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A Survey on Simultaneous Wireless Information and Power Transfer With Cooperative Relay and Future Challenges

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ABSTRACT The integration of simultaneous wireless information and power transfer (SWIPT) and cooperative relay (CoR) techniques has evolved as a new phenomenon for the next-generation wireless communication system. CoR is used to get energy and spectral efficient network and to solve the issues of fading, path loss, shadowing, and smaller coverage area. Relay nodes are battery-constrained or battery-less devices. They need some charging systems externally as replacing or recharging of their batteries sometimes which are not feasible and convenient. Energy harvesting (EH) is the most cost-effective, suitable, and safer solutions to power up these relays. Among various types of the EH, SWIPT is the most prominent technique as it provides spectral efficiency by delivering energy and information to the relays at the same time. This paper reviews the combination of CoR and SWIPT. From basic to advanced architectures, applications and taxonomies of CoR and SWIPT are presented, various forms of resource allocation and relay selection algorithms are covered. The usage of CoR and SWIPT in the fifth-generation wireless networks is discussed. This paper focuses on the integral aspects of the CoR and SWIPT to other next-generation wireless communication systems and techniques such as multiple-input-multiple-output, wireless sensor network, cognitive radio, vehicular ad hoc network, non-orthogonal multiple access, beamforming technique, and the Internet of Things. Some open issues and future directions and challenges are given in this paper.

INDEX TERMS Cooperative relay, SWIPT, energy harvesting, 5G, resource allocation, relay selection, IoT, next-generation wireless communications.

I. INTRODUCTION

Next generation wireless networks (NGWNs), such as 5G, will bestow numerous applications and conveniences to make lives easier, smoother and more comfortable with the better quality of service (QoS) at low cost and complexity. 5G is expected to provide 1$\sim$10 Gbps data rate which is around 10 times more, nearly 10 times lower latency, and almost 100% connectivity and availability by spending 90% less energy consumption compared to 4G network [1]. Nevertheless, energy efficiency (EE) and spectral efficiency (SE) remain the key issues to be addressed in NGWNs.

Cooperative relay (CoR) is a technique in which nodes are helping each other on their communication. A node in between source and destination relays information and provides spatial diversity. CoR ameliorate the effects of fading, path loss, shadowing, small coverage, and low signal-to-noise ratio (SNR) [2] in order to increase bandwidth availability and spectral utilization [3]. In general, relay nodes are either battery-constrained *(or have limited battery lifetime)*or battery-less and so their life cycle depends on the life cycle of the battery. Since relaying data incurs energy consumption, the battery of a relay node drains quicker than a non-relaying node. Yet, in many cases, such as sensors used inside the human body, devices placed inside the wall, or nodes placed in a toxic environment, charging and replacing batteries can be very costly and not feasible. For these purposes,

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radio frequency (RF) energy harvesting (EH) (or RF-EH) [4] enables relay nodes to convert wireless signals received from a hybrid access point (AP) or base station (BS) into electrical power in order to boost up the battery power of nodes. Simultaneous wireless information and power transfer (SWIPT), which has been proposed for EH, can transfer power and information simultaneously in order to decode information and recharge batteries using the same wireless signal [5]. As the same signal is used for both power and information transfer, no additional signal or spectrum is needed for energy transfer or information transfer, therefore SWIPT provides spectral efficiency to the networks. Therefore, in SWIPT-based CoR network, the relay nodes will increase their battery power level or just harvest sufficient energy for relaying another nodes' information. Relay's spending power will be compensated by providing wireless power by the SWIPT enabled BS or AP.

A. MOTIVATION: NEED FOR SWIPT AND CoR

The motivation of using SWIPT and CoR is to provide EE and SE in NGWNs. One of the major concerns of 5G, massive IoT, sensors, and other emerging technologies in the coming years is to ensure reliable communication at low complexity, cost, and power [6]. The energy consumption of networking devices has increased exponentially due to the extensive advancement of various applications. For example, the deployment of IoT is expected to involve from 26 billion to 46 billion IoT devices by 2020 according to Bell lab, Cisco and Gartner [7]. With billions of IoT devices, many batteries are needed, and they must be properly maintained and disposed of. In addition, the global electric power consumption by the information and communications technology industry has reached 616 TWh in 2013, and it is forecasted to grow to 910 TWh by 2020 [8]. It is also estimated that the annual carbon emissions will reach up to 235 Mto by 2020 [9], [10]. This alarming situation has raised great issues for researchers to minimize energy consumption and carbon emission. Millions and billions of devices will cost millions and billions of batteries. These batteries should be maintained and properly disposed of for the betterment of the ecosystem. SWIPT-based cooperative relay network can be a promising solution to solve this issue.

The life cycle of a node, including both source and relay nodes, depends on its battery life cycle. So, by enlivening the life cycle of batteries, the lifetime of devices can increase, which is important for future wireless networks and its QoS provisioning. Moreover, in some cases, such as sensors used inside the human body, devices placed inside the wall, and nodes placed in a toxic environment, changing batteries can be very costly and not feasible. So, effective and efficient energy saving mechanism is necessary: a) to reduce the high aggregated energy consumption incurred by devices and networks, b) to reduce carbon footprint and c) to reduce e-waste (i.e., waste from electrical and electronic equipment). For these purposes, EH is one of the best and effective solutions [4]. EH is a process by which a node can increase its energy level by using any ambient sources like solar, wind, vibration or radio frequency (RF). This helps to extend the lifecycle of devices and nodes for attaining self-sustainability [11]. Interference is one of the major challenges to mitigate in wireless communication. But this interference can be made beneficial for wireless communication. EH can be done by properly exploiting interference to provide power to the wireless nodes [12]. Ghosh *et al.* [13] showed that in terms of energy efficiency and spectral efficiency, two-way communication with RF-EH with co-channel interference (CCI) performed better than the case of without CCI.

Whenever the distance between a source node and a destination node is long, they may either be out of each other's transmission range or may require higher transmission power for data exchange. In this situation, a relay node can be placed between the source and destination nodes [2]. So, relay nodes can: a) increase the coverage area of nodes and ameliorate the fading problem, b) reduce transmission power, and c) increase bandwidth (or spectral utilization) [3]. There are two main cases: a) a conventional relay system in which relay nodes forward packets only and do not generate own packets, and b) a CoR system in which a relay node can generate and receive packets, as well as forward packets [14]. While multiple input multiple output (MIMO), a well-established technique in which both the wireless transmitters and the receivers use multiple antennas to multiply the capacity of the radio link, provides the same advantages as CoR, or even more, it is not suitable for low-powered and small-sized wireless sensor nodes as multiple antenna setup is not practically feasible [15].

Like source nodes, relay nodes are also battery-constrained (i.e. with limited battery lifetime). To relay information, relay node incurs energy consumption. For this problem, EH is the solution. So, relay nodes first power up its energy by EH, and the harvested energy is used for relaying purposes [5]. The relay nodes harvest energy from the wireless power sent by AP or BS to increase its battery level. The AP, (also called hybrid AP or HAP) can transmit wireless power and information simultaneously, which is an EH mechanism known as SWIPT [16].

CoR is a well-established technique in the literature from the last few decades, but the integration with SWIPT opens another dimension of CoR. The integration of CoR and SWIPT provides energy and spectral efficiency for improved quality of service (QoS) in a wireless network as SWIPT is a complement for the energy constrained CoR. The highly potential SWIPT applied to CoR has stimulated a rapid research development for a further revolution in wireless networks. Fig. 1 displays some of the advantages of SWIPT and CoR.

B. CONTRIBUTIONS OF THIS SURVEY ARTICLE

In the field of the integration of SWIPT and CoR, lots of research works have been going on in recent years, providing practical advantages and solutions to many problems and

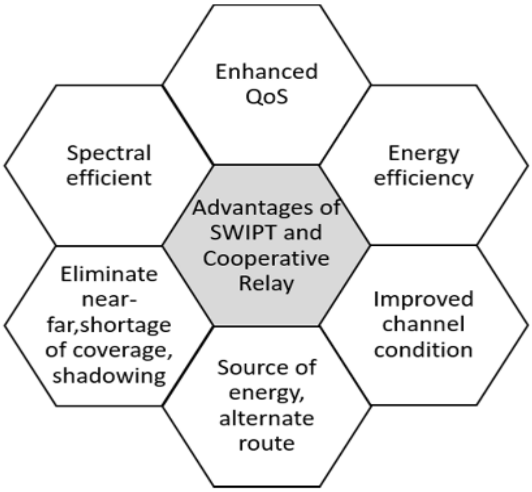


FIGURE 1. Some benefits of the combined usage of SWIPT and cooperative relay.

research potentials. There are several survey articles that review SWIPT and CoR separately with a limited discussion on their integration. *To the best of our knowledge, there is no prior survey that focuses on the integral aspects of SWIPT and CoR in detail and their applications in the next generation wireless communication system.* Table 1 shows some comparisons of the existing papers with this paper.

In this article, a comprehensive survey of SWIPT-CoR is provided. Following are some of the contributions of this paper:

- The focus is not only given to SWIPT and CoR individually, but it emphasizes their integral usages and applications.
- An overview, including the architectures and taxonomies of CoR, EH and SWIPT, and their integration, are discussed in detail.
- Resource allocation schemes, relay selection algorithms and security issues related to SWIPT- CoR are presented.
- SWIPT-CoR is presented in the context of next-generation communication systems like 5G, MIMO, cognitive radio, wireless sensor network, wireless body area network, vehicular ad hoc network, non-orthogonal multiple access, beamforming and IoT.
- Open issues, challenges, and future research directions for SWIPT- CoR are mentioned.

