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Review of Simultaneous Wireless Information and Power Transfer in Wireless Sensor Networks

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Abstract

Recently, there has been an increase in research on wireless sensor networks (WSNs) because they are easy to deploy in applications such as internet-of-things (IoT) and body area networks. However, WSNs have constraints in terms of power, quality-of-service (QoS), computation, and others. To overcome the power constraint issues, wireless energy harvesting has been introduced into WSNs, the application of which has been the focus of many studies. Additionally, to improve system performance in terms of achievable rate, cooperative networks are also being explored in WSNs. We present a review on current research in the area of energy harvesting in WSNs, specifically on the application of simultaneous wireless information and power transfer (SWIPT) in a cooperative sensor network. In addition, we discuss possible future extensions of SWIPT and cooperative networks in WSNs.

Index Terms: Cooperative sensor networks, Energy harvesting (EH), Simultaneous wireless information and power transfer (SWIPT), Wireless power transfer (WPT), Wireless sensor network (WSN)

I. INTRODUCTION

A wireless sensor network (WSN) is a wireless network of spatially distributed, autonomous devices acting as sensors to monitor and record physical or environmental conditions [1-3]. Humidity, pressure, temperature, power-line voltages, flow, and vital body functions are some of the physical or environmental conditions monitored and recorded in WSNs [1-3]. A WSN consists of wireless sensor nodes, a gateway, and a wired central system/station as shown in Fig. 1 [1]. The wireless sensor nodes perform the monitoring and recording functions, whereas the gateway supports communication between the central system and the sensor nodes [1, 2]. The central system performs the task of organizing the data collected by the wireless sensor nodes [1-3]. The number of sensor nodes within the network may range from hundreds to thousands. A WSN has one of five basic topologies: bus, star, cluster tree, circular, and mesh, as shown in Fig. 2 [1-4]. Each sensor node within the network is furnished with an antenna, microcontroller, interfacing electric circuit, and an energy source [1-3]. The sensor node may possess a single antenna or multiple antennas; hence, the sensor nodes may operate in a single-input-single-output (SISO) mode, single-input-multiple-output (SIMO) mode, multiple-input-single-output (MISO) mode, or multiple-input-multiple-output (MIMO) mode [1, 5]. An example of the influence of spatial diversity introduced by antenna configuration is seen in the plot presented in Fig. 3, which shows the uplink (UL) and downlink (DL) trade-off curve for a point-to-point (P2P) communication between a base station (BS) and an energy harvesting (EH) mobile user (MS). As seen from the plot, with an increase in the number of antennas at the MS, the

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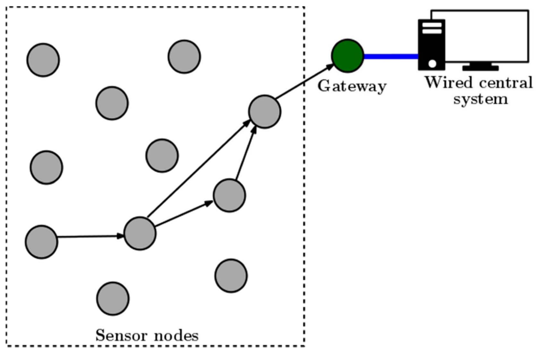

Fig. 1. Wireless sensor network consisting of sensor nodes, gateway, and wired central systems.

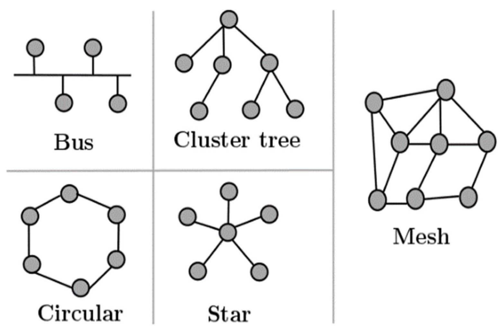

Fig. 2. Wireless sensor network topologies.

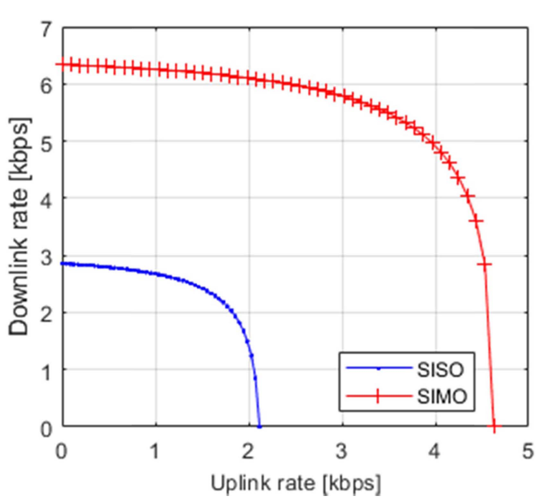

Fig. 3. DL and UL rate trade-off curves for a SISO and SIMO P2P communication system.

