Outage-Performance for Power Beacon-Assisted Wireless Powered Cooperative Communications

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***Abstract*—To move towards next generation of green communications, we study a power beacon (PB) assisted wireless powered cooperative communication network (PB-WPCCN). We propose a new system model with a source and a number of candidate relays that are not directly connected to the power grid. System harvests energy from RF broadcast signals radiated from PB, and works cooperatively to successful deliver information to the target device through relay network. System executes this process in two stages relay selection decode then forward, namely, (2SRS-DF). First of all, select a group of relay candidates who can successfully decode the received signal from the source. Secondly, choose the best relay with the capability to forward the decoded message to the destination from the group which successfully decodes the source signal in the first stage. The closed-form expression for the average outage probability and the throughput of the proposed system is derived and presented. We validate the theoretical results by numerical simulations. The impact of position and number of relay terminals along with time allocation parameters are also studied.**

***Index Terms*—Cooperative-networks, relay selection, energy harvesting, power-beacon.**

I. Introduction

Radio frequency (RF) energy harvesting methods have recently attracted significant attention and become another method for assisting the next-generation wireless networks [1]. Radio frequency (RF) signals radiated by ambient sources can be considered as a fertile new source for energy harvesting, as these ambient transmitters support the wireless devices to harvest the energy from RF signals for their information and transmission functionality. Although, these wireless devices capture small amounts of available energy from the environment and convert it to usable electrical energy, some significant advances in wireless power technologies [2] and the existing of ambient energy like (e.g.TV towers and cellular signals), have greatly improved the viability and sustainability of wireless energy scavenging in real wireless applications [3]. Furthermore, in cooperative networks where the relay terminals are presented between the source node and the destination node, more power can be harvested due to the reduced of fading in small distances system topologies.

Recently, Wireless-Powered Cooperative Communications Networks (WPCCNs) are becoming promising study area due to their potential to perform green wireless communication and important amount of study papers that focused on this area were proposed e.g., [4]–[6]. Most of these researches generally are based on three-node model compose from source, relay and destination terminals. In the context that source or relay nodes have no fixed energy supply. Therefore, they have to harvest energy from the RF signal broadcasted from ambient or dedicated sources and use it to forward the information to the destination.

These WPCCN schemes are investigated based on decode-and-forward relay (DFR), amplify-and forward relay (AFR) in [4]. All the communication between source and destination nodes is predictable to be forwarded through the relay terminal, distributed relay selection algorithms were considered and it shows that single-relay selection (AFR) protocol is outage optimal under local channel state knowledge. In [5] relay selection with outdated channel state information in cooperative (DFR) protocol was analysed. A three node cooperative network was proposed in [6], where single relay node has to switch between energy harvesting and information forwarding to the destination where the source is the only available radio frequency (RF) signal transmitter.

Trade-offs between energy harvesting and data decoding become a recent topic and have been addressed in many research papers e.g., [7]–[9], where the design of simultaneous wireless information and power transfer (SWIPT) is proposed. Unlike WPCN, data and energy are sent in the same direction over the downlink. The focus of [10] and [11] is about full-duplex communication in which the access point (AP) has two antennas one for receiving the information from the users over the uplink and allocates whereas the second antenna to broadcast energy toward the users over the downlink at the same time. The authors in [4] defined opportunistic relaying protocols for half duplex dual-hop communication where outage probability was analyzed for opportunistic (DFR) relaying and opportunistic (AFR) relaying significantly.

The authors in [12] examined harvest-then transmit (HTT) protocol. First of all the users harvest energy from single antenna access point over the downlink then with this energy the users transmit their data over the uplink using TDMA. The study in [13] extended the two nodes (HTT) system model to three nodes harvest-then-cooperate (HTC) protocol for single and multi-relay scenario. In which both, the source and the relay harvest energy from the AP in the first time slot then cooperatively work to forward the sources information to the destination.

