mean values λ_r, λ_f, and λ_d, respectively. Since we have assumed that the channel gain is circular symmetric complex Gaussian random variables with zero mean and unit variance, we get $\lambda_r = \lambda_f = \lambda_d = 1$. Furthermore, we assume that $d_{p_{k-2},i}d_{i,p_{k-1}}$ is constant and equal to d_c. Also, d_{p_{l-1},p_l}, which is the distance from p_{l-1} to p_l, is set to be constant value d_d. Consequently, we can obtain

$$(l-1)\log_2\left(\eta^2\frac{N_r}{d_c^m}\right) \geq \log_2\left(\frac{2^{R_0}-1}{P_s}d_d^m\sigma^2\right), \quad (7)$$

where we let σ_{p_{l-1},p_l}^2 be equal to constant value σ^2. In formula (7), if $(2^{R_0}-1)d_d^m\sigma^2 > P_s$, that is, $\log_2(P_s/(d_d^m\sigma^2)+1) < R_0$, the signal cannot be transmitted from the source node to the next hop for satisfying the targeted throughput R_0. Therefore, for multihop transmission, it is required that $(2^{R_0}-1)d_d^m\sigma^2 < P_s$. Furthermore, we consider that, in a routing path (such as in Figure 1), the transmission power of node p_{i+1} is lower than that of node p_i because the transmission power of node p_{i+1} is charged from the node p_i. So, it is also required that $\eta^2(N_r/d_c^m) < 1$. Note that we do not consider the case of $\eta^2(N_r/d_c^m) \geq 1$ because, in this case, the transmission power of node p_{i+1} is greater than that of node p_i so that the information can be transmitted all the time. Accordingly, we can derive the largest number of hops $L_{\max}^{\text{cfp}}$ supported by the CFP scheme as follows:

$$L_{\max}^{\text{cfp}} = 1 + \left\lfloor\frac{\log_2\left(\left(\left(2^{R_0}-1\right)/P_s\right)d_d^m\sigma^2\right)}{\log_2\left(\eta^2\left(N_r/d_c^m\right)\right)}\right\rfloor, \quad (8)$$

where $\lfloor . \rfloor$ denotes the round down function. From formula (8), we can find that the largest number of hops is affected by the parameters P_s, η, α, N_r, and d_c. In simulation, we will give the detailed analysis for these parameters.

5.2. For CFIP Scheme. Unlike CFP scheme, in CFIP scheme, a relay i not only harvests the power, but also decodes the information from the transmitter. So, we have $\alpha_i \neq 0$. If we consider that the transmitter is the source node, a relay i harvests the power $E'_{r,i}$ as follows:

$$E'_{r,i} = \frac{\eta(1-\alpha)P_s|h_{s,i}|^2 T_{t,v}}{d_{s,i}^m}. \quad (9)$$

Note here that, for ease of analysis, we let α_i be constant and equal to α. Let $P'_{p,j-1}$ denote jth ($j \geq 2$) hop transmission power, where the signal is transmitted from p_{j-1} to p_j through multiple relays; we can obtain

$$P'_{p,j-1} = (\eta(1-\alpha))^{2(j-1)} P_s \times \prod_{k=2}^{j}\left(\sum_{i=1}^{N'_r}\frac{|h_{p_{k-2},i}|^2 |h_{i,p_{k-1}}|^2}{d_{p_{k-2},i}^m d_{i,p_{k-1}}^m}\right), \quad (10)$$

where N'_r is the average number of relay nodes in cooperative set. Note that, because only the relay, which can decode the information successfully, becomes one member of the cooperative set in CFIP scheme, we have $N'_r \leq N_r$. Let γ'_j denote SNR at the receiver node p_j; we can derive

$$\gamma'_j = \eta(1-\alpha)\sum_{i=1}^{N'_r}\frac{P'_{p,j-1}|h_{p_{j-1},i}|^2 |h_{i,p_j}|^2}{d_{p_{j-1},i}^m d_{i,p_j}^m \sigma_{i,p_j}^2}, \quad (11)$$

where σ_{i,p_j}^2 is the variance of additive white Gaussian noise at receiver p_j. Similarly to the above analysis for CFP, while requiring $\log_2(1+\gamma'_l) \geq R_0$, we can obtain