C. RELATED WORKS

In this survey, SWIPT-based CoR networks are covered. While there is a wide range of literature available providing surveys on CoR and SWIPT techniques separately, *to the best of our knowledge, we have not found any comprehensive survey that covers the incorporation of SWIPT in CoR networks.*

There is a contemporary survey literature on SWIPT in [17]. The authors presented SWIPT and wireless power transfer (WPT) in details, providing a vast overview of SWIPT in prominent technologies such as 5G, IoT, cognitive radio (CR), Massive MIMO, D2D communication, and NOMA. Another extensive survey [18] provided a detailed system architecture of SWIPT focusing on hardware circuitry of rectenna and practical scenarios in the context of CoR networks. Another survey [19] focuses on the applications and the structures of SWIPT, including smart antenna systems and MIMO, and a brief discussion on the combination of CoR and SWIPT. In [20], a survey on RF energy harvesting techniques and its applications, including the state-of-the-art circuitry implementations and designs of RF energy harvesting along with their communication protocols, SWIPT and relaying techniques, are presented. In addition, SWIPT was analyzed in D2D communication in details in [21]. Several receiver structures were introduced for SWIPT in two-user broadcast channels in [22]. Later in [23] and [24], the works were extended to multi-user channels, and in [25] it is extended to relay channels. Other important issues of SWIPT, including achievable rate-energy (R–E) trade-offs usage of game theory, throughput maximization etc. were discussed in [26]–[29]. Survey regarding the exploitation of interference for energy harvesting was done in [12].

A survey of CoR was presented in [30]. Sang *et al.* [30] discussed the basic model of CoR, various modes, channel capacity analysis, and power allocation mechanisms. An extensive survey work was done in [31] where CoR was discussed in more details. Various types of relaying, performance metrics, design issues and challenges in the context of full-duplex communication were described. Another survey was done covering SWIPT and CoR in 5G networks in [32]. They emphasized SWIPT techniques in several aspects of 5G.

Mansourkiaie and Ahmed [33] presented a survey of routing techniques in CR networks, including performance analysis, taxonomy and related challenges. This survey gives an up-to-date review of SWIPT- CoR, including supporting architectures, applications, types of relaying, resource allocation and relay selection procedures, and its integration with some other advanced technologies like MIMO, CR and so on. The paper also presents roles of SWIPT-CoR in 5G and IoT. Current challenges and future research directions towards SWIPT- CoR are outlined.

D. ORGANIZATION OF THE ARTICLE

The rest of this paper is organized as follows: Section II provides an overview of CoR, EH and SWIPT techniques, their taxonomies, types and other important issues. Detailed concepts and several issues regarding the integration of SWIPT and CoR are discussed in Section III. Resource allocation, relay selection schemes, security issue of SWIPT-CoR integration are discussed. Section IV presents the important roles of SWIPT and CoR in 5G networks. Section V describes various aspect of the amalgamation of SWIPT-CoR in various emerging techniques and prominent networks. Section VI outlines some open issues, challenges, and future research directions, and finally, Section VII concludes the paper. The acronyms and their definitions used in this paper are

TABLE 1. Comparisons of some of the Literature Reviews on the related domains of SWIPT and CoR.

Reference	Topics covered	Focus	Extension made in our paper compared to the existing reference
Perera et.al. **[17]**	EH and SWIPT	• SWIPT in prominent technologies such as 5G communication, IoT, cognitive radio, MIMO, D2D communication, and NOMA.	• *We also focus on CoR system along with covering their main focuses.*
I. Krikidis et.al. **[18]**	EH and SWIPT	• SWIPT architecture. • Hardware circuitry of rectenna. • Practical scenarios in the context of CR and resource allocation.	• *We extended the discussion in the relay-based network.*
Z. Ding et. al. **[19]**	EH, SWIPT and very brief on CoR	• A very brief survey covering various prominent techniques. • Applications of the smart antenna system and MIMO related to SWIPT. • very brief discussion incorporating relay node.	• *More topics and more detail discussions are done in our paper.*
X. Lu et. al. **[20]**	EH, SWIPT and very brief on CoR	• Presented RF energy harvesting techniques and its existing applications. • Emphasized on circuit implementations and design.	• *We also present various SWIPT-CoR applications.*
R. Zhang et. al.**[22]**	EH and SWIPT	• Focused on receiver structures of SWIPT.	• *We include the discussion of CoR along with their topics.*
W. Sang *et. al.*[30]	CoR	• Discussed the basic model of CoR, its working modes, channel capacity analysis and power allocation mechanisms.	• *We include SWIPT and EH along with CoR.*
G. Liu et. al.**[31]**	CoR	• Various types of relaying, performance metrics, design issues. • In the context of full-duplex communication.	• *We also focus on EH and SWIPT.*
Mukhlif et al. **[32]**	EH, SWIPT and CoR	• Emphasized on 5G for EE and greener network. • Focused on the Cloud radio access network (C-RAN) of 5G.	• *We emphasize more scopes on EH, SWIPT, and CoR.*
F. Mansourkiaie et. al.**[33]**	CoR	• Relay network's routing techniques' taxonomies and their performances analysis.	• *We also incorporated EH and SWIPT.*

given in Table 2 and Table 3 shows the thematic review table discussed in this paper. Fig. 2 shows the overall organization of the paper.

II. RELAY AND RELAY NETWORK, ENERGY HARVESTING AND SWIPT: AN OVERVIEW

This section presents a fundamental overview of the relay, relay network, EH and SWIPT techniques.

A. RELAY AND COOPERATIVE RELAY NETWORK

The concept of relay was first introduced in [34]. Here, the authors considered a 3-node communication (source-relay-destination). Relay nodes play the role of a 'via' [1] and forward packets from the source node to the destination node in a multi-hop wireless communication so that devices located out the range of an AP or BS can communicate with them. Relaying have been applied in several types of wireless network, including WSN, WBAN, VANET, long-term evaluation-A (LTE-A) and WiMAX multi-hop relay networks (or IEEE 802.16j) [31].

A typical wireless cooperative relay network is shown in Fig. 3. The AP is SWIPT-enabled, and it is called 'hybrid AP' or HAP. In a CoR network, the signal can be sent to the destination directly whenever possible, and/ or through relay node(s). For example, to reach Destination-1, HAP can either send its data directly or through two relay nodes (i.e., Relay node-1 and Relay node-2). Both users (i.e., the relay and source nodes) can mutually benefit from a relay system because relay will get the chance to be powered up and source will get better radio link to the destination [35].

On the other hand, a destination may not be reachable directly, so a relay node is necessary. For example, for Destination-2, there is a lack of a direct link from the HAP, so the HAP uses Relay node-3 for transmitting its packets. In a CoR network, a single relay or multiple relays can be used [36].

As the HAP is SWIPT-enabled, it transmits wireless power to relay nodes using the same signal used for information transfer for energy harvesting [37]. There are several variations of SWIPT techniques discussed in the rest of this subsection.

TABLE 2. List of acronyms and their definitions.

Acronyms	Definition	Acronyms	Definition
3GPP	3rd Generation Partnership Project	NGWNs	Next generation wireless networks
5G	5th generation	NOMA	Non-orthogonal multiple access
AF	Amplify-and-forward	OSTBC	Orthogonal space-time block codes
AP	Access point	PS	Power splitting
AS	Antenna switching	PSR	PS relaying protocol
bps	Bit per second	PHY	Physical
BS	Base station	PU	Primary user
CF	Compress-and-forward	QoS	Quality of services
CoR	Cooperative relay	RF	Radio frequency
CPU	Central processing unit	SE	Spectral efficiency
CR	Cognitive radio	SNR	Signal to noise ratio
CRC	Cyclic redundant check	SU	Secondary user
CRN	Cognitive radio network	SWIPT	Simultaneous wireless information and power transfer
CSI	Channel state information	TAS	Transmit antenna selection
D2D	Device-to-Device	TDMA	Time division multiple access
DC	Direct current	TS	Time switching
DF	Decode-and-forward	TSR	TS relaying protocol
EE	Energy efficiency	TWh	Terra watt-hour
EH	Energy harvesting	UAV	Unmanned Aerial Vehicles
GSC	Generalized selection combiner	UE	User equipment
HAP	Hybrid access point	UER	User equipment relays
HSPA	High-speed packet access	UWB	Ultra-wide band
ID	Information decoding	V2I	Vehicle to infrastructure
IoT	Internet of things	VANET	Vehicular ad hoc network
IR-HARQ	Incremental redundancy-hybrid automatic repeat request	WBAN	Wireless body area network
ISM	Industrial, Scientific, and Medical	WET	Wireless energy transfer
LTE-A	Long-Term Evaluation-A	Wi-fi	Wireless fidelity
MIMO	Multiple-input-multiple-output	WiMAX	Worldwide Interoperability for Microwave Access)
MRC	Maximum ratio combining	WPT	Wireless power transfer
Mto	Metric ton	WSN	Wireless sensor network

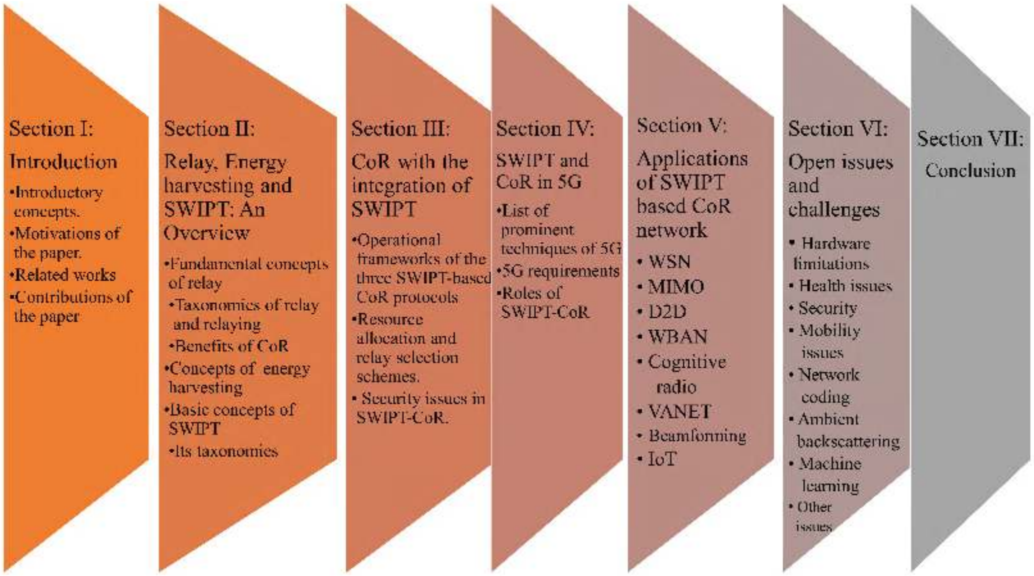


FIGURE 2. Organization of the paper.