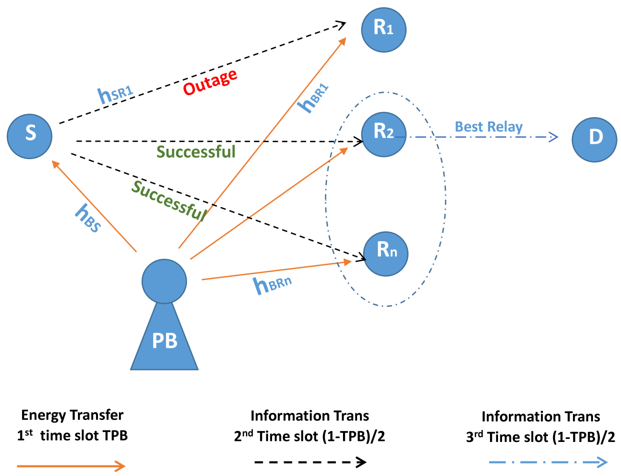

Fig. 1. Power Beacon assist Wireless-powered cooperative communication network (PB-WPCCN) with two stage relay selection decode-and-forward (2SRS-DF).

In all previous papers, only the AP is proposed as energy source. In [14], the authors introduced power beacon as dedicated power source in the network, using the stochastic geometry theory, outage probability was studied regarding density and the transmit power. In [15], PB-based WET and the user equipment can jointly harvest the energy from both AP and PB, optimal resource allocation is analysed for cooperative and non-cooperative cases over the downlink and the information is transmitted over the uplink.

To the best of our knowledge, there is no study considers four nodes cooperative network system model. We propose a dedicated power beacon assisted WPCCN (PB-WPCCN) with relay candidates where both source and relay set have no embedded energy equipping, they need to harvest energy from the RF broadcast signals radiated from PB. Furthermore, a new two stage relay selection namely (2SRS-DF) cooperative network is proposed and confirm with simulation. In the first stage selection, the relay candidates who can correctly decode the received signal from the source are selected for the second round selection; secondly choose the best relay among these relays with the best channel condition capability to forward message to the destination.

This paper is structured as follows. In section II we describe the system model, the channel model and the parameters consider to perform the proposed scenario. In section III the outage probability exact closed form expression for considered schemes are derived, over Rayleigh fading channels. The throughput performance analysis for the considered model is also given. Numerical results and discussions are present in section IV to confirm the analytical findings for different number of relays. The impact of other system parameters, such as time portion, number and position of relays on the throughput performance are also investigated. Finally, Section V is Conclusion.

II. System Model

We consider power beacon PB assist a source S, a destination D and N relay candidates system model where $(N > 1)$, as depicted in Fig. 1. Assuming the S-D link experience high path loss, so no direct link between S and D is available, and all communications are carried out through intermediate relay candidates. Each terminal have a single received or transmit antenna and works in half-duplex mode. We consider that the source and N relay candidates have no fixed energy supply so they depend on the energy broadcasted by the power beacon for charging their battery. The source delivers information to the relays by using the energy harvested from the power beacon, while all relay candidates receive the transmitted signal from the source.

It is proposed that the best relay candidate denoted R_s is selected after two stages relay selection decode and forward namely (2SRS-DF) includes two rounds of selections. First of all, we select the group of relay candidates denoted (Ω_j), whose their SNR satisfy predefined threshold γ_0 and can successfully decode the received signal from the source. Secondly, the destination will choose a best relay candidate from the group (Ω_j) which guarantee the best $Rj - D$ link, to forward the information to D using max$\{\gamma_{RjD}\}$ over Rayleigh fading channel.

In the follow-up, we denote P_{PB} as the transmit power at the power beacon in the first time slot. The set of relays R_i while $i \in \{1, 2, 3, ...n\}$. Let denote $h_{AZ} \sim CN\left(0, \sigma^2_{AZ}\right)$ the channel coefficient from A to Z with A and Z could be replaced by first terminals letter $\{B, R, S, D\}$. $h_{AZ} = \left|\widehat{h}_{AZ}\right|^2$ follows the exponential distribution, i.e. $h_{AZ} \sim EXP\left(\sigma^2_{AZ}\right)$ and the channel gains remain constant in the same time block like in [16].