$$(l-1)\log_2\left((\eta(1-\alpha))^2\frac{N'_r}{d_c^m}\right) \geq \log_2\left(\frac{(2^{R_0}-1)d_c^m\sigma^2}{\eta(1-\alpha)N'_r P_s}\right), \quad (12)$$

where we let σ_{i,p_j}^2 be equal to constant value σ^2. In formula (12), we have $(\eta(1-\alpha))^2(N'_r/d_c^m) < 1$ because the transmission power of node p_{i+1} is lower than that of node p_i. Furthermore, for multihop transmission, we have $(2^{R_0}-1)d_c^m\sigma^2/\eta(1-\alpha)N'_r P_s < 1$; that is, $\log_2(\eta(1-\alpha)P_s N'_r/d_c^m\sigma^2+1) > R_0$. Otherwise, the information cannot be transmitted from the source to p_1. Consequently, the largest number of hops $L_{\max}^{\text{cfip}}$ supported by the CFIP scheme can be given as follows:

$$L_{\max}^{\text{cfip}} = 1 + \left\lfloor\frac{\log_2\left((2^{R_0}-1)d_c^m\sigma^2/\eta(1-\alpha)N'_r P_s\right)}{\log_2\left(\eta^2(1-\alpha)^2(N'_r/d_c^m)\right)}\right\rfloor. \quad (13)$$

5.3. For DFIP Scheme. Unlike CFP and CFIP schemes, in DFIP scheme, the receiver harvests the power and decodes the information from the transmitter directly without relay cooperation. Therefore, if we consider that the transmitter is the source node, the receiver p_1 harvests the power $E_{d,1}$ as follows:

$$E_{d,1} = \frac{\eta(1-\alpha)P_s|h_{s,1}|^2 T_{t,v}}{d_{s,1}^m}, \quad (14)$$

where $h_{s,1}$ is channel gain from the source node to receiver p_1 and $d_{s,1}$ is the distance from the source to p_1. Then, the node p_1 transmits the information to the next hop node p_2 using the power $P_{d,1} = E_{d,1}/T_{t,v}$. Let $P_{d,j-1}$ denote jth ($j \geq 2$) hop transmission power, where the signal is transmitted from p_{j-1} to p_j; we can obtain

$$P_{d,j-1} = (\eta(1-\alpha))^{(j-1)} P_s \prod_{k=2}^{j}\left(\frac{|h_{p_{k-2},k-1}|^2}{d_{p_{k-2},k-1}^m}\right). \quad (15)$$

So, we can obtain SNR γ_j^d at receiver p_j as $\gamma_j^d = P_{d,j-1}|h_{p_{j-1},p_j}|^2/(\sigma_{p_{j-1},p_j}^2 d_{p_{j-1},p_j}^m)$. Similarly to the above analysis for CFP and CFIP, while requiring $\log_2(1+\gamma_l^d) \geq R_0$, we can obtain

$$(l-1)\log_2\left(\frac{\eta(1-\alpha)}{d_d^m}\right) \geq \log_2\left(\frac{2^{R_0}-1}{P_s}d_d^m\sigma^2\right). \quad (16)$$

Accordingly, we can derive the largest number of hops $L_{\max}^{\text{dfip}}$ supported by the DFIP scheme as follows:

$$L_{\max}^{\text{dfip}} = 1 + \left\lfloor\frac{\log_2\left(\left((2^{R_0}-1)/P_s\right)d_d^m\sigma^2\right)}{\log_2\left(\eta(1-\alpha)/d_d^m\right)}\right\rfloor. \quad (17)$$

In formula (17), we have $\eta(1-\alpha)/d_d^m < 1$ because the transmission power of node p_{i+1} is lower than that of node p_i. For multihop transmission, it is required that $(2^{R_0}-1)d_d^m\sigma^2 < P_s$. Otherwise, the information cannot be transmitted from the source to p_1.

6. Numerical Results and Analysis

In this section, we perform computer simulations to validate our theory analysis and gain insights into the multihop capabilities of the proposed CFP, CFIP, and DFIP schemes. Also, we need to observe whether the values of $L_{\max}^{\text{cfp}}$ scheme are larger than the values of $L_{\max}^{\text{cfip}}$ and $L_{\max}^{\text{dfip}}$ with the given targeted throughput R_0 under the effect of different network parameters. In the following simulations, we set $\sigma^2 = -70$ dB, $R_0 = 2$ bits/sec/Hz, and $m = 2.7$ (which corresponds to an urban cellular network environment [5]) and give the numerical results considering the effect of parameters P_s, η, α, N_r, and d_c. For simplicity, we assume that $d_d = d_c$ and $N'_r = N_r$.