In a CoR system, relay nodes are not dedicated to relaying, and these nodes also transmit their own information. Relaying other's information is on a voluntary basis [14], which is a concept also known as cooperation diversity or cooperative diversity [38]. In CoR, every node can be a source and/ or a relay node. Relays are of two kinds standardized by the

TABLE 3. Few topics of SWIPT and CoR covered in this paper.

Relay, Cooperative relay, and network	
Area or domain/topic	**References**
Basic overview & Survey on CoR	[1]-[3], [14], [30]-[32], [34], [36], [38]
Routing in CoR	[33]
Types of Relaying	[39], [40], [44]-[57]
Benefits of CoR	[3], [15], [19], [31], [33], [35], [41]-[43], [58]-[63]

Integration of SWIPT and CoR network	
Basic overview and benefits	[25], [83], [84], [87]
SWIPT-based CoR protocols	[13], [25], [81], [89], [85]
RA in SWIPT-CoR	[88]-[97]
Relay selection in SWIPT-CoR	[5], [63], [78], [98]-[104]
Security issues in SWIPT-CoR	[105]-[115]

SWIPT-CoR in 5G
[1], [32], [116]-[123]

Applications of the SWIPT-based CoR network	
WSN	[114], [115], [124]-[135]
MIMO	[12], [14], [19], [84], [139]-[145]
D2D Communications	[146]-[150]
WBAN	[151]-[158]
CRN	[159]-[172]
VANET	[173]-[180]
Beamforming technique	[181]-[186]
NOMA	[187]-[191]
IoT and relevant issues	[7]-[10], [192], [193]

Energy Harvesting and SWIPT	
Area or domain/topic	**References**
Basic overview & Survey on EH	[4], [12], [18], [20], [64], [65], [69]
Usages of EH	[11]-[13], [70]-[75]
Basic overview & Survey on SWIPT	[5], [16]-[19], [37], [77]-[81]
SWIPT receiver structures	[20], [22]-[25], [37], [80], [82]-[86]
Benefits of SWIPT	[17]-[19], [24], [37], [80] [83]
Miscellaneous issues of SWIPT	[21], [26]-[29]

Open issues with SWIPT-CoR	
High speed mobility	[194], [195]
Health issue	[196], [197]
Network Coding Techniques	[198]-[202]
SWIPT based full-duplex relaying	[87], [203], [204]

Other issues	
Friis equation	[66]
Two ray ground models	[67]
RF propagation models	[68]
Nikola Tesla's WPT	[76]
UAV	[129]

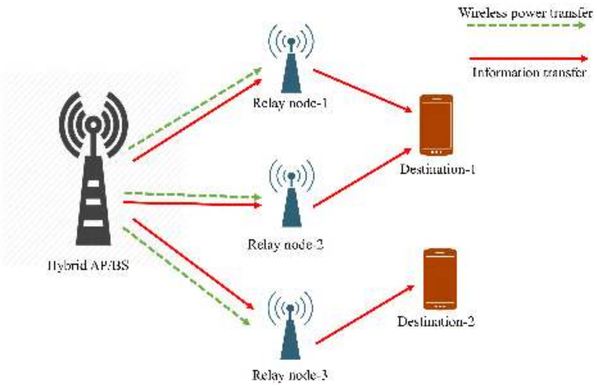


FIGURE 3. Wireless Relay Network with SWIPT enabled Access point.

3rd Generation Partnership Project (3GPP): i) Type- I and ii) Type- II. Their comparisons are given in Table 4 [39], [40].

Relay nodes are not only providing higher network connectivity to remote devices but also increasing EE. Energy consumption of devices is depending on the amount of the data to be transmitted or received, and the distance between a source node and a destination node. The larger the distance between the source and the destination, the higher the power required for reliable transmission.

TABLE 4. Comparison of type-I & type-II relay [39], [40].

Features	Type-I relay	Type-II relay
Relaying mode	Can be in-band and out-band	In-band
Transparency	Non-transparent	Transparent
Having own physical cell identification	Yes, and used for coverage extension	No
Usage	For transmitting synchronization signals and resource allocation	for enhancing throughput and QoS of user equipment
Communication mode	works both half-duplex and full-duplex	half- duplex
Implementation	complex and higher cost involvement	simpler and low-cost

The high-power transmission can lead to faster battery drain of nodes, shortening their battery lifetime. Relay nodes can reduce the distance between them to achieve EE [41], which is one of the important tools for alleviating the fading effect of wireless channels in transmission [42].

By relaying using multiple relays, the overall throughput of a network can increase. So, relay nodes can increase

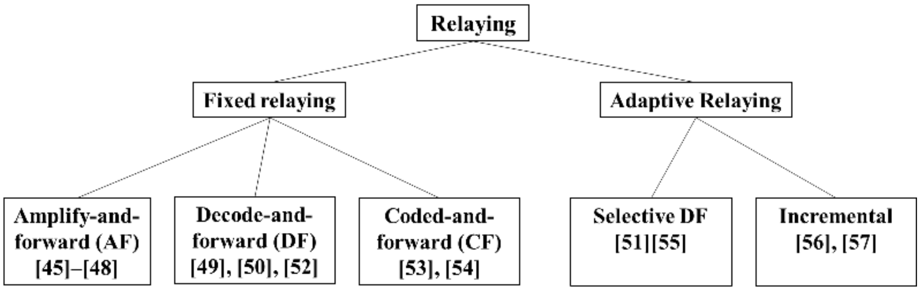


FIGURE 4. Taxonomy of relaying strategies.

EE and SE [3]. For the long-haul transmissions and in hierarchical network designs, relaying is found to be the very cost-effective solution [41]. Fading is one of the major problems in wireless networks. To tackle this problem, CoR is found to be very helpful. By providing spatial diversity, it gives enhanced throughput to the network [35], [43].

1) TAXONOMY OF RELAYING

There are several types of relaying systems categorized under fixed relaying and adaptive relaying. Fig. 4 shows the taxonomy of relaying. In fixed relaying, the relay nodes are always in active mode, and hence leading to spectral inefficiency. Moreover, it does not emphasize the error of the message and the link quality. While in adaptive relaying, the relays are only active while they need to relay information, otherwise, they remain silent or inactive and hence leading to SE and reliability, but it needs more computational power, creating some delays [44]. Descriptions of various types of relaying mechanisms are given below:

a: AMPLIFY-AND-FORWARD (AF) RELAYING

The AF relaying concept was first introduced by Laneman *et al.* [45]. This relaying scheme is referred to as non-regenerative relaying. In this scheme, the relay simply amplifies the received signal from the source and then forwards the amplified signal towards the destination. It provides a simpler form of relaying to achieve spatial diversity at very low computation cost, transparent to the modulation type and consist very short delay. But the main drawback is that it also amplifies the intrinsic noise along with the signal, thus it degrades the overall QoS of the network [46]. AF is very hard to implement in TDMA systems due to its large storage requirement for keeping a large amount of analog data [47]. More details regarding AF can be found in [48].

b: DECODE-AND-FORWARD (DF) RELAYING

In DF relaying, which is also known as regenerative relaying, the relay node decodes the received information signal sent by a source node, re-encodes it, and then forwards it to the destination node [49]. Conventional DF protocol, proposed by Cover and Gamal [50], uses block Markov superposition coding. As the conventional DF relaying mechanism does node perform error corrections at the relay node, it can propagate erroneous information towards the destination node, and degrade the overall system performance [51]. It needs more careful self-interference cancellation process (a signal processing system by which a radio transceiver can transmit and receive on a single frequency) [52].

c: COMPRESS-AND-FORWARD (CF) RELAYING

Another technique of relaying is CF. Here, the source sends the message directly to the destination and the relay node also sends the compressed version of the signal to the destination. Relay nodes use Wyner-Ziv code for the compression and don't do the decoding and encoding like in the case of DF. The receiver correlates signals received from the source and the relay nodes. Then it decodes the original message. CF has been shown to outperform AF and DF, especially when the relay node is located closer to the destination node [53], [54].

d: SELECTIVE DF (S-DF) RELAYING

In AF, described earlier, the drawback is that noises are amplified along with the message signals. On the other hand, in the conventional DF approach, the relay node does not check for any errors. So, incorrect messages can be relayed. In S-DF, which is a type of adaptive relaying, solves this drawback of both AF and DF approaches. Here, the relay node decodes messages received from a sender node, and if it can correctly decode them after an error checking, it forwards the messages towards a receiver node, otherwise, it does not forward or remains silent [51], [55]. Some error detection methods, like CRC or mechanisms based on SNR (signal to noise ratio) threshold value, have been used.

e: INCREMENTAL RELAYING

This adaptive relaying method is based on the feedback system. It was first proposed by Laneman *et al.* [45]. If the direct transmission between a sender and a receiver is error free, the relay node remains silent. But if the error is found (based on the SNR value), the relay node relays the message by using the AF method. This means the relay nodes relay messages only when the error is detected. In other words, a receiver node can send feedbacks to a sender node so that it can retransmit the message, whereby the sender node sends to the relay node, and then the relay node relays the message to the receiver node. The receiver uses a technique called

TABLE 5. Advantages & limitations of various types of relaying.