As described in flow-chart Fig. 2, the different stages transmission in Power Beacon assist WPCCNs protocol are conducted as follow:

- In the first time slot τ, the power beacon broadcasts RF energy signal to both, the source and N relay candidates. The source and the relays terminals have no embedded energy supply so they need to harvest the energy from the RF signal broadcasted by PB. Like [12], we assume that the transmit power at power beacon P_{PB} is sufficient large and no power noise was consider at the source S. The harvested energy at the source and the relay candidates can be expressed as:

$$E_s = \eta\tau P_{PB} h^2_{BS} \quad (1)$$

$$E_{R_i} = \eta\tau P_{PB} h^2_{BR_i} \quad (2)$$

where $0 < \eta < 1$ denotes the energy harvesting conversion efficiency factor, and τ is the duration time of

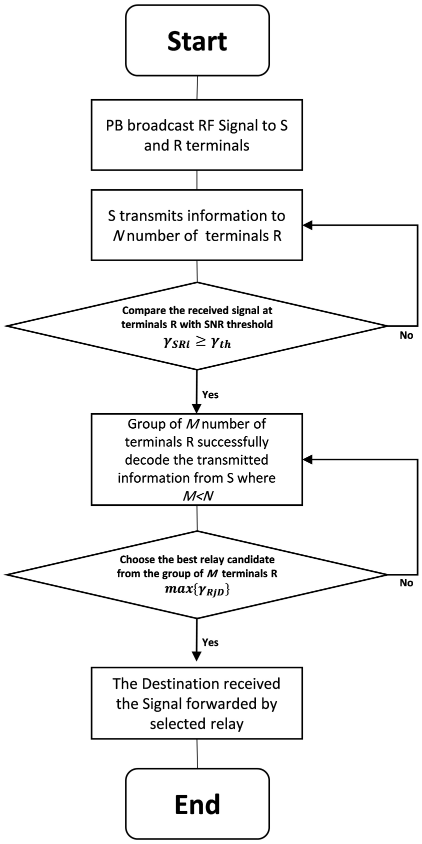

Fig. 2. Flow-chart of two stages relay selection decode and forward process (2SRS-DF)

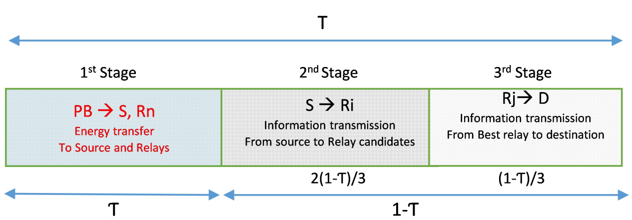

Fig. 3. Diagram of time allocation for energy harvesting and information transmitting.

the power beacon broadcasting the RF signal. We denote h_{BS}^2, $h_{BR_i}^2$ are channels gain between PB and source S, PB and relays R_i respectively.

- In the 2nd stage, the source delivers information to the relays by using the energy harvested in the 1st stage, while all relay candidates receive the transmitted signal from the source. Based on time allocation between energy harvesting and information decoding shown in Fig. 3, we can express the transmit power at the source:

$$P_S = \frac{E_s}{2(1-\tau)/3} = \frac{3\eta\tau P_{PB} h_{BS}^2}{2(1-\tau)} \quad (3)$$

- In the 3rd stage, the best relay forwards the information to the destination using the energy harvested in the 1st stage, the transmit power at relay terminals are given:

$$P_R = \frac{E_{R_i}}{(1-\tau)/3} = \frac{3\eta\tau P_{PB} h_{BR_i}^2}{1-\tau} \quad (4)$$

We consider that both the source and the relay candidates exhaust their energy in the information transmission like [13]. Note that power allocation can also be applied to further improve the system performance. However, this topic is out of the scope of this work to consider power control. This work could be considered as lower bound scenarios.