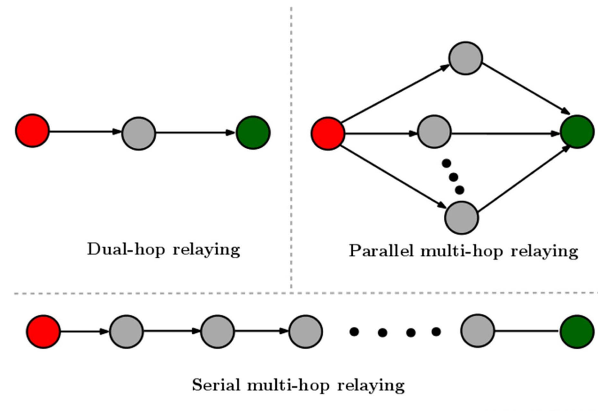

Fig. 4. Types of relaying configuration.

system's achievable rate for UL and DL increases, which is due to the diversity gain introduced by the antennas. In addition, the sensor nodes in the network may have identical configuration and hardware, or different configuration and hardware; such WSNs are known as a homogeneous WSN and a heterogeneous WSN, respectively [1]. Communication between a sensor node and the gateway is facilitated by routing algorithms [1, 4]. Routing can be achieved by either a direct communication between a sensor node and the gateway or by relaying radio frequency (RF) signals through other sensor nodes to the gateway [1, 4, 6].

Routing through relaying can be achieved through three basic cooperative communication methods. These methods are the amplify-and-forward (AF) method, the decode-and-forward (DF) method, and the compress-and-forward (CF) method [7]. An AF relay node (i.e., sensor node), amplifies the signal it receives and forwards the amplified signal to the next node in the relaying steps or to the destination node [7], [8]. A DF relay node decodes the information it receives and retransmits the decoded information signal to the next node or to a destination node [8]. If a relay compresses the information it receives before transferring it to another node or to the destination node, it is operating in the CF mode [9]. Routing through relaying of the information signal from a source node through a single relay sensor node before reaching the destination node is called a dual-hop relay system [10]. However, when the information signal from the source node is transferred through multiple sensor nodes before reaching the destination node, it is known as a multi-hop relay system [10]. Multi-hop relaying may have a serial or parallel configuration to support communication between the source and destination nodes [10]. Fig. 4 shows the dual-hop, parallel multi-hop, and serial multi-hop configurations. Relays not only facilitate information transfer but may also increase a communication system's throughput [11, 12]. A major disadvantage of relaying involves its parasitic nature when it comes to the resources of the relay node [13, 14]. For relay purposes, the relay node would use its own computational power and power supply to process the information being relayed and to support all relaying activities, respectively. This means that, apart from supporting its own duties (i.e., monitoring or detection), each sensor node acting as a relay has the additional task of supporting relay activities. However, wireless sensor nodes have major issues concerning constraints such as power, computation capabilities, sensor network lifespan, and quality-of-service (QoS) [13]. To reduce the strain on a sensor node during relaying, EH from received RF signal at each relay sensor node has been a focus of current research on WSN power constraints [15, 16].

Energy harvesting is the process of scavenging energy from an external energy source [15, 16]. Traditional sources of energy include batteries, wind power, solar power, thermal power, and vibrational power [17]. These energy sources are typically unstable, being affected by unpredictable factors such as weather [17]. A more stable, available, and reliable source of energy to facilitate relaying is the RF energy signal [17]. The process of transferring RF signals and harvesting energy from the signal is known as wireless power transfer (WPT) [15, 16]. WPT is also referred to as wireless energy transfer (WET) and is the transmission of electrical energy from a power source to an electrical load (i.e., here the electrical load refers to the relay sensor node) without the use of an interconnecting wire [15-17]. WPT can be achieved in two ways: by "near-field" electromagnetic (EM) induction (e.g., inductive coupling and capacity coupling) for short distances (i.e., less than a meter) or by "far-field" EM radiation (e.g., microwaves and lasers) for longer distances [18, 19]. There are two basic techniques used in accomplishing WPT, simultaneous wireless information and power transfer (SWIPT) and wireless powered communication networks (WPCN) techniques, as shown in Fig. 5. SWIPT is the concurrent transfer of both a wireless information signal and a wireless energy signal to a wireless communication node [15, 16, 20].

Fig. 6 shows three SWIPT antenna architectures currently being considered by researchers. These antenna configurations are the separate receiver architecture (i.e., the information and energy receivers are equipped with separate antennas), the co-located receiver architecture (i.e., the information receiver and energy receiver circuits are separate, but share the same antenna), and the integrated receiver architecture (i.e., the information receiver and energy receiver circuit are integrated via a rectifier) [19]. The time switching (TS) scheme and the power splitting (PS) scheme are two ways to achieve the SWIPT technique under the co-located antenna configuration that is being extensively studied [17, 21, 22]. Dividing the signal reception time interval for a node into two time intervals is the TS scheme. The first time period is