Types of relaying	Advantages	Performance metrics enhanced	Limitations	References
AF	A simpler form of relaying with Lower processing and hardware cost. Transparent to the specific modulation. No decoding or quantizing operation is needed to perform	Least delay.	It also amplifies the residual noise. Degrades the QoS of the network. Hard to implement in TDMA systems.	[45]–[48]
DF	Eliminates the noise.	Lower error rate.	Computational delay & complex. Error propagation problems might arise	[49], [50], [52]
CF	Reduce the data load by compressing.	Better throughput. Low bit error rate.	Need direct path between source and destination. Computational cost is higher	[53], [54]
S-DF	Relaying only the errorless message. Eliminates the noise.	Lower bit error rate. Higher spectral efficiency.	Increased delay. Security vulnerability.	[51], [55]
Incremental	Error-free or errorless. Easy to implement and no need for CSI.	Higher spectral efficiency.	Higher signaling efforts. Higher system complexity.	[56], [57]

maximum ratio combining (MRC) to combine two signals, one direct message received from a sender node, and another indirect message received from a relay node [56].

The following Table 5 shows the summary of the advantages and the drawbacks of various relaying techniques.

2) BENEFITS OF CoR

Table 6 lists some benefits of CoR.

B. ENERGY HARVESTING (EH)

EH is a technique to convert various types of energy like solar energy (light), piezoelectric or vibration, thermoelectric (heat), and electromagnetic energy into electricity [64]. Among the various types of EHs, radio frequency (RF) EH is the most suitable technique for various reasons. It has a sustainable and controllable power supply, easily available in the form of transmitted energy (TV/ radio broadcasting, cellular networks' signal, and handheld radios), cheaper as no additional cost for the spectrum usage and easy to implement [65]. Even interference can be exploited as beneficial by EH.

The RF source of energy are classified into two types: i) dedicated sources, which are dedicated devices for power transfer, such as Powercast, and ii) ambient sources, which are not dedicated devices, such as *an access point* [20].

In EH networks, there are two types of power management schemes [20]:

1. *Harvest-use:* the harvested energy is used instantly, rather than being stored for future use. For this reason, the amount of harvested energy must be greater than the consumed energy of a node.
2. *Harvest-store-use:*the harvested energy is stored in energy storage mechanisms like rechargeable batteries or super-capacitors for future use when the amount of harvested energy is greater than consumed energy.

TABLE 6. Some benefits of CoR.

No.	Benefits	References
1	Increases the bandwidth or spectral utilization	[3]
2	Provides spatial diversity *(like MIMO provides)*	[15]
3	Similar benefits of MIMO can be obtained, but MIMO is very difficult for practical implementation	[19]
4	Increases the overall QoS of the network by increasing throughput	[35]
5	Eliminates channel impairments like path loss, shadowing, and fading by utilizing cooperative spatial diversity	[58]
6	Provides EE; as CoR node placed in between the source and destination, it reduces the energy requirement of the distant-source	[59]
7	It provides better channel condition in both links, this results in the reduction of the interference	[60]
8	Provides communication reliability as there is alternate (more than one) path exists in CoR network	[61]
9	Reduces the overall operational cost for many reasons. As CoR is energy efficient, so less energy will be needed for the operation. CoR is the cheapest alternative to the expensive BS deployment to increase the coverage area, it also needs lower installation and maintenance costs compared to BS	[62]
10	Reduces the system's outage probability	[63]

In RF-EH, the frequency range of the medium that carries electromagnetic signals is from 3kHz to 300GHz. Beside RF-EH (far-field or for longer distance energy transfer technique), the other wireless energy transfer techniques are inductive coupling and magnetic resonance coupling

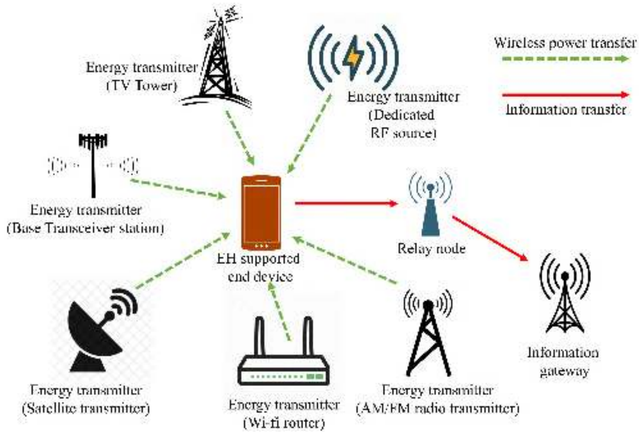


FIGURE 5. RF-EH Network.

TABLE 7. Description of the notations used in the equations.

Symbol	Meaning
P_R	received power
P_T	transmitted power
G_R	the gain of the receive antenna
G_T	the gain of the transmit antenna
λ	signal wavelength
L	path loss factor
d	the distance between the transmit antenna and the receiver antenna
h_t	the height of the transmit antenna
h_r	the height of the receiver antenna

TABLE 8. Experimental data of RF-EH [20], [69].

Source	Source power	Frequency	Distance	Amount of energy harvested
Isotropic RF transmitter	4W	902–928MHz	15m	5.5µW
	1.78W	868MHz	25m	2.3µW
	1.78W		27m	2µW
TX91501 Powercast transmitter	3W	915MHz	5m	189µW
			11m	1µW
TV tower	960KW	674-680MHz	4.1km	60µW
	1000KW		6.4 km	16 µW
	50kW	1584 kHz	50m	2.3mW
			3km	0.5 µW
AM Radio	150kW		20km	240 µW

(near-field or very short distance energy transfer technique) which are explained details in [20].

A generalized view of RF-EH network (EHN) is shown in Fig. 5. In general, there are three main components in RF-EHN. They are:

1) RF energy sources (like AP, BS, dedicated devices like Powercast, or even TV or cellular tower and so on).
2) Information gateways (like BS, AP, routers, relay nodes etc.). Here, BS and AP are hybrid and used both for energy source and information gateway.
3) Network nodes/devices (end users like sensors,

Theoretically, the harvested RF received power from a transmitter in the free space wireless communication can be derived by using the Friis equation developed by Friis [66] (see Table 7 for descriptions of notations):

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi d)^2 L}, \tag{1}$$

Friis equation is assumed to have single path line-of-sight communication between a sender and a receiver. But practically, due to several reasons like scattering and reflection, RF signal propagates in multiple paths. In this case, the two-ray ground model gives us a more practical equation for calculating the RF received power. The equation is as follows [67] (see Table 7 for descriptions of notations):

$$P_R = \frac{P_T G_T G_R h_t^2 h_r^2}{d^2 L}, \tag{2}$$

The above two models are based on general deterministic models. But there are many probabilistic and practical RF propagation models like the Rayleigh model, Hata model, Nakagami model and so on. Interested readers can refer to [68] for more details.

Table 8 presents some of the experimental data of the amount of energy harvested from various sources with their operating frequencies and distance between the source node and the harvesting node. From the data, the amount of harvested energy depends on the source power and the distance between the power source and the harvesting node.

RF-EH is used in sensor nodes [70], health care and medical services [71], [72], RFID (radio frequency identification) [73], to provide charging to the low power devices like smartwatches, hearing aids, mp3 players, wireless keyboards and mouse, and so on [74], [75].

C. SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER (SWIPT)

The concept of wireless energy transfer (WET) was first introduced by Tesla at 1891 [76]. But due to the usage of higher power transfer, it was hazardous to use. After a century, the concept of WET has gained importance in research again due to the low-power transfer (which is now not hazardous) and improvements of low power devices [77].

One of the latest research trends in wireless communication is SWIPT. Here, both information and energy are carried by the same wireless signal [78]. Varshney [37] first gave the theoretical concept regarding SWIPT. Later his work was extended by Grover and Sahai [79]. Both works considered single-input-single-output (SISO) flat-fading channels. They have shown that there is a tradeoff between the achievable rate and the harvested energy in SWIPT system.

Due to the low cost, wide operating range and possible to apply on the small-sized receiver, WET with RF is a promising tool to wirelessly power up devices or nodes. Along with WET, information can also be transmitted

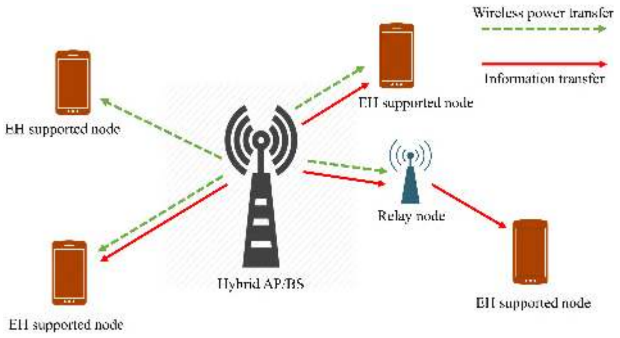


FIGURE 6. A general network of SWIPT.

simultaneously using the same signal. This design is known as SWIPT, which is more efficient in terms of the spectrum [80].