III. Outage Probability,Thrughput Analysis

A. Outage Probability

We assume each relay candidate sends its state information and the amount of the harvested energy in the 1st stage to the destination. Then, the destination first compares the received SNR over S-R link with a predefined SNR threshold γ_0 for each relay candidate. Therefore, there are $M(0 <= M <= N)$ relay candidates are chosen for next round. In this work, we define this selected group as Ω_j satisfy $\gamma_{SRi} >= \gamma_0$

$$\Omega_j = \left\{ j : \gamma_{SRi} \geqslant 2^{2R} - 1 \right\} \quad (5)$$

where R is the fixed transmission rate at the source.

Next, the destination will choose the a best relay candidate by using $\max\{\gamma_{RjD}\}$, We can define the received SNR from the source to the relay candidates link and from the relays to the destination link respectively:

$$\gamma_{SRi} = \frac{P_s h_{SRi}^2}{\sigma_{SR}^2} \quad (6)$$

$$\gamma_{RjD} = \frac{P_R h_{RjD}^2}{\sigma_{RD}^2} \quad (7)$$

where $0 <= j <= M$, and γ_{RjD} is the received SNR form the link j_{th} relay candidates to the destination. We define Ω_j^M the j_{th} decoding selected group of M possible successfully decoding groups from N relay candidates. We can easily compute the outage probability as [4]:

$$P^{out} = \sum_{M=0}^{N} \sum_{j=1}^{\binom{N}{M}} Pr\left(outage \mid \Omega_j^M\right) Pr\left(\Omega_j^M\right) \quad (8)$$

where $Pr\left(\Omega_j^M\right)$ is the probability of the decoding group is selected:

$$Pr\left(\Omega_j^M\right) = \prod_{i\in\Omega_j} Pr\left\{\gamma_{SRi} \geqslant 2^{2R} - 1\right\} \prod_{i\notin\Omega_j} Pr\left\{\gamma_{RiD} \leqslant 2^{2R} - 1\right\} \quad (9)$$

$Pr\left(outage \mid \Omega_j^M\right)$ is the probability that the selected decoding group is in outage where:

$$Pr\left(outage \mid \Omega_j^M\right) = \prod_{i\in\Omega_j} Pr\left\{\gamma_{SRi} < 2^{2R} - 1\right\} \quad (10)$$