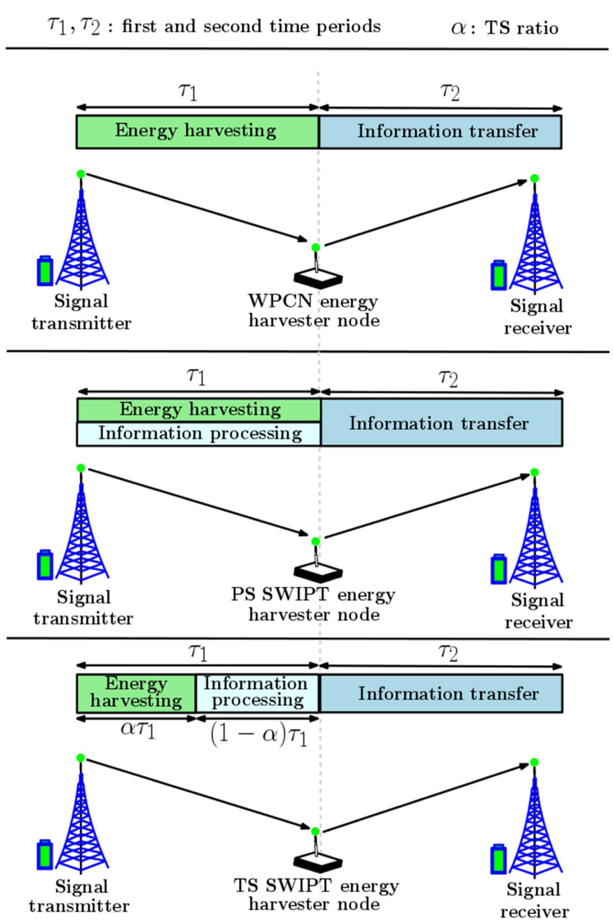

Fig. 5. WPT schemes.

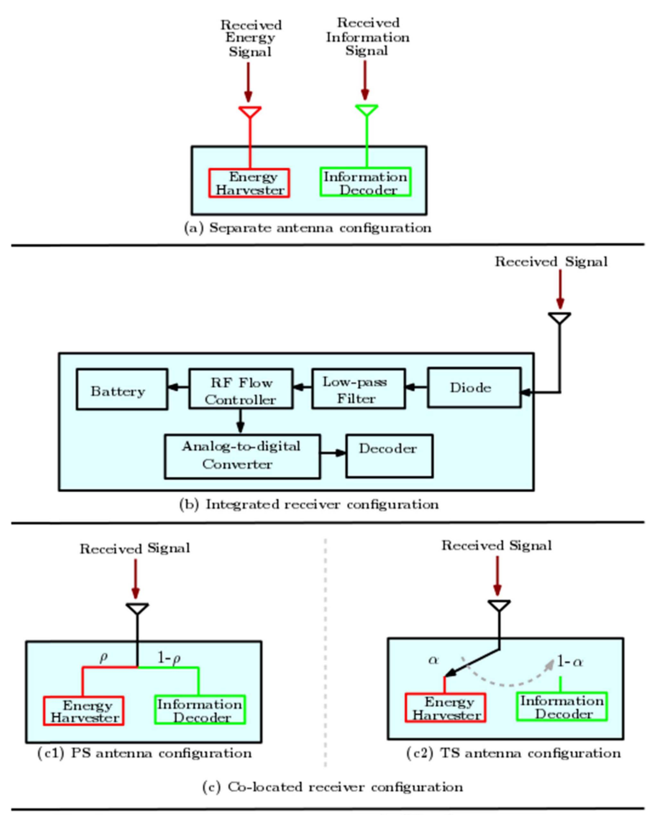

Fig. 6. SWIPT antenna configurations.

used to harvest energy from the received RF signal, while the second time slot is used for information decoding at a node [15, 16, 20, 23]. With the PS scheme, a PS ratio is used to divide the RF signal into two, one portion for energy harvesting and the other portion for information processing [17, 21, 22]. WPCN involves the transfer of RF energy signals to a node to power the node's information transfer or processing [24, 25]. WPCN receives energy signals to facilitate its function in a successive manner, but SWIPT receives information and energy at the same time, and this is the major difference between the two techniques. An example that shows the impact of relays on improving system performance in terms of achievable rate is presented in Fig. 7, which shows a plot of system rate against transmit power for different numbers of EH relay nodes supporting communication between a source node and a destination node. The system model used in Fig. 7 consists of a single antenna source node communicating with a single antenna destination node through SWIPT EH parallel multi-hop single antenna relay nodes. The system rate is maximized based on the joint optimization of the PS ratio at each relay node. From Fig. 7, we can observe that as the number of relay nodes increases, the achievable rate at the destination node also increases. The influence in improving system rate through spatial diversity introduced by relays is better observed in Fig. 8 which is a plot of rate against an increasing number of relay nodes for the same system mode. Hence, our previous statement on relay nodes improving system throughput is affirmed.

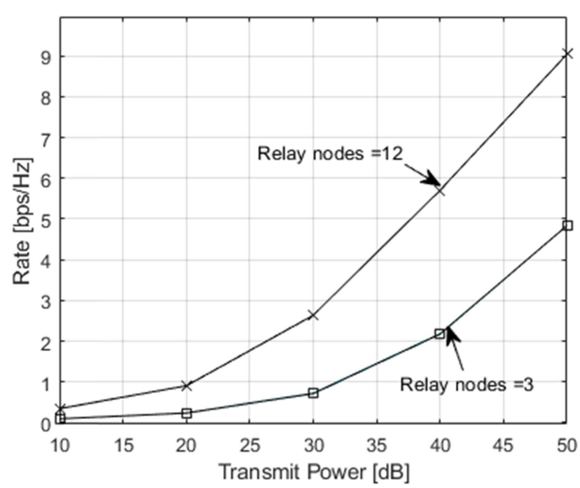

Fig. 7. Rate against source transmit power.