SWIPT, unlike conventional EH methods, is less reliant on surrounding environments and can ensure stable energy supply in all kinds of weathers. Therefore, for a longer lifespan of energy constrained systems, SWIPT has been considered as a prominent choice [81]. Fig. 6 shows the general view of the SWIPT network.

1) ARCHITECTURE OF SWIPT

Theoretically, a SWIPT receiver can harvest energy and decode information from the same waveform [37]. But due to the circuit constraint like different receiving antenna power sensitivities, its implementation is not practically possible yet. To be noted here that, −10 dBm power sensitivity is required for EH and −60 dBm is for ID [18]. For practical implementation, there are a few structures available for SWIPT as follows [22] and they are described in the rest of this subsection:

a. time switching
b. power splitting
c. integrated information decoding (ID)/ EH receiver
d. antenna switching

a: TIME SWITCHING (TS)

In TS, the receiver uses the same antenna for EH and ID. In this receiving architecture, there is a switch that changes the type of antenna in each time slot for either ID or EH operations. TS architecture is known as co-located receiver architecture as the same antenna is used for both EH and ID [80].

b: POWER SPLITTING (PS)

In PS scheme, in the EH receiver, a power splitter is used. It splits a received wireless signal into two streams of different power levels, one for ID and another one for EH [82]. In terms of tradeoffs between information rate and the amount of RF energy transferred, PS has shown to perform better than TS [83].

TABLE 9. Advantages and limitations of various receiver architectures of SWIPT.

Types of receiver architectures	Advantages	Limitations	References
TS	Simple hardware implementation. Applicable for the single antenna device.	Faces synchronization problem. Needs proper schedule. Delay occurs	[80], [17]
PS	Applicable for the single antenna device. Instant ID and EH. Less prone to delay.	More complex than TS. Needs proper optimization of the PS factor: α.	[82] [86]
Integrated ID/EH	Smaller hardware formation. Single antenna transmitter.	More complex architecture. Prone to interference in the lower power region.	[83]
AS	Performing both EH and ID simultaneously.	Needs multiple antennas. Prone to optimization error.	[20], [22], [84]

c: INTEGRATED ID/EH RECEIVER

This architecture has been first proposed in [83]. Here, a rectifier is used to convert RF-to-baseband to generate DC current. Then, the DC current is divided by a power splitter into two power streams. One is used for EH and another one for ID.

d: ANTENNA SWITCHING (AS)

AS architecture is discussed in details in [84]. Here, the EH receiver and ID receiver are both equipped with separate and independent antennas that can detect different channels. As a result, this SWIPT system can perform EH and ID in a consecutive manner. This system is also known as 'separate receiver architecture' [20].

When the power consumption of the circuit is low and more harvested energy is expected, integrated ID/EH SWIPT architecture outperforms PS, TS, and AS receiver architectures. But when the power consumption of the circuit is higher PS, TS, and AS performs better [83]. It is also found in [85] that PS performs better than TS in terms of throughput at high SNR and TS performs better than PS in low SNR.

Table 9 shows the advantages and limitations of various SWIPT architectures.

2) BENEFITS OF SWIPT

Usage of SWIPT in the network has several benefits as shown in Table 10.

TABLE 10. Benefits of SWIPT.

No.	Benefits of SWIPT	References
1	Power supply and information exchange simultaneously.	[18]
2	Provides significant SE.	[80]
3	Provides EE.	[83]
4	Extends the lifetime of energy-constrained nodes/devices.	[37]
5	Green communication system.	[24]
4	Mitigates path-loss effects and to supports high throughputs and energy sustainability.	[18]
5	Practical implementation is more easy and beneficial compared to the Power-line communication (PLC) *(the wired connection technique which can carry information and power simultaneously).*	[17]
6	Proper interference management and reduces transmission delay.	[19]

III. CoR WITH THE INTEGRATION OF SWIPT

SWIPT based CoR is one the most promising wireless technologies nowadays. This combination brings lots of advantages for the upcoming energy-constrained wireless networks while improving the overall QoS [87].

Benefits of each technique are listed in the previous section. The benefits of the integration of SWIPT and CoR are listed in Tables 6 and 10. Moreover, the individual performance of SWIPT and relay can be boosted up if they are used both together. For example, Ding *et al.* [88] demonstrated that the outage probability of SWIPT-CoR is much lower than the conventional CoR system without SWIPT.

A. SWIPT BASED RELAYING PROTOCOLS

Now, this part of the paper discusses various types of SWIPT based relaying protocols.

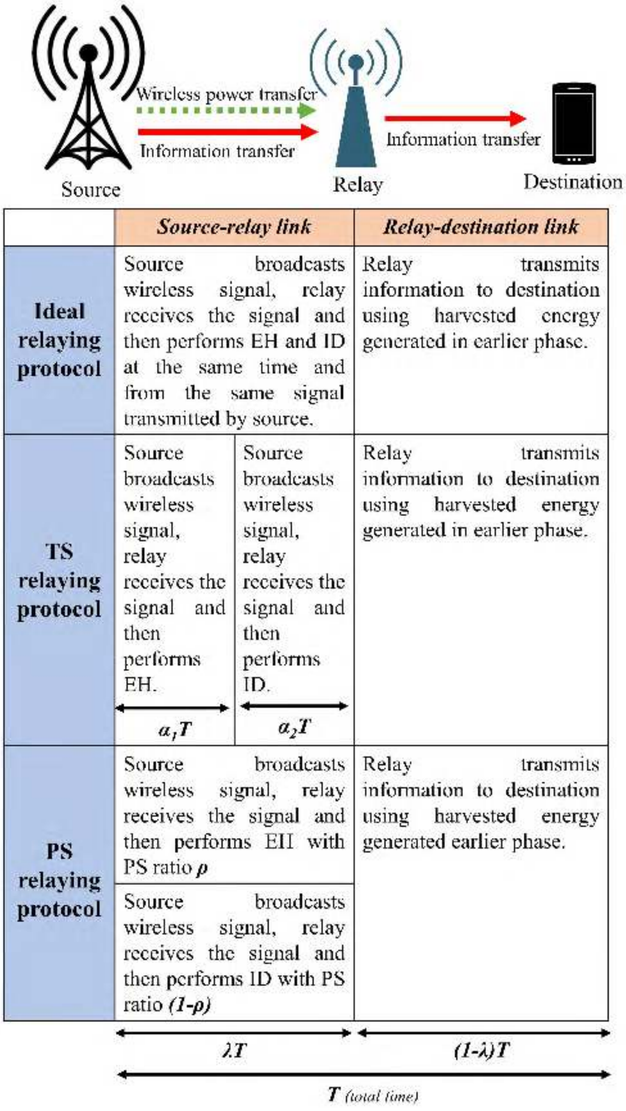
Fig. 7 shows the operational framework of three SWIPT enabled CoR protocols. Consider that the relay node can harvest energy by using the wireless signal sent by the source. The source broadcasts its signal, then all the surrounding nodes receive the signal. The relay node after receiving the signal, it does the energy harvesting by using that signal. Only the selected relay does the ID and then sends the information to the destination.

1) IDEAL RELAYING PROTOCOL

In general, half-duplex case, the first time-slot *(say, λ part of total time T)* is used for EH and ID and the next time-slot *(remaining 1 − λ part of total time T)* is used for relaying *(transmitting to the destination)* by using the harvested energy. EH and ID are done in the same time-slot with the same signal. This is the ideal case of the relaying protocol. The ideal relaying protocol is not practically implementable, but its theoretical performance is considered as the upper bound of the system [81].

2) TS RELAYING (TSR) PROTOCOL

In TS protocol, the first time-slot is divided into two sub-time-slots. Say, for example, an α_1 fraction of T is for EH and α_2 is for ID. Here, $\alpha_1 + \alpha_2 = \lambda$. Then, the relay transmits information to the destination in the remaining $(1 - \lambda)$ part of total time T [89].



	Source-relay link		*Relay-destination link*
Ideal relaying protocol	Source broadcasts wireless signal, relay receives the signal and then performs EH and ID at the same time and from the same signal transmitted by source.		Relay transmits information to destination using harvested energy generated in earlier phase.
TS relaying protocol	Source broadcasts wireless signal, relay receives the signal and then performs EH. $\alpha_1 T$	Source broadcasts wireless signal, relay receives the signal and then performs ID. $\alpha_2 T$	Relay transmits information to destination using harvested energy generated in earlier phase.
PS relaying protocol	Source broadcasts wireless signal, relay receives the signal and then performs EH with PS ratio *ρ* Source broadcasts wireless signal, relay receives the signal and then performs ID with PS ratio *(1-ρ)*		Relay transmits information to destination using harvested energy generated earlier phase.

FIGURE 7. Operational frameworks of the three SWIPT-based CoR protocols, (a)Ideal protocol; (b) TS protocol and (c) PS protocol (redrawn from [81]).

3) PS RELAYING (PSR) PROTOCOL

In PS protocol, the received broadcast signal is divided into two power streams with the ratio of ρ (where $0 \leq \rho \leq 1$) for example for EH and $(1 - \rho)$ for ID at the selected relay node. Then the relay node forwards the information to the destination. Here, EH and ID are done in the same time-slot *i.e.* simultaneously [81].