First, we observe the numerical results about the values of $L_{\max}^{\text{cfp}}$, $L_{\max}^{\text{cfip}}$, and $L_{\max}^{\text{dfip}}$ affected by the values of cooperative transmission distance (CTD) d_c that denotes the product of two distances from sender to relay and from relay to receiver, which are shown in Figure 2. From Figure 2, we can find that the analytical results are practically consistent with the simulation results, which verifies the effectiveness of our theory analytical model. Note that, for CFIP scheme, the

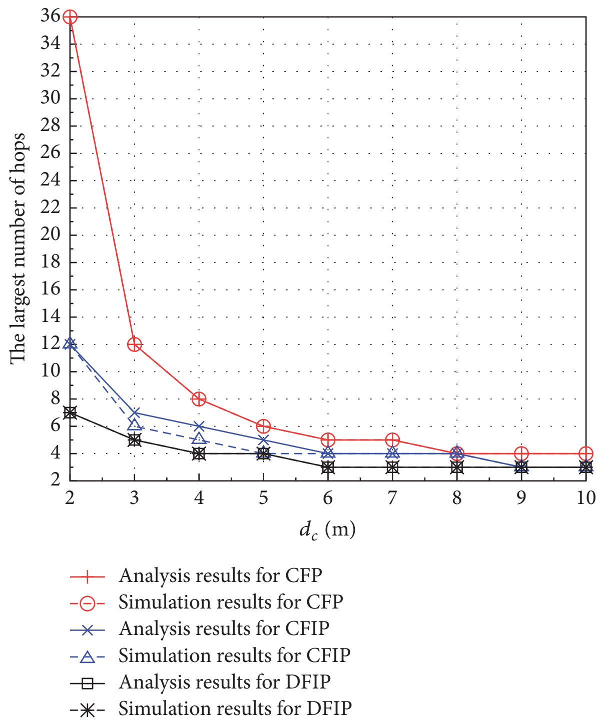

FIGURE 2: Analytical versus simulation results with different CTD, where $P_s = 2$ W, $\eta = 0.6$, $\alpha = 0.5$, and $N_r = 10$.

simulation results are not in full agreement with the analysis results because N_r' is smaller than N_r in practice. Besides, we can also observe the following:

(1) The CTD has an important impact on the largest number of transmission hops; it is because, with the increase of d_c, both the harvested energy and received signal strength at sender node of the next hop decrease due to the larger path loss. Consequently, the achievable number of transmission hops is reduced with no sufficient energy, especially for the larger values of d_c.

(2) The multihop capability of CFP is better than CFIP and DFIP; it is because, in CFP scheme, multiple relays forward only the power (not the information) towards the receiver cooperatively so that the sender node of the next hop can obtain more energy to support the larger transmission hops, especially for the smaller values of d_c.

(3) The multihop capability of CFP and CFIP is better than DFIP since they use multiple relays to harvest energy. It can be observed in (8) and (13) that the values of $L_{\max}^{\text{cfp}}$ and $L_{\max}^{\text{cfip}}$ increase with the increase of N_r and N_r'. Furthermore, if we consider the fact that the value of N_r is larger than N_r', this can further the multihop capability of CFP compared to CFIP.

As the analytical results agree well with the simulation results, for the purpose of conciseness, in the following, we will plot the simulation results for different parameters η, α, N_r, and P_s when $d_c = 3$ m. But for $d_c = 8$ m and $d_c = 15$ m, we only give analytical results. Next, we investigate the impacts of two parameters η and α on the largest number of transmission hops, respectively, with considering the effect of CTD d_c. From Figures 3 and 4, we can obtain the following:

(1) For the small values of d_c, by increasing the value of η or reducing the value of α, the largest number of transmission hops can be improved. But if increasing the value of d_c, the largest number of transmission hops cannot obtain obvious improvement through changing the values of η or α. In (8), (13), and (17), because η and α have a limited range of values ($\in [0, 1]$), while d_c has a larger value, the values of $L_{\max}^{\text{cfp}}$, $L_{\max}^{\text{cfip}}$, and $L_{\max}^{\text{dfip}}$ cannot be affected obviously by changing the values of η or α.