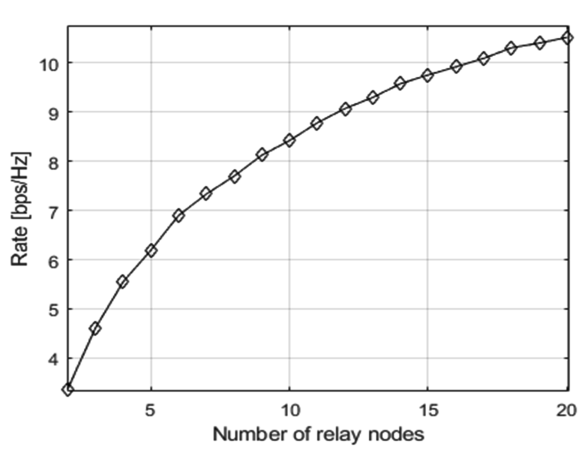

Fig. 8. Rate against increasing number of relay nodes.

The comprehensive review presented in this paper focuses on current work in the area of SWIPT in WSN. We further focus on cooperative sensor network operations (i.e., routing in WSN using relaying). The papers reviewed in this work consider AF and DF relaying configurations for both dual-hop and multi-hop techniques. Initial discussions on two recent review papers are first discussed. Next, we discuss current papers in the area of SWIPT cooperative sensor network systems. The discussion on current reviews in WPT WSN is presented in Section II. Reviewed papers on dual-hop SWIPT relaying and multi-hop SWIPT relaying are presented in Sections III and IV, respectively. Finally, we discuss possible future extensions of SWIPT cooperative sensor networks and present our concluding remarks in Sections V and VI, respectively.

II. CURRENT REVIEWS ON WPT

In this section, we discuss two published reviews in the area of SWIPT. The authors of [26] review and discuss current progress in signal theory and the design of wireless information and power transfer (WIPT). A summary of each review and its focus is presented in Table 1. The review in [26] approached its discussion from the hardware point of view. It also discusses the trade-off between the wireless transmission of information and power. A review and discussion on cooperative relaying and SWIPT from the application point of view are discussed in [27]. We will first discuss the review presented in [26], followed by the review in [27]. The authors of [26] discuss the evolution of WPT, the advantages of implementing WPT, and the application of WPT in future technologies in their introduction. Within the introduction, the authors discuss the challenges of implementing WIPT, which include the range of power transfer, the power transfer efficiency, the ability to support both line-of-sight (LOS) and non-LOS (NLOS) WPT, how to support EH in mobile users, safety and health issues, and the seamless integration of WPT into wireless communication [26]. The authors also categorize WIPT into three groups; namely, SWIPT, WPCN, and wireless powered backscatter communication (WPBC) [26]. Finally, they discuss the importance of modeling EH in their introductory section [26]. The authors then proceed to discuss analytical models for the antenna and rec-

Table 1. Summary of review papers

Reference	Summary	Conclusions
Clerckx et al. [26]	a) A general overview of WIPT, its challenges, and its technologies. Also covered is the importance of modeling energy harvesters. b) Analytical models of rectenna designs are discussed considering the rectenna behavior, antenna modeling, linear and nonlinear diode models, comparison of rectenna models, and future considerations for rectenna modeling. c) Single-user WIPT and multi-user WIPT models, antenna designs, and rate-energy regions are also discussed.	a) More research into the design and modeling of WIPT rectenna and system models is essential for the realization of WIPT systems.
Hossain et al. [27]	a) An overview of cooperative networks, EH and SWIPT in terms of their types, characteristics, advantages, and disadvantages. b) A discussion on the roles of SWIPT and cooperative relay networks is presented and extended to the role of SWIPT and cooperative relays in other network models, such as WSN. c) Current issues, challenges, and future research extensions are also discussed.	a) The authors consider research extensions of SWIPT and cooperative relays in other network models, application of machine learning in SWIPT and cooperative relaying systems, and their implementation in other technologies such as unmanned aerial vehicles.

tifier (i.e., the rectenna) [26]. The discussion on the rectenna consists of a review on rectenna behavior with the aid of circuit design and plots on input power versus harvested power, antenna modeling, linear and nonlinear models, nonlinear saturation diode models, comparison of the rectenna models, and future works on rectennas. Their discussions on the rectenna involve the use of mathematical and schematic models and plots (e.g., harvested energy vs. supplied power) to explain their models [26].

Regarding future extensions, the authors discuss the development of a combined model for the diode and saturation nonlinear models, alternative or enhanced diode and saturation models, considerations for other sources of nonlinearity in the energy harvester, considerations for nonlinearities at the receiver side as well as the transmitter side, and modeling of the energy harvester for different frequency bands such as millimeter-wave bands [26]. Single-user WIPT and Multi-user WIPT are also discussed [26]. Concerning the two user types of WIPT, the authors discuss the signal and system model for each user type. They then talk about the receiver architectures for the user types. Finally, they discuss rate-energy trade-off region and problem formulations, considering and categorizing reviews based on diode linear models, diode nonlinear models, and nonlinear saturation models [26]. Under each rate-energy trade-off review, the authors further categorize the reviews into single-subband (i.e., one band used in the communication), multi-subband (i.e., multiple subbands are used in the communication), and multi-antenna transmission [26]. The authors also discuss future extensions for single-user and multi-user system architectures. For the single-user architecture, the authors' stated extensions into the design of channel-state-information (CSI) acquisition for nonlinear models are very important in WIPT [26]. Considerations for practical and efficient modulations and waveforms for SWIPT in nonlinear models should also be considered for future research [26]. Error-correction code design, optimal input distribution for diode and saturation nonlinear models, and secure SWIPT communication are also future considerations for WIPT [26].