Nasir *et al.* [25] presented these TSR and PSR protocols in details and analyzed throughput performance. They did the analysis in both Delay-Tolerant Transmission and Delay-Limited Transmission. The key findings of the article are given in Table 11. In terms of peak energy-efficiency, PSR is superior to TSR protocol [13].

TABLE 11. **Throughput analysis of PSR vs TSR [25].**

Performance metrics		Throughput	
		PSR	TSR
Noise variance	↑	↓	↑
	↓	↑	↓
Source to relay distance	↑	↑	↓
	↓	↑	↓
Transmission rate	↑	↓	↑
	↓	↑	↓
Energy harvesting efficiency	↑	↓	↑
	↓	↑	↓

(higher/larger: ↑ lower/smaller: ↓)

B. RESOURCE ALLOCATION AND RELAY SELECTION IN SWIPT-CoR NETWORK

In the cooperative energy constraint relay network, bandwidth, power and time are considered as resources that are very limited. For the proper utilization of these resources, its needed to design an optimal RA scheme to get the energy and bandwidth efficient relay network. In the literature, RA problems analyze power allocation for a fixed bandwidth, or bandwidth allocation for fixed energy level, and/or considering time as a fixed resource. But to make the RA mechanism more efficient, the joint effect of these limited resources has to be considered [90].

Ahmed *et al.* [91] proposed an online power allocation scheme for buffer–aided link adaptive EH relaying. They considered EH- DF relay which operates in half-duplex mode *(relays receive a packet in one time slot from the source and forward it in the next time slot to the destination).* In buffer-aided relays, packets are temporarily stored until the channel condition between the relay and destination gets improved. Ahmed *et al.* [92] proposed joint relay selection and power allocation schemes of an AF cooperative communication system to maximize the throughput. They considered single relay situation (not the multiple relays).

Power allocation mechanism for the multiple sources-destinations for the cooperative network has been investigated in [88]. They used the water filling algorithm to design such power allocation. In [93], the power allocation solution was proposed. The solution was based on the average harvested energy and named as 'asymptotically optimal power allocation'.

In [94], two types of power allocation mechanisms were analyzed, they were water-filling power allocation algorithm and power allocation based on channel capacity. It was shown that more power is allocated to the channels with less noise. An incremental redundancy-hybrid automatic repeat request (IR-HARQ) power allocation scheme was proposed in [95]. They claimed that their proposed scheme would improve the reliability of the network, increase the efficiency and improve the overall network throughput. In [96], RA and RS schemes were proposed. Here, AF relay node and PSR protocol and TSR were considered. Liu [97] for multi-antenna relay based SWIPT network.

Table 12 shows the summary of the RA schemes discussed in this subsection.

Another important phenomenon is needed is the proper RS algorithm [78]. RS in CoR network is to select the best relay node(s) from the multiple relays to improve the overall QoS of the network and to minimize the energy consumption. There are several proposed relay selection mechanisms available in [5], [98], and [99].

The RS problem in energy harvesting relay networks is still at the beginning stage. In [78], RS was proposed for full duplex communication based on power-splitting EH. They compared with single relay vs general relay selection. From [100], it has come to know that a relay network with EH and a relay network without EH differs significantly. According to their model, the relays were selected based on the average rate of harvested energy, transmit power and the total number of relays in the system. Butt *et al.* [63] investigated the relay selection problem in SWIPT based CoR network based on the CSI. On their results, it was found that the availability of CSI at relays enhances the system's overall performance significantly and a tradeoff exists between a few relays involvement to the system versus EH efficiency of the relay nodes.

Several studies showed that the concept of multiple selected relays cooperating performed better than a single relay selection in terms of energy and bandwidth [5], [42]. Luo *et al.* [98] proposed a cooperation strategy as the transmit power minimization for wireless networks with the help of EH relays. Here, multiple relays with multiple source-destination were considered. Relay selection based on the battery's power level was proposed in [101]. Above mentioned relay selection methods were based on the stationary nodes. There are few works that were done considering the mobility effect of the nodes [102], [104].

Table 13 shows the summary of various RS schemes.

C. SECURITY ISSUES IN SWIPT-CoR NETWORK

Security is one of the biggest concerns in communication systems. There are lots of security vulnerabilities in SWIPT based CoR networks. As the same signal is used for both ID and EH, malicious users can get the chance to eavesdrop the message of the legitimate users by exploiting the RF signal. On the other hand, any malicious node can advertise itself as the best relay to the legitimate nodes for the message forwarding. This will create the man-in-the-middle attack. Therefore, security measures must be taken while choosing the best relay. PHY layer security in SWIPT-CoR networks has attracted great attention among the researchers. Relevant work was done in [105]. They considered power splitting-based relaying scheme for EH at the relay nodes in a cognitive radio network (CRN) environment. They investigated the secrecy outage probability for a dual hop DF relaying system.

TABLE 12. Review of various resource allocation schemes.

Paper	Key features	Relay type	Performance metrics	Channel Model	Simulation tool	Results/Findings	Remark
[88]	Multiple sources-destinations scenarios. Used the water filling algorithm. Auction-based power allocation scheme.	DF	Outage probability	Rayleigh fading	MATLAB	0.01 Outage probability at 40 dB SNR.	Might face faster battery drain as a source needs to use large transmission power
[91]	Online and offline power allocation scheme, used Dynamic programming. Buffer–aided link adaptive EH relaying. Operates in half-duplex mode.	DF	Throughput vs SNR and harvested energy Execution time vs time slot The probability of dropped bit and delay	Rayleigh fading	MATLAB	(offline) 31 and (online) 28 transmitted bits at 30 dB SNR. Execution time 0.001 s for the number of time slot up to 140.	High complexity. Only applicable for single relay situation. Needs buffering.
[92]	Buffer–aided power allocation scheme. Solved offline optimization problem by the generalized Bender's decomposition.	AF	Throughput vs number of time interval	Block fading	MATLAB	350 transmitted bits at 50 times intervals and 680 at 100.	Needs buffering. Only applicable for single relay situation.
[93]	Based on the average harvested energy. Derived the asymptotically optimal online power allocation.	AF	Outage probability vs harvested energy Throughput vs harvested energy	Rayleigh fading	Monte-Carlo simulation on MATLAB	0.01 Outage probability at 20 dB transmit power.	Considered unlimited capacity of the battery, which is not feasible.
[94]	Used water-filling power allocation algorithm and investigated with Maximal Ratio Combining (MRC) Based on channel capacity (asymptotically optimal power allocation) and noise level.	AF	Power allocation vs noise level Channel capacity vs number of users	Rayleigh fading	MATLAB	1.1250 W power for noise level 3 dB and while 3.625 dB at 0.5W. Allocated power is proportional to the channel capacity of the user.	Very simplified theoretical evaluation.
[95]	Incremental redundancy-hybrid automatic repeat request (IR-HARQ) power allocation scheme. For the six-sector urban cell model cellular network.	DF and Partial DF	Throughput vs SNR Energy consumption	Block fading	NS2 and MATLAB	0.9 nats (natural unit for information) per channel use (npcu) at 10 dB SNR.	EH was not considered.
[96]	Joint resource allocation and relay selection scheme. PSR and TSR were considered. Solutions obtained using the Karush-Kuhn- Tucker (KKT) conditions.	AF	Maximum achievable rate vs energy harvesting threshold. Maximum achievable rate vs total transmitted power of the transceivers	Rayleigh fading	MATLAB	14 bps/Hz at 0.01 W 15 bps/Hz at 30 dB	Not considered the effect of noise.
[97]	Proposed RA for multi-antenna relay system. Antenna clustering scheme was proposed. Harvest-then-use criteria followed.	DF	Rate performance vs source transmit power	Rayleigh fading	*Not specified*	TS scheme outperforms PS in lower SNR region while PS scheme outperforms TS scheme over a wide range of SNR. 3 bps/Hz at 40 dB.	Relay placement in the middle of source and destination found the worst. CCI issue was ignored.

Another work was done in [106] regarding the PHY layer security issues. Aggregating received power at two-way DF relay was used to define power shortage event on their scheme. In [107], harvest-and-jam relay protocol was proposed for the securing the PHY layer of SWIPT-CoR network. Zhou *et al.* [108] investigated opportunistic relay (OR)

TABLE 13. Review of various relay selection methods.