(2) The multihop capability of CFP is better than CFIP and DFIP, especially for the smaller values of d_c, which is because multiple relays forward only the power cooperatively. For example, from Figure 3, we can observe the impact of parameter η on results and obtain that when $d_c = 3$ m, the average largest number of hops of CFP, CFIP, and DFIP is 18, 8, and 4.9, respectively; when $d_c = 8$ m, the average values are 4.5, 3.8, and 2.9, respectively; when $d_c = 15$ m, the average values are 3.1, 2.8, and 2, respectively.

Finally, let us study the impacts of two parameters N_r and P_s on the multihop capability, respectively. In Figure 5, we give the simulation results for the effect of parameter N_r with considering the effect of d_c. Considering that $X < 1$ of fractional denominator $\log_2 X$ in (8) and (13), we consider a larger range of values of N_r and vary the values of N_r for different values of d_c (i.e., let the maximum value of N_r be equal to $\lfloor d_c^{2.7} \rfloor$). In order to facilitate drawing, a numerical value x on the x-axis of Figure 5 only denotes an exponential quantity, and in fact, the corresponding value of N_r is equal to $\lfloor d_c^{x} \rfloor$. From Figure 5, we can see the following:

(1) With the increase of N_r, the multihop capabilities of three schemes are improved correspondingly, and the multihop capability of CFP is better than CFIP and DFIP. Specifically, when $d_c = 3$ m, the average largest number of hops of CFP, CFIP, and DFIP is 10.3, 6.3, and 5, respectively; when $d_c = 8$ m, the average values are 7.5, 5.1, and 3, respectively; when $d_c = 15$ m, the average values are 6, 4.6, and 2, respectively.

(2) Although, with the increase of d_c, the multihop capabilities of three schemes are weakened correspondingly, the degree of weakening is depressed compared with the case of considering the effect of parameters η or α. For example, considering that the value of d_c changes from 3 m to 15 m in CFP scheme, the degree of weakening is $(10.3 - 6)/10.3 \times 100\% = 27.18\%$ when considering the effect of parameter N_r, but the value is $(18 - 3.1)/18 \times 100\% = 82.78\%$ when considering the effect of parameter η. Therefore, increasing the number N_r of relay nodes can improve the multihop capabilities effectively when the CTD d_c