The authors of [27] discuss SWIPT in relay systems and SWIPT future challenges. First, they give an overview of relays, relay networks, and WPT—specifically SWIPT. The authors also discuss the types of relay and configurations, i.e., AF, DF, CF, dual-hop, and multiple-hop relays, in their introductory section. Regarding EH, the authors discuss the two types of energy storage schemes, i.e., harvest-and-use, and harvest-store-and-use [27]. With harvest-and-use, the energy harvested is immediately used, while with harvest-store-and-use, the harvested energy is stored and used when the harvested energy becomes greater than the consumption energy [27]. Finally, within the introduction, the authors give an overview of SWIPT design, schemes (i.e., TS and PS), and the benefits of implementing SWIPT systems in cooperative relay systems [27]. Next, the authors of [27] discuss cooperative relay systems using the dual-hop technique; this section of the paper includes reviews on relay selection methods. This section of the review also considers only AF and DF relay configurations. In the review of SWIPT dual-hop relays, the authors first discuss the ideal (i.e., EH and information decoding (ID) occurring in different time slots for half-duplex (HD) communication), TS (i.e., the time slot for the first phase in the HD mode is split between EH and ID), and PS (i.e., during the first phase, the received signal is split into two for EH and ID) relaying protocols [27]. The reviewers then discuss resource allocation and secrecy issues within SWIPT cooperative relay systems. Afterward, the reviewers discuss the role of SWIPT with cooperative relays in 5G networks. The authors then delve into the application of SWIPT and cooperative relaying in other network configurations such as WSN, MIMO cooperative networks, wireless body area network (WBAN), a cognitive radio network (CRN), and the internet-of-things (IoT) [27]. Finally, future extensions of SWIPT cooperative schemes in the previously mentioned network areas are discussed [27]. The reviews

Table 2. Summary of dual-hop SWIPT research

Reference	Summary	Contribution
Chen et al. [28]	a) A dual-hop DF sensor network with destination and relay sensor nodes are equipped with SWIPT architecture for EH. b) Energy efficiency maximization based on either optimizing the TS ratio or the PS ratio.	a) Considered a bidirectional relaying system model. b) TS and PS protocols for energy efficiency optimization.
Lu et al. [29]	a) An AF dual-hop two-way relaying system with a SWIPT EH relay node. b) Sum-rate maximization is considered based on the joint optimization of the power allocation and PS ratio	a) The authors consider a two-way AF dual-hop system and sum-rate maximization.
Liu et al. [30]	a) A DF SWIPT dual-hop MIMO relay system is considered. b) Two protocols of PS ratio application are considered: individual PS ratio calculation or cluster PS ratio calculation. c) The end-to-end throughput for the system model is optimized by considering the PS ratio protocol used.	a) Authors introduce the PS clustering protocol. b) End-to-end throughput maximization by jointly optimizing the PS ratio and power allocation at the relay nodes.
Malik et al. [31]	a) Authors consider a system model were a FD DF relaying in a MIMO node structure. b) The achievable rate is optimized by jointly optimizing the power allocation for the source and relays as well as the PS ratios at the relay node.	a) Authors introduce a FD DF relaying in a MIMO dual-hop system. b) Authors propose rate-maximization algorithms based on a uniform or non-uniform PS ratio determination.

presented in the next section are based on current research results in SWIPT research.

III. SWIPT DUAL-HOP RELAY SYSTEMS IN WSN

In this section, we discuss four research papers which studied SWIPT implementation in a dual-hop cooperative network. The reviews cover both AF and DF cooperative techniques as well as SISO antenna configuration, SIMO to MISO antenna configuration (i.e., source-to-relay, and relay-to-destination), and MIMO antenna configuration. In addition, the reviews consider significate issues pertaining to SWIPT, such as energy efficiency and rate maximization. Table 2 contains a summary of the papers reviewed. A study on "Energy efficiency analysis of bidirectional wireless information and power transfer for cooperative sensor networks" [28], considers a simple DF sensor network where the base station (BS) communicates with a sensor node (SN) via a relaying sensor node (RN). The SN and RN nodes harvest energy to recharge their batteries. Each node in their system model is equipped with a single antenna and operates in the HD mode [28]. The simulation results are on energy efficiency vs TS ratio, energy efficiency vs PS ratio, and energy efficiency vs transmit power for the TS scheme [28]. The contributions of [28] are the introduction of a bidirectional communication protocol and energy efficiency optimization. The article entitled "OFDM based SWIPT for two-way AF relay network" [29] considers a system configuration in which a source node communicates with a destination node facilitated by a SWIPT AF relay node. Each node has a single antenna and operates in both the HD mode and the orthogonal frequency division multiplexing (OFDM) mode [29]. With the two-way protocol, during the first phase, the two source nodes transmit information to the relay node [29]. The relay harvests energy and processes information (i.e., amplifying and forwarding) by grouping the subcarrier signals for the two functions [29]. The authors of [29] jointly optimized the subcarrier grouping, pairing, and power allocation to maximize the sum-rate for the system. The simulation results in [29] compare their optimal proposed algorithm to two conventional benchmark algorithms (i.e., the power average allocation (PAA), and the subcarrier allocation based (SAB) algorithms) [29]. In [29], the optimal proposed protocol outperforms the benchmark protocols.