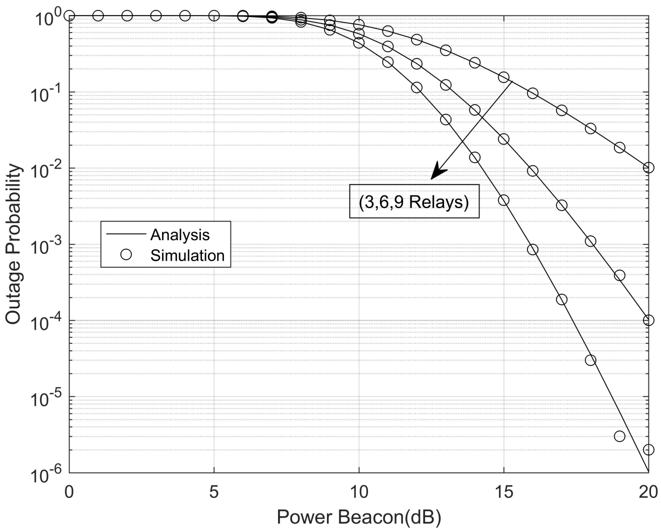

Fig. 4. Outage Probability Vs Power of Power Beacon P_{PB} scheme

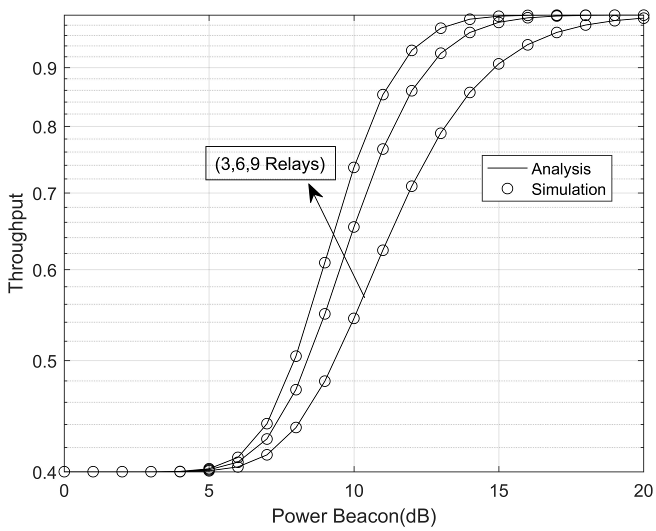

Fig. 5. Throughput Vs Power of Power Beacon P_{PB} RF Signal

Note that (10) states that if the relay which have the strongest R-D link best relay fails, then all the other j^{th} relay candidates in $Pr\left(\Omega_j^M\right)$ fails. With replacement of eqs. (9) and (10) in (8) we get a 2-SRS final outage-probability formula:

$$P_{out} = \prod_{j=1}^{N} \left[1 - exp\left\{ -\frac{2^{2R}-1}{2\eta P_{PB}} \left(\frac{1}{h_{SRi}} + \frac{1}{h_{RiD}} \right) \right\} \right] \tag{11}$$

B. The System Throughput

In the proposed system model, we can simply calculate the throughput by the following expression [1]:

$$Throughput = R\left(1 - P_{out}\right)\left(1 - \tau\right) \tag{12}$$

where R is the transmission rate and $(1-\tau)$ is the time allocated for the source and the relays to deliver the information to the destination D.

IV. NUMERICAL RESULTS

Channels in wireless power transfer are determine not only the reception reliability but also the attenuation of RF source transmission power, which is fundamentally different from conventional cooperative networks. This difference makes the distances between node terminals more important. To track the effect of node distance we follow some latest papers [13], [17], [18]. We consider that the relay terminals are placed between the source and the destination which are all on one straightness so $d_{SR} = d_{SD} - d_{RD}$. The power beacon is located at the same distance from the source and from the relay set. Without loss of generality, we consider the distance between the source and the destination $d_{SD} = 10m$, and the distance between the power beacon and the harvested nodes $d_{BS} = d_{BRi} = 3m$, for all simulation. We let the time block $T = 1$, the noise power $N = -80dBm$, the energy harvesting efficiency $\eta = 0.6$ and the transmission rate of the source $R = 1$ by bit per channel.

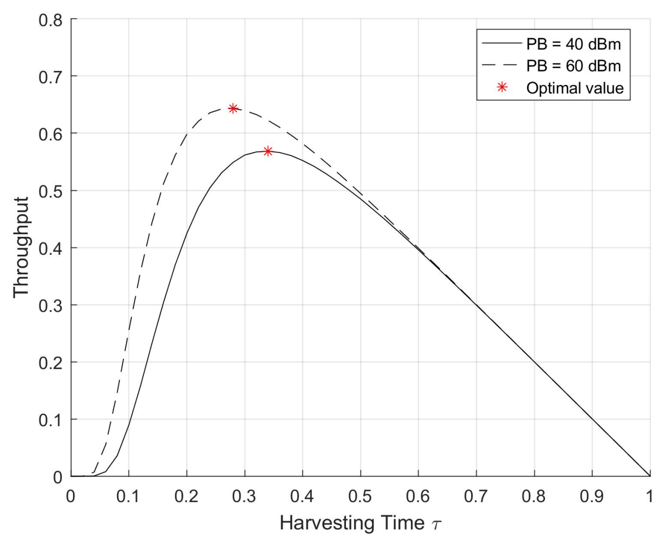

Fig. 6. Throughput Vs Time of Power Beacon Transmission τ ,for P_{PB} = 40 , dBm P_{PB}= 60 dBm and d_{SR} = 3 m .