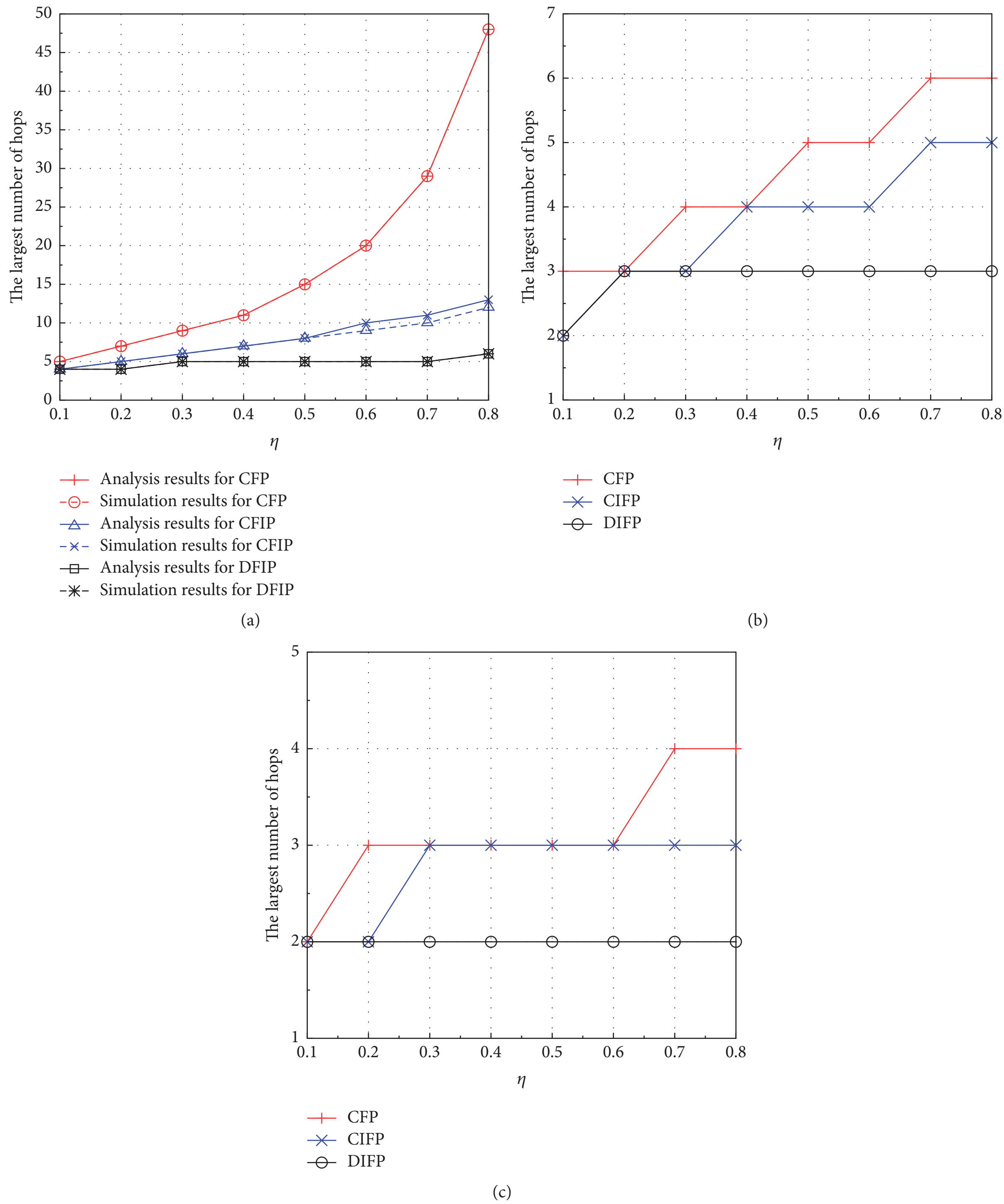

Figure 3: Numerical results for the impact of parameter η on the multihop capability with different values of CTD: (a) $d_c = 3$ m, (b) $d_c = 8$ m, and (c) $d_c = 15$ m, where $P_s = 2$ W, $\alpha = 0.5$, and $N_r = 20$.

increases; it is because N_r has a larger range value and can affect the values of $L_{\max}^{\text{cfp}}$, $L_{\max}^{\text{cfip}}$, and $L_{\max}^{\text{dfip}}$ in (8), (13), and (17), obviously.

In Figure 6, we investigate the impact of parameter P_s on the numerical results with considering the effect of d_c. In order to compare the results with parameter N_r in a larger range of values, we also let a numerical value x on the x-axis of Figure 6 only denote an exponential quantity, where the corresponding value of P_s is equal to $\lfloor d_c^x \rfloor$. From Figure 6, we can observe the following:

(1) With the increase of P_s, the multihop capabilities of the three schemes are improved correspondingly,