The article entitled "Joint resource allocation in SWIPT-based Multi-antenna decode-and-forward relay network" [30] considers a system model consisting of a single antenna source node communicating with a single antenna destination through a multi-antenna SWIPT relay node as there is no direct link between the source and destination [30]. The system model is based on the DF relaying technique. The authors' goal was to maximize the end-to-end achievable rate based on the joint optimization of the transmit power and PS ratio on each relay antenna. The work reported in [30] presents two approaches for optimizing the end-to-end achievable rate, i.e., the antenna PS optimization approach (PS) and the antenna cluster PS optimization approach (AC). The antenna clustering approach is proposed to reduce the strain on the hardware implementation of the PS scheme. The authors propose two clustering algorithms; namely, the optimal antenna clustering algorithm (optimal AC) and the greedy antenna clustering algorithm (greedy AC) [30]. Optimal AC involves the use of an exhaustive line search method to find the power allocation. This exponentially increases the computational strain on the relay node resource (i.e., the relay's computational capabilities); hence the greedy AC algorithm is proposed [30]. For the simulation results, the authors compare the PS approach, optimal AC approach, greedy AC approach, and TS ratio approach (i.e., the TS ratio approach is considered as a benchmark) [30]. As expected, the PS, optimal AC, and greedy AC outperform the TS approach. The order of performance in descending order is as follows: the PS approach, the optimal AC approach, the greedy AC approach, and then the TS approach. The work presented in [30] not only optimizes the PS ratios for each antenna but introduces a new antenna configuration of clustering to ease the SWIPT hardware design and implementation for a multi-antenna node.

Finally, we discuss a paper on full-duplex (FD) application in a SWIPT relay system. The article entitled "Optimal transmission using a self-sustaining relay in full-duplex MIMO system" considers a MIMO antenna configuration at each node [31]. While the source and destination operate in HD mode, the SWIPT relay node not only possesses multiple antennas but operates in both the FD and DF modes [31]. The optimization problem considered by the authors of [31] is the achievable rate maximization problem based on the joint optimization of the PS and the source and relay precoders [31]. The system achievable rate problem with the joint optimization of the PS ratio and precoders is found to be a semi-definite programming problem. Hence, the maximization problem is converted to a dual problem. The authors then find optimal solutions for non-uniform (i.e., different PS ratios for each antenna at the relay nodes) and uniform PS (i.e., the same PS ratio for the antennas at the relay node) ratios for the FD SWIPT relay node [31]. From the dual problem solution, the authors propose a primal-dual algorithm which solves the rate optimization problem [31]. Simulation results on the algorithm convergence, effects of residual self-interference, effect of changing distance between source and relay, and the performance of the proposed scheme compared to other SWIPT schemes are presented [31]. The non-uniform PS ratio schemes outperform the uniform scheme as expected [31]. In addition, the non-uniform scheme also outperforms existing SWIPT schemes [31]. From the reviews of dual-hop relay systems, we conclude that there is interesting research being pursued in this area. Further research on system models and other scenarios in dual-hop relay systems can be considered. Secrecy issues can also be investigated for dual-hop system models, different antenna configurations, and SWIPT implementation techniques. FD SWIPT implementation at each node, interference cancellation, residual interference scenarios, and multi-user systems can be considered as extensions of the dual-hop system to improve system performance.

IV. SWIPT MULTI-HOP RELAY SYSTEMS IN WSN

In this section, we discuss SWIPT parallel and serial multi-hop relay system models in subsections IV.A and IV.B, respectively. We discuss four papers in the area of serial multi-hop relays and three papers in the area of parallel relays. The papers reviewed in this section cover the performance matrices of outage probability and system achievable rate. In addition, we present a summary of the reviewed multi-hop papers in Tables 3 and 4 for the parallel and serial configurations, respectively

A. Parallel Multi-Hop Relays

The article entitled "Simultaneous wireless information and power transfer for cooperative networks with battery," a source node communicates with a destination node facilitated by parallel AF multiple relays [17]. There is also a direct link between the source and the destination node [17]. Each node in the model is equipped with a single antenna

Table 3. Summary of Parallel Multi-hop papers reviewed

Reference	Summary	Contribution
	Parallel multi-hop relay review	
Sumiala et al. [17]	a) An AF SWIPT relay with a direct link between source and destination is considered. b) The outage probability of the system is optimized with consideration for the PS ratio of the relay nodes. c) Relay selection based on MRC and min-max approaches is also investigated.	a) The authors introduce the application of the min-max and MRC approaches for relay selection. b) A PS ratio protocol based on outage probability is also introduced.
Asiedu et al. [21]	a) An AF multi-hop SWIPT relay system is considered. b) By optimizing the power allocation factor and PS ratio at each relay node, the destination rate is optimized.	a) The authors show that the relays transmit an amplified information signal with the full harvested energy. b) A suboptimal closed-form solution with less computational complexity is proposed.
Mohjazi et al. [32]	a) An AF relay and a direct link between the source and destination are considered. b) Two noise models and two EH models are considered in the system model. c) The normal relaying approach, the blind relaying approach, and CSI assisted relaying for PEP are considered.	a) The authors introduce two relaying approaches in addition to normal relaying with SWIPT. b) The authors also consider instantaneous EH and average EH protocols.