Paper	Key features	Relay type	Performance metrics	Channel Model	Simulation tool	Results/Findings	Remark
[63]	Based on CSI and EH efficiency	DF	Outage probability	Block fading	*Not specified*	Single relay selection: outage probability 1 at 2.5 bps/Hz Multiple relay selection: outage probability 1 at 3 bps/Hz	Considered battery of infinite capacity. Delay
[78]	RS for full duplex communication. Based on power-splitting EH. Compared with single relay vs general relay selection.	AF	Sum capacity and outage probability vs source transmission SNR Sum capacity vs selected relays.	Rayleigh fading	MATLAB	10^8 bps at 35 dB source transmission. 0.00001 outage probability at 35 dB source transmission. Capacity increases and outage probability decreases with increases in the number of relays.	Assumed that the sources have perfect knowledge of all channels. The power level of the relays was not considered.
[98]	Multiple relays selection in multiple source-destination scenarios.	AF	Source transmit power versus the relay number	Block fading	*Not specified*	Transmit power decreases with the increases of relay number. The proposed scheme needs 5 relays to have the source transmit power less than 0.08 W.	Assuming no co-channel interference. This is impractical.
[100]	The scheme was based on the following parameters: a) the average rate of harvested energy b) transmit power and c) total number of relays in the system	AF	Symbol error rate	Block fading Rayleigh	Monte Carlo simulations on MATLAB	Relay's harvested energy depends not only on the average rate but also on the transmit power and a total number of relays in the system. SER decrease when transmit power increases.	The effects of noise were ignored. Single source and destination situation.
[101]	Based on the battery's charging/discharging behavior.	DF	Outage probability	Rayleigh fading	*Not specified*	0.001 outage probability at 40 dB transmit power. Battery status into relay selection significantly improves the outage performance	Single relay selection. Effect of noise and delay issues were not considered.
[102]	Relay selection algorithms with considering the mobility effects. UAV-enabled mobile relaying.	Mobile relaying	Throughput	Free-space path loss model	*Not specified*	5 & 8 bps/Hz at 20 & 30 dBm transmit power respectively.	Using UAV in high mobility relay selection is very challenging. SWIPT was not considered.
[103]	Proposed hybrid time switching and power splitting relaying protocol (HTPR)	AF	Average EH and ergodic capacity. Throughput vs	Rayleigh fading	MATLAB	2.8 bps/Hz at 10 dB Ergodic capacity 3.5 bps/Hz at average harvested energy 1 and transmit power is 5dB.	Battery level of the relay was ignored.

selection in multi-antenna AF relay communication networks to protect from the eavesdroppers. Liu *et al.* [109] presented secured DF relay SWIPT systems with PS schemes by considering linear and nonlinear energy harvesting models. Beamforming algorithm which minimizes the total transmit power to secure the network from the eavesdroppers was proposed in [110]. Usage of artificial noise (AN) technique is another dimension of security on this network [111]. Power beacon is another way to secure such network [112]. Some other relevant works on security in SWIPT-CoR network were done in [113]–[115].

Table 14 presents the critical review of these PHY layer security issues in SWIPT-CoR network.

IV. ROLES OF SWIPT AND CoR IN 5G NETWORK

The 5th generation or 5G is an emerging wireless cellular network which is expected to tackle the challenges faced by the 4th generation wireless cellular networks. 5G is envisioned to provide higher data rates, lower end-to-end latency, ubiquitous connectivity, lower energy consumption with minimum cost compared to 4G [1]. Researchers are creating new applications in directions of augmented and virtual reality, IoT, ultra-fast internet connectivity, automated cars, D2D communications, e-health care, Machine to Machine (M2M) communications, smart cities or homes and many more.

5G is a network which comprises various tiers of the network with different sizes and transmit-powers. It consists

TABLE 14. Review of the Papers related to the PHY layer Security in SWIPT-CoR.

Paper	Key features	Relay type	Relaying protocol	Layer	Performance metrics	Simulation tool	Results/Findings	Remark
[105]	The impact of power splitting factor (PSF) was investigated in SWIPT-CoR based underlay CRN to detect the presence of an eavesdropper.	DF	PSR	Physical	Secrecy outage probability (SOP)	MATLAB	SOP can be reduced by higher transmit power of secondary user, higher tolerable primary interference threshold and higher conversion efficiency with an optimal PSF value.	Prone to the issue of false detection of an eavesdropper. Practical implementation is very complex.
[106]	The impact of power splitting factor (PSF) was investigated. Considered interception probability and power shortage constraint of the relay.	DF	PSR	Physical	Outage probability	MATLAB	Outage probability increases as the relay activation threshold or receiver average SNR or eavesdropper increases.	Relay activation threshold (minimum power level for relaying) was introduced for the performance analysis.
[107]	Harvest-and-jam relay protocol was proposed. Used artificial noise (AN) to interfere with the eavesdropper.	AF	*Not specified*	Physical	Secrecy rate vs source transmit power Secrecy rate vs relay transmit power	*Not specified (numerical simulation)*	5bps/Hz at 0.4 W and 5.1 bps/Hz at 1 W 5.5bps/Hz at 0.4 W and 5.99 bps/Hz at 1 W	Additional multi-antenna helping nodes are needed.
[108]	Proposed opportunistic relay selection scheme considering the security issue in SWIPT-CoR network.	AF	*Not specified*	Physical	Ergodic achievable secrecy capacity vs SNR and number of relay	*Not specified (numerical simulation)*	2.8 at 25 to 50 dB 1.5 at 5 number of relays and 2 at 8 number of relays.	Power constraint of the relays was not considered.
[109]	Security issues investigated on linear and non-linear models of EH.	DF	PSR	Physical	Harvested energy, outage probability and optimal PS ratio vs source power. Outage probability vs location.	*Not specified (numerical simulation)*	If eavesdropper is present, increasing the source power transmission does not provide better system outage performance and has an optimal value.	Interception capability and power shortage constraint of the relay were not considered.
[110]	Designed a secure beamforming scheme considering power splitting SWIPT and MISO based multi-users.	---	---	Physical	Transmission power vs secrecy rate. Transmission power vs harvested power.	*Not specified (numerical simulation)*	Compared to another scheme it achieved similar secrecy rate but with a lower total transmit power considering the same energy harvesting constraints.	Relay node was not considered.
[111]	Splitting the transmit power into two parts: i) to send the confidential message to the information receiver and ii) to send artificial noise (AN) to the energy receiver which might be an eavesdropper.	---	----	Physical	Outage probability. Harvested power vs non-outage probability and ergodic secrecy capacity.	*Not specified (numerical simulation)*	Achieved better ergodic secrecy capacity and rate-energy tradeoff gains as compared with the non-AN scheme.	Extra cost involvement as additional AN has to use. Prone to excessive interference.
[113]	Proposed secure relay beamforming (SRB) scheme for SWIPT in a nonregenerative multiantenna relay network.	AF	*Not specified*	Physical	average secrecy rate vs the maximum transmit power of the relay to noise power ratio	*Not specified (numerical simulation)*	Achieved better secrecy rate and lower computational complexity than the non-SRB schemes. 2.7 bps/Hz at 25 dB	The relay is equipped with multiple antennas while the source with a single antenna.

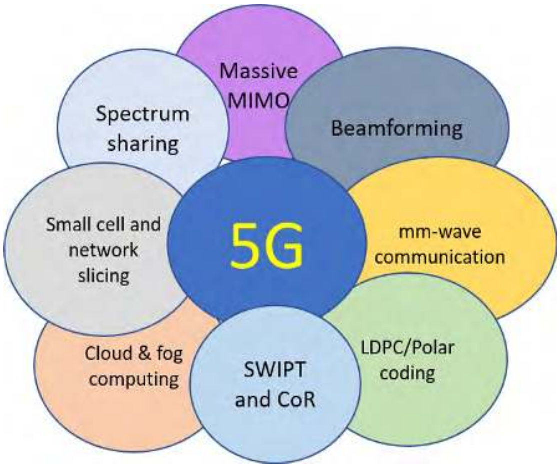


FIGURE 8. Some prominent techniques of 5G [1], [117].

TABLE 15. Some requirements of 5G [1], [116], [118]–[121] and Roles of SWIPT and CoR.

Requirement	Description	SWIPT	Relay
Data rate	1~10 Gbps data rates [60] or beyond		✓
Latency	2-5 ms as end-to-end latency [64] *(some researchers suggest 1 ms round-trip latency* [60])		✓
Needs more bandwidth	To support a huge number of connected devices for longer duration in a place. Allows connections of more than 1 million devices per square km. Need to use millimeter-wave frequency bands		✓
To support the massive number of devices	Cope up with the IoT vision, a huge number of devices, relays would be connected, needs BS densification. Implementations of D2D and mMTC (massive Machine-type communication).		✓
Always available	Perceived availability of 99.999%		✓
Ubiquitous connection	100% coverage for any time and anywhere.		✓
Energy efficiency	Energy reduction by almost 90% and green communication system. SWIPT is a promising EH technology for 5G wireless networks in this regard.	✓	✓
Longer battery life	Power consumption reduction and longer battery life of the device	✓	

of various backhaul connectivity and several radio access technologies (RATs) that can support a giant number of smart and heterogeneous wireless devices [116].

5G is a collection of several prominent technologies, some are inherited from 4G and some are new innovations. Some of those prominent techniques are listed in Fig. 8.

Some of the major requirements of 5G compared to 4G or backward systems identified by the researchers are given in Table 15. CoR and SWIPT can play very vital roles in 5G implementations and to fulfill some of the requirement. EE and longer battery life requirement can be fulfilled by SWIPT [116] and CoR [117], [122]. Moreover, by using CoR, we can ensure the ubiquitous connection and all-time connectivity requirement. If the devices are in a distant location and cannot communicate directly to the eNodB, relay mechanism can help the device to communicate. As already discussed in previous sections, CoR and SWIPT together can provide better throughput, so to achieve higher data rate, these techniques can be used in 5G. In the case of 99.999% availability requirement, relay nodes create the alternative/backup routes for the devices and provide reliable communication [122].

There is a paradigm shift observed in the 5G network; the networks before 5G were BS centric, but now the network architectures have been shifted to the user-centric. User devices are now not only used as the end devices but also used in relaying, data storing and computational functions cooperatively [1]. In summary, it can be said that CoR and SWIPT would be an integral part of 5G to meet some of the requirements effectively and efficiently. Relays are helping the network to reach to the remote networks. The eNodeB can be SWIPT enabled to transfer power to the nearby relays, UEs or to the other receivers that can do energy harvesting for powering up [116]. Numerous works were done with the integration of SWIPT and CoR in 5G to make it more energy and spectral efficient and greener network. The roles of SWIPT and CoR in 5G networks for ensuring the EE were discussed in [32]. They emphasized the greener 5G networks. They reviewed SWIPT-CoR in 5G along with C-RAN (cognitive radio access network). Na *et al.* [123] proposed sub-carrier allocation based SWIPT algorithm in 5G OFDM (Orthogonal frequency-division multiplexing) communication systems considering AF relay.