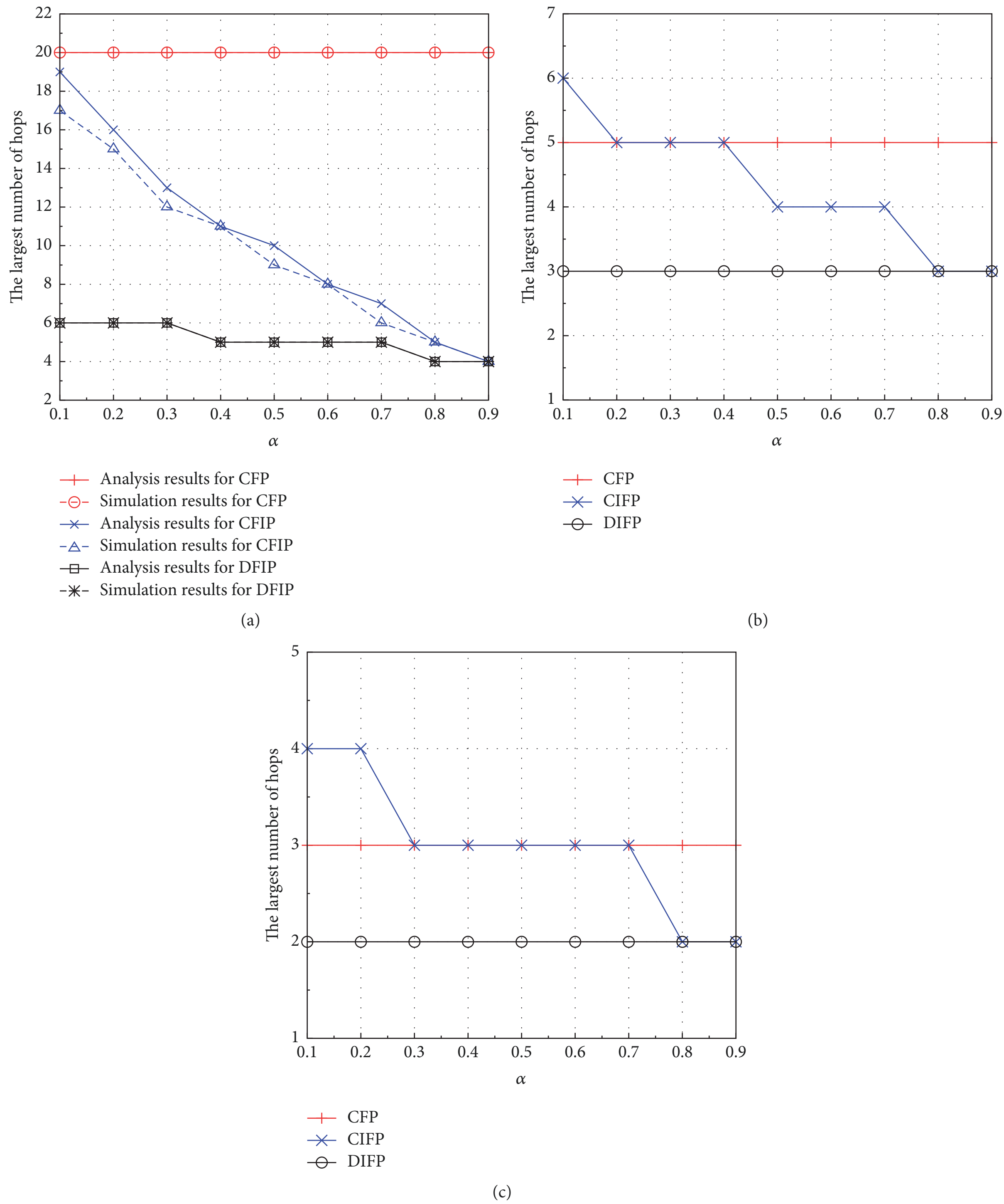

Figure 4: Numerical results for the impact of parameter α on the multihop capability with different values of CTD: (a) $d_c = 3$ m, (b) $d_c = 8$ m (c), and $d_c = 15$ m, where $P_s = 2$ W, $\eta = 0.6$, and $N_r = 20$.

and the multihop capability of CFP is better than CFIP and DFIP. However, with the increase of d_c, the multihop capabilities of the three schemes are weakened correspondingly. Specifically, when $d_c = 3$ m, the average largest number of hops of CFP, CFIP, and DFIP is 21.4, 9.9, and 5.5, respectively; when $d_c = 8$ m, the average values are 5.9, 4.8, and 3.4, respectively; when $d_c = 15$ m, the average values are 4.1, 3.6, and 2.8, respectively.

(2) Compared with the case of considering the effect of parameter N_r, the degree of weakening is much