Table 4. Summary of Serial Multi-hop papers reviewed

Reference	Summary	Contribution
	Serial multi-hop relay review	
Chen et al. [33]	a) Authors consider a scenario where the source, relays and destination nodes facilitating communication harvest energy from cochannel interference signals. b) Based on the PS ratios, the authors optimize the outage probability for the system model.	a) This work introduced the idea of all communicating nodes harvesting energy from cochannel interference to facilitate communication.
Mao et al. [34]	a) The authors considered the application of both TS and PS in both AF and DF relaying protocols. b) The focus of this work was on the determination of the number of relay nodes needed to support communication between the source and the destination.	a) The work determined the number of relay nodes aiding end-to-end communication.
Liu et al. [35]	a) An AF MIMO cooperative system were each relay node undergoes SWIPT EH was considered in the paper. b) The PS and TS ratios, and the source and relay precoders were considered in maximizing the system rate.	a) The authors maximized the system rate for a MIMO serial multi-hop system model.
Fan et al. [36]	a) A DF multi-hop relay system was considered by the authors' investigation. b) The system throughput was maximized based on either the TS ratio, PS ratio, or a hybrid TS-PS ratio scheme.	a) The authors introduced the hybrid TS-PS ratio in a serial multi-hop relay system model.

and the relay node undergoes EH to charge its battery. The optimum outage probability for the system model is derived based on maximum-ratio-combining using a single relay node (i.e., the source-destination communication by a single relay node combined with the direct link between the source and destination nodes). From this outage probability solution, the authors propose an optimal relay selection method, where a single relay among the multiple relays supports communication between the source and the destination [17]. The authors further propose a min-max suboptimal method for relay selection (i.e., it is based on using the distance between the source-to-relay and relay-to-destination distances to select a single relay to forward the information signal to the destination) [17]. From the results, the maximum ratio combining (MRC)-based relay selection method yields better results in comparison to the min-max method [17]. Next, the article entitled "Optimal power splitting for simultaneous wireless information and power transfer in amplify-and-forward multiple-relay systems" considers a parallel multi-hop SWIPT relay system supporting communication between a source node and a destination node [21]. The study focuses on maximizing the system achievable rate based on the PS ratio and the power allocation factor at each relay node [21]. In addition, the authors also consider relay selection in their proposed solutions for the operation of the multi-hop AF relay system model. From their optimal solution, the authors established that each relay node facilitates communication with all the energy it harvests. Also, a suboptimal, less complex solution is found for the parallel multi-hop relay system model [21]. The authors compare the proposed optimal algorithm, the proposed suboptimal algorithm, and the relay selection method. From their simulation results, the optimal method gave the best results, followed by the suboptimal method, followed by the relay selection method [21]. The contributions of studies [17] and [21] are in their system models and the proposal of optimal schemes for the various models. Additionally, a contribution of [21] is the demonstration that there is no need for power allocation at the relay nodes for single antenna AF parallel multi-hop configurations.

The article entitled, "Performance analysis of SWIPT relaying systems in the presence of impulsive noise" considers two AF SWIPT relays in the parallel configuration and the existence of a direct link between the source and the destination nodes. The relay nodes harvest energy in two ways: instantaneous EH (IEH) and average energy harvesting (AEH). Each node has a single antenna, and signal transmission is affected by both the background noise and the impulsive noise [32]. Normal relaying, blind relaying (i.e., the relay nodes do not have knowledge of its source-to-relay fading coefficient), and channel-state-information (CSI) assisted relaying are also considered [32]. The performance matrix considered is the pairwise error probability (PEP). Under two noise categories (i.e., noise model 1, where the background noise and impulse noise are the same, and noise model two, where the two noise values are different), the authors derive the PEP for each relaying model [32]. From their simulation results, the blinding relaying approach yields the best performance in terms of the PEP. Also, for all the relaying approaches, the IEH outperforms the AEH EH method.

B. Serial Multi-Hop Relays

The article entitled "Multi-hop cooperative relaying with energy harvesting from cochannel interference" considers the application of SWIPT in a serial AF SWIPT multi-hop relaying system. A novel multi-hop relay transmission strategy, where energy is harvested by the source, the relay nodes, and the destination node from the co-channel interference is presented. The energy harvested is then stored and used later. Due to the extreme complexity in using a large number of nodes, the authors derive a tight upper bound end-to-end (e2e) signal-to-interference-and-noise-ratio (SINR) for their system model [33]. Two cases of cochannel interference are studied: symmetric channels (i.e., the channels have similar characteristics) and non-symmetric channels [33]. From the SINR expressed, the authors derive the cumulative density function (CDF) and the probability density function (PDF). The PS ratio for the source and AF-SWIPT multi-hop relay nodes are optimized based on a given outage probability threshold. In [33], the authors identify the maximum number of AF-SWIPT multi-hop nodes that can support information transfer between a source node and a destination node. With the work presented in [33], the authors introduce EH from cochannel interference. Also, each node in the system model undergoes EH. Research on "Multi-hop relaying using energy harvesting" is investigated in [34]. DF SWIPT and AF SWIPT multi-hop relay configurations considering both the TS ratio and the PS ratio techniques are investigated in [34]. Each node possesses a single antenna. While the source and destination have their own power sources, the serially arranged relay nodes function using the SWIPT energy harvesting technique [34]. The authors derive the signal-to-noise-ratio (SNR) expressions for both the TS and PS SWIPT methods. The authors of [34] aimed to find the maximum number of nodes which support communication between a source and a destination given a rate threshold constraint. The only contribution made by this study is in determining the number of relay nodes that can support communication between the source node and the destination node [34]. The determined number can be used in routing algorithms. However, the optimal values for the TS and PS ratios were not found [34].