A general 5G network architecture is illustrated in Fig. 9. Various networks and applications of 5G have been shown along with the concept of SWIPT and CoR. 5G is a multi-tier network consists of several microcells, picocells, and femtocells.

V. INTEGRAL ASPECTS OF SWIPT AND CoR TO OTHER PROMINENT NETWORKS AND TECHNIQUES

This section presents some integral aspects of SWIPT and CoR to some NGWNS and techniques. the amalgamation of these two emerging technologies can be used in various wireless networks and techniques like device-to-device (D2D), vehicular ad hoc network (VANET), wireless body area network (WBAN), wireless sensor network (WSN), MIMO, CRN and so on (see Fig. 10).

A. CoR-SWIPT ENABLED WSN

Academics and industries have a huge interest in the wireless sensor network due to its recent advancements, versatile applications, increased performances and possessing of very low cost. A WSN is a network consists of tiny wireless nodes (called sensors), having embedded CPU and limited computational power, used to monitor various parameters

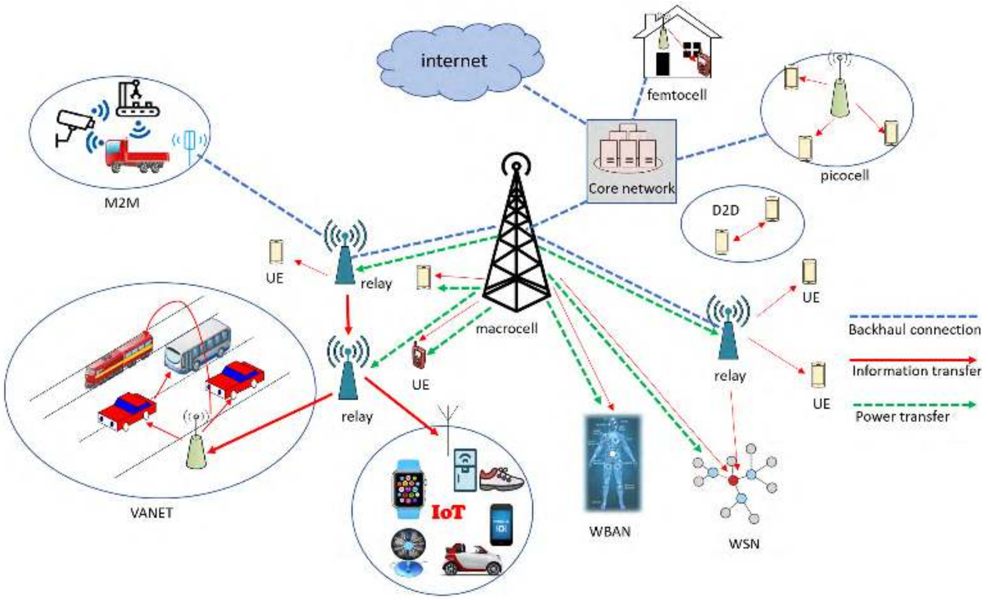


FIGURE 9. General 5G Network Architecture with CoR and SWIPT.

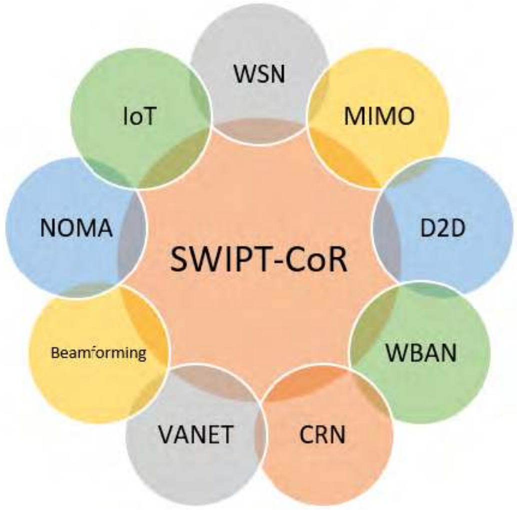


FIGURE 10. Some prominent networks and techniques with SWIPT-CoR.

like temperature, humidity, pressure, movement and so one. After sensing the value of these parameters, it sends to the receiver or to the sink by its own transmitting antenna [124].

The sensor is a very battery-constrained device and sometimes it is not feasible to change its battery (like the sensors inside the wall or volcano). So, any external power supply should be provided and has to ensure EE communication [114]. Incorporation of CoR and SWIPT in WSN is a fantastic idea to provide the EE, longer battery life and enhanced QoS [115].

A typical network of SWIPT-relay enabled WSN is shown in Fig. 11. There are three clusters shown in the figure. A sensor node in this cluster network cannot send information directly to the sink, it has to send to the cluster head of its own cluster then the cluster head will transfer the information to the sink. A relay node can relay the sensor's information to the cluster head or the cluster head's information to the sink. In return, these relay nodes do the energy harvesting by utilizing the energy getting from the cluster heads. One cluster head can also send wireless power to another cluster head [125].

Here, by using the CoR and SWIPT, the WSN can get the following benefits [125]:

i. Sensor who are quite far away to the cluster head can send the message via the relay node, so it solves this sensor node's shortage coverage problem. Moreover, it saves its energy too as it spends less energy compared to the case of without using a relay.

ii. The relay node will get the compensation by doing the energy harvesting by utilizing the energy receives from the cluster head.

iii. Overall network performance increases.

Zhou *et al.* [126] gave comparisons with noncooperative transmission schemes with the cooperative scheme and found that significant amount of energy can be saved. Their proposed cooperative transmission scheme was based on distributed space-time block code targeted to reduce the energy consumption by the sensors. In their scheme, only the sensor which can decode the message can participate in the cooperative transmission. They used packet-error-rate on their analysis.

The WiTricity Corp. [127] and Qualcomm [128] created small-sized and light weighted products equipped with wireless charging vehicle (WCV) to perform wireless power transfer. Sensors can be also charged by the unmanned aerial vehicles (UAVs) [129].

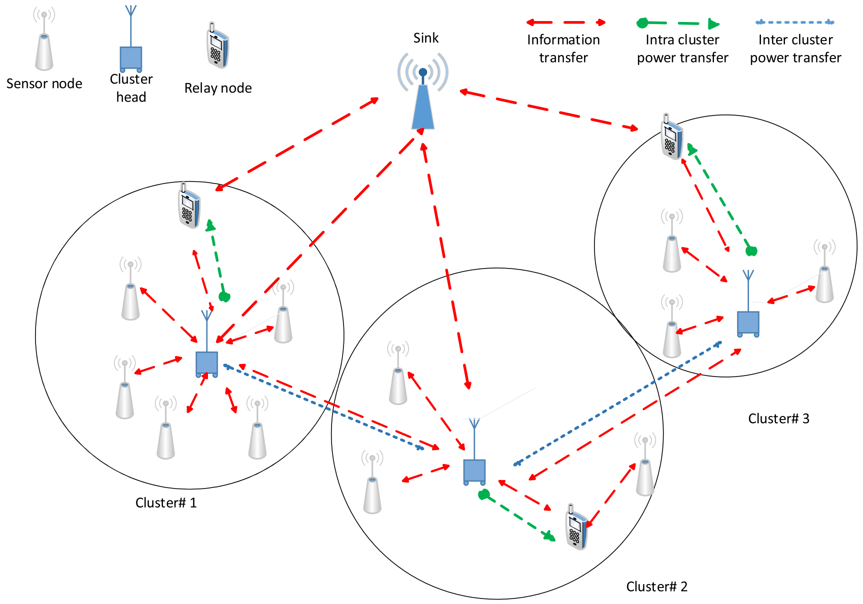


FIGURE 11. **Cluster-based WSN with SWIPT and a cooperative relay node (redrawn from [17] and [125]).**

Li *et al.* [130] proposed a charging-aware routing protocol (J-RoC) for energy efficient WSN. Theoretical studies on the efficient use of wireless power transfer in WSNs conducted in [131]. Dynamic routing algorithm was proposed for renewable WSN with wireless power transfer in [132]. Simultaneous data gathering and recharging the sensor related works were done in [133]–[135].

Future Research Issues: The mobility of the sensor node, choosing the cluster head based on battery power level, the positioning of the sensors and fading of the channels are few of the several challenges are still having to face by the researchers in this relay-SWIPT WSNs. Works on energy storage capability and PHY layer are still on demand.

B. MIMO-SWIPT BASED CoR NETWORK

Multiple input multiple output or MIMO is an antenna method which multiplies the capacity of the wireless channel by exploiting multiple transmit and receive antennas. Lots of research works have been done for the last two decades. The technique is now used in almost all the prominent wireless networks like IEEE802.11n (Wi-fi), HSPA (high-speed packet access), LTE (Long-term evolution), WiMAX (Worldwide Interoperability for Microwave Access). MIMO significantly improves the reliability and capacity of these wireless networks [136]. Now, MIMO's trends have changed from single user to multi-user. In multi-user MIMO, a base station (BS) consists multiple antennas can serve several single users consisting single antenna with the benefits of multiplexing gain [137]. Massive MIMO (also known as large-scale antenna systems or very large MIMO) is MIMO's recent advancement which contains many transmitter and receiver antennas. This sub-6 GHz physical-layer technology multiplies the advantages of simple MIMO and now is an integral part of 5G or the next generation wireless system [138].

Incorporation of CoR and SWIPT in MIMO system can enhance the overall network performance with more spectral and energy efficient manner [139].

A typical MIMO based SWIPT-CoR network is illustrated in Fig. 12. Here, the energy