In Fig. 4 and Fig. 5, we plot the system outage probability and throughput respectively for different number of relay candidates, where $d_{SR} = 3m$ and $\tau = \frac{2}{5}T$. From the plot, we can see that analytical curves of outage probability and throughput are exactly match with the simulation results, and this validates our theoretical expressions derivation for the proposed four nodes two stages relay selection decode and forward system model. In the high power beacon RF signal broadcasts regime, the throughput get saturated. And this due to less harvesting time is required, which gives more time to source and relay set to deliver information to the destination. This is clearly shown in Fig. 6 where the optimal harvesting time for $40dBm$ power beacon is $\tau = 0.35$, and this parameter

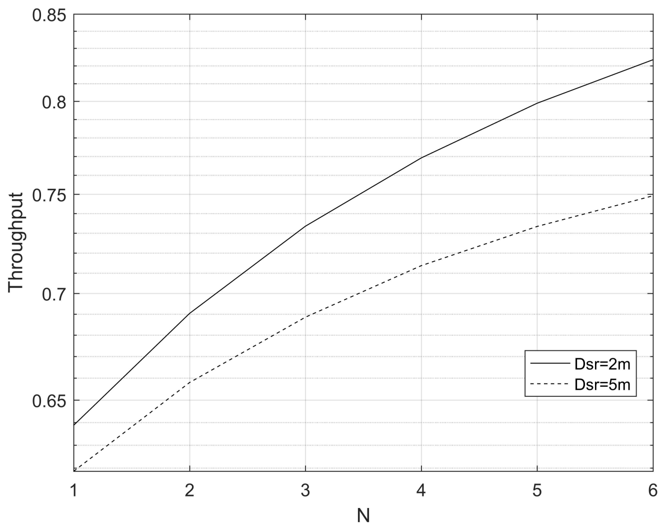

Fig. 7. Throughput Vs number of relay where P_{PB} = 25 dBm ,Optimal τ and with two relay position d_{SR} = 2 m and d_{SR} = 5 m .

reduces to $\tau = 0.25$ when power beacon broadcasts $60dBm$ of RF signal. Moreover, the system throughput performance is proportional to the number of relay set. When more relay candidates are available, better throughput performance we achieved, similar as shown in Fig. 7 when the number of relay candidates increases. This can be explained by the high system diversity between the source and the destination when there are more relay terminals taking place.

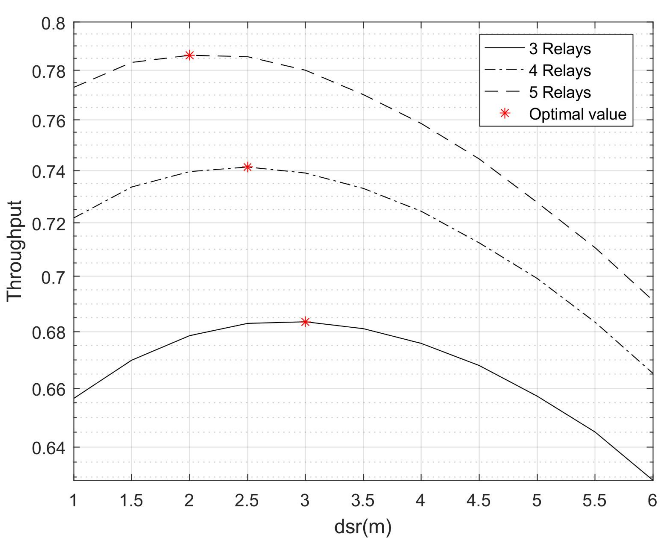

Fig. 8. Throughput Vs Relay position when P_{PB}= 45 dBm and Optimal τ .

In Fig. 8, we illustrate the effect of relay terminals position on the throughput performance. The distance between the source to the relay set d_{SR} are plotted versus the throughput performance for different number of relay candidates for $PB = 45dBm$ and optimal τ. We can see from the curves that the system throughput performs better when the relay candidates are deployed relatively close to the source. Furthermore, the optimal d_{SR} value is reduced more when the number of relay set increases and network throughput performance improves. This is because the $S-Ri$ link is more important in term of outage compared to the $Rj - D$ link. Based on this, if the source fails to deliver the information, then the whole system fails. On the contrary, there is high diversity in the $Rj - D$ link due to the presence of multiple relays which could harvest and forward the information to the destination successfully.

V. Conclusion

In the proposed system model, power beacon-assisted wireless-powered cooperative communications networks (PB-WPCCNs) is studied. We derived the exact closed-form expression of outage probability over Rayleigh fading channel where the best relay is selected with two stage relay selection decode-and-forward, namely (2SRS-DF). We provided numerical simulation which excellent coincided and validated our proposed theoretical models. The effect of time allocation and the number of relay candidates as well as position is also studied.