A SWIPT AF MIMO relay node is investigated in "Joint source and relay beamforming design in wireless multi-hop sensor networks with SWIPT" [35]. Each node in the system model possesses multiple antennas, and each relay node undergoes EH as a power source to support its functions. In deriving the rate maximization problem, the authors consider both the PS and TS ratio schemes. Hence, two separate rate maximization problems are presented in [35]. The achievable rate is maximized by optimizing the source and relay beamforming vectors, the power resource of each node, and the TS and PS ratios. As expected, the PS ratio scheme yields better performance compared to the TS ratio scheme [35]. The main contribution of the study is the introduction of a multiple antenna node system into the network model [35]. Authors of "Throughput maximization for multi-hop decode-and-forward relay network with wireless energy harvesting" consider the application of both the TS and PS SWIPT protocols in a serial multi-hop relay system [36]. The SWIPT protocols used are the TS, PS, and a hybrid TS-PS protocol. The relay nodes support their operations by using energy harvesting while the source and destination nodes possess their own energy resources [36]. The system rate is maximized based on the joint optimization of the time resource and either the TS ratio, PS ratio, or hybrid TS-PS ratio based SWIPT protocol being considered [36]. From the simulation results, the hybrid protocol has better performance compared to the PS protocol at low source transmit power, but both protocols have similar performance at high transmit power [36]. The TS protocol has the worst performance in all comparisons made in the simulations [36]. The hybrid system introduced by the authors is advantageous at lower source transmit power for the system model. However, the hardware considerations and implementations of the hybrid system will be difficult.

V. EXTENSIONS AND FUTURE WORK

From the papers reviewed, we notice that most models consider the quality-of-service (QoS) (i.e., system throughput performance) constraint and power constraints (i.e., the use of EH to solve power constraint problems) in a sensor network, yet they ignore other constraints such as computational constraints and the lifespan of the sensor network. What we can state is that energy harvesting helps to improve the lifespan of a sensor network by reducing or totally eliminating its dependence on an external power source. Therefore, the possibility exists that batteries will no longer die and need to be changed out from the sensor node. However, the lifespan of a sensor node must also consider the total communication time within which node communication occurs. By optimizing the node communication time, the system performance is improved, and an adequate amount of energy is harvested. Therefore, optimization of the communication time not only improves operation time, but it also increases the lifespan of the sensor network. Another area which can improve sensor lifespan and computational constraints is the introduction of very simple algorithms (i.e., algorithms that puts minimal strain on the computational power of a sensor node) or closed-form solutions for the implementation of energy harvesting techniques. Simple algorithms and closed-form solutions reduce the power consumed for signal processing at each node, leading to a longer lifespan for the sensor node.

In addition to the introduction of EH solutions and their simple implementations, new approaches for the implementation of SWIPT in WSNs can be considered. One such approach is the use of machine learning at the central system to predetermine the PS, TS, or time interval for WSN communication. Machine learning can also help to improve system performance. Most models considered in the reviews assumed perfect CSI; however, CSI estimation is often imperfect. Therefore, future system models should consider imperfect CSI in their models. Also, more of the relay models are single antenna systems, but with the demand for higher data rates (i.e., QoS), systems with MIMO antenna capabilities should be considered in future system models. From the downlink-uplink rate trade-off curve presented in Fig. 3 for a point-to-point system, where a base station communicates with an EH mobile station, we see that the SIMO (i.e., single antenna BS and the EH MS with 3 antennas) has an improved rate trade-off curve compared to SISO (i.e., single antenna BS and a single antenna EH MS). This improvement is due to the diversity gain introduced by the increase in the MS' number of antennas. Hence, considering special diversity improvement in SWIPT research introduces a diversity gain in the system model. Finally, most researchers do not consider the training stage (i.e., channel gain estimation stage) in the design of EH schemes in a sensor network. The inclusion of the training stage is a more realistic scenario as the training stage for a sensor node without a power source would also need to harvest energy for that stage. Hopefully, future research in the area of SWIPT cooperative sensor networks will consider the above issues.

VI. CONCLUSIONS

The implementation of SWIPT and cooperative networks in WSNs continues to receive a lot of traction in current WSN research. In this review, we consider current research works in the area of SWIPT cooperative sensor networks. The reviewed papers considered dual-hop and multi-hop cooperative systems. This review also covers both the DF and AF cooperative techniques for SISO and MIMO relaying scenarios. In addition to our review of the literature, we discuss future extensions for research in the area of SWIPT and cooperative networks in the field of WSN.

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