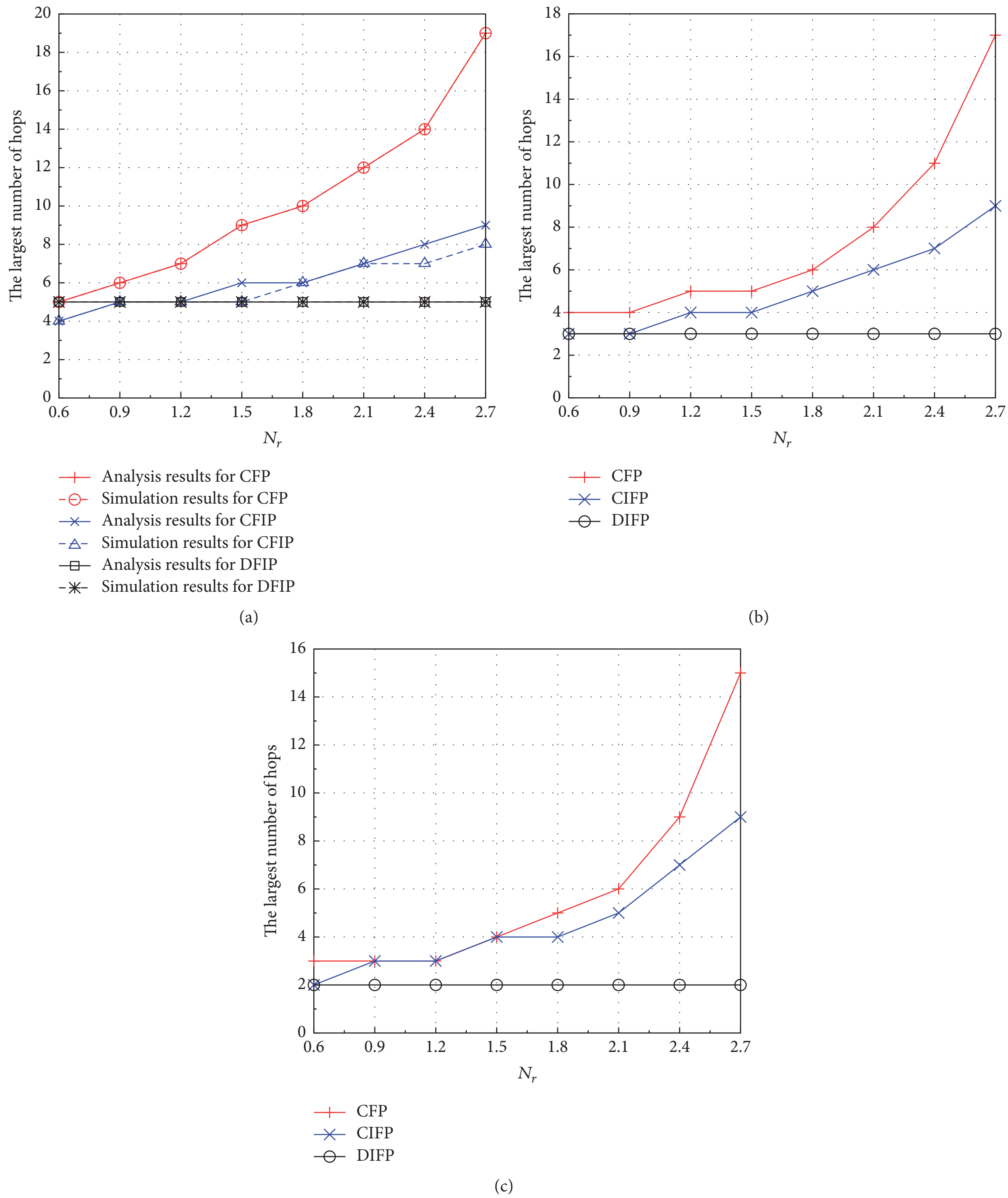

Figure 5: Numerical results for the impact of parameter N_r on the multihop capability with different values of CTD: (a) $d_c = 3$ m, (b) $d_c = 8$ m, and (c) $d_c = 15$ m, where $P_s = 2$ W, $\eta = 0.6$, and $\alpha = 0.5$.

worse. For example, considering that the value of d_c changes from 3 m to 15 m in CFP scheme, the degree of weakening is $(21.4-4.1)/21.4\times100\% = 80.8\%$ when considering the effect of parameter P_s, but the value of the degree of weakening is $(10.3-6)/10.3\times100\% = 27.18\%$ when considering the effect of parameter N_r. Therefore, for improving the multihop capabilities, increasing the value of parameter N_r is more effective.

According to the abovementioned results and analysis, we can obtain the important conclusions as follows: (1) the multihop capability of CFP is better than CFIP and DFIP,