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References

[1] O. Ozel, K. Tutuncuoglu, J. Yang, S. Ulukus, and A. Yener, "Transmission with energy harvesting nodes in fading wireless channels: Optimal policies," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 8, pp. 1732–1743, 2011.

[2] V. Liu, A. Parks, V. Talla, S. Gollakota, D. Wetherall, and J. R. Smith, "Ambient backscatter: wireless communication out of thin air," in *ACM SIGCOMM Computer Communication Review*, vol. 43, no. 4. ACM, 2013, pp. 39–50.

[3] J. R. Smith, *Wirelessly Powered Sensor Networks and Computational RFID*. Springer Science & Business Media, 2013.

[4] A. Bletsas, H. Shin, and M. Z. Win, "Cooperative communications with outage-optimal opportunistic relaying," *IEEE Transactions on Wireless Communications*, vol. 6, no. 9, 2007.

[5] D. S. Michalopoulos, H. A. Suraweera, G. K. Karagiannidis, and R. Schober, "Amplify-and-forward relay selection with outdated channel estimates," *IEEE Transactions on Communications*, vol. 60, no. 5, pp. 1278–1290, 2012.

[6] I. Krikidis, S. Timotheou, and S. Sasaki, "Rf energy transfer for cooperative networks: Data relaying or energy harvesting?" *IEEE Communications letters*, vol. 16, no. 11, pp. 1772–1775, 2012.

[7] I. Krikidis, "Simultaneous information and energy transfer in large-scale networks with/without relaying," *IEEE Transactions on Communications*, vol. 62, no. 3, pp. 900–912, 2014.

[8] Z. Ding and H. V. Poor, "Multi-user swipt cooperative networks: Is the max–min criterion still diversity-optimal?" *IEEE Transactions on Wireless Communications*, vol. 15, no. 1, pp. 553–567, 2016.

[9] D. Wang, H. Yu, H. Lei, T. Li, J. Zhang, G. Pan, and Y. Chen, "Outage of relay simultaneous wireless information and power transfer with gsc and finite storage in nakagami-m fading," *IET Communications*, vol. 11, no. 12, pp. 1871–1881, 2017.

[10] H. Ju and R. Zhang, "Optimal resource allocation in full-duplex wireless-powered communication network," *IEEE Transactions on Communications*, vol. 62, no. 10, pp. 3528–3540, 2014.

[11] X. Kang, C. K. Ho, and S. Sun, "Full-duplex wireless-powered communication network with energy causality," *IEEE Transactions on Wireless Communications*, vol. 14, no. 10, pp. 5539–5551, 2015.

[12] H. Ju and R. Zhang, "Throughput maximization in wireless powered communication networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 1, pp. 418–428, 2014.

[13] H. Chen, Y. Li, J. L. Rebelatto, B. F. Uchôa Filho, and B. Vucetic, "Harvest-then-cooperate: Wireless-powered cooperative communications." *IEEE Trans. Signal Processing*, vol. 63, no. 7, pp. 1700–1711, 2015.

[14] K. Huang and V. K. Lau, "Enabling wireless power transfer in cellular networks: Architecture, modeling and deployment," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 902–912, 2014.

[15] Y. Ma, H. Chen, Z. Lin, Y. Li, and B. Vucetic, "Distributed and optimal resource allocation for power beacon-assisted wireless-powered communications," *IEEE Transactions on Communications*, vol. 63, no. 10, pp. 3569–3583, 2015.

[16] M. K. Simon and M.-S. Alouini, *Digital communication over fading channels*. John Wiley & Sons, 2005, vol. 95.

[17] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Transactions on Wireless Communications*, vol. 12, no. 7, pp. 3622–3636, 2013.

[18] Z. Ding, S. M. Perlaza, I. Esnaola, and H. V. Poor, "Power allocation strategies in energy harvesting wireless cooperative networks," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 846–860, 2014.