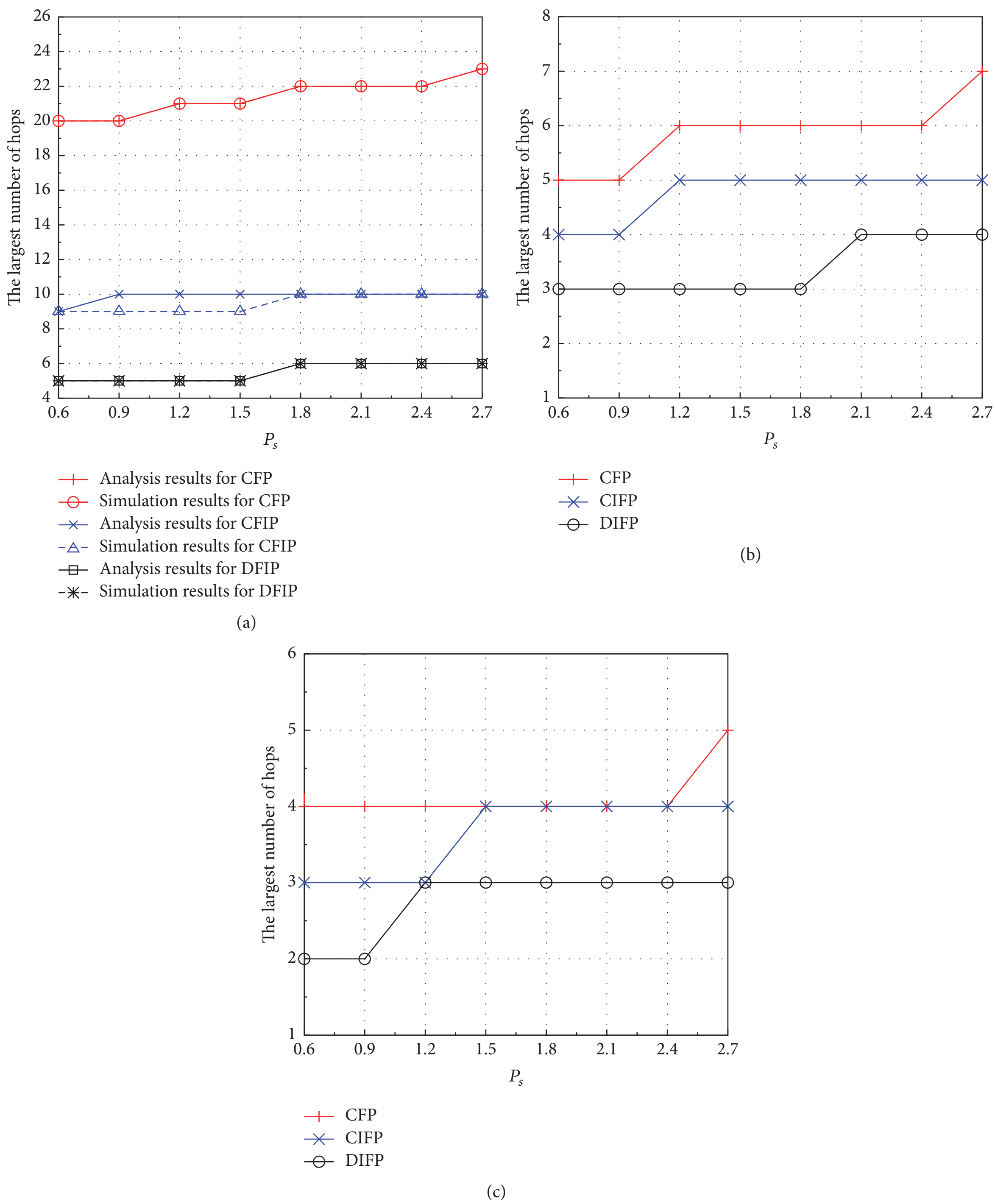

FIGURE 6: Numerical results for the impact of parameter P_s on the multihop capability with different values of CTD: (a) $d_c = 3$ m, (b) $d_c = 8$ m, and (c) $d_c = 15$ m, where $\eta = 0.6$, $\alpha = 0.5$, and $N_r = 20$.

(2) all of the parameters P_s, η, α, N_r, and d_c can affect the multihop capability of the three schemes, where the parameter d_c can produce an important effect, and (3) for improving the multihop capability, it is best effective to increase the value of parameter N_r. Of course, we can further improve the multihop capability by simultaneously adjusting the values of parameters P_s, η, and α.

7. Conclusions

In this paper, we study SWIPT in multihop wireless cooperative networks, where the multihop capabilities of CFP, CFIP, and DFIP schemes, are analyzed. For this purpose, we construct analysis model to investigate the multihop capabilities of CFP, CFIP, and DFIP schemes, respectively.

Finally, numerical results show that the multihop capability of CFP is better than CFIP and DFIP, and for improving the multihop capabilities, it is best effective to increase the average number of relay nodes in cooperative set.

Through the analysis model proposed in this paper, the appropriate values of related parameters, that is, initial energy of source node, the number of relay nodes, the energy harvesting efficiency coefficient, and power splitting coefficient, can be set to achieve the given transmission hops from source to destination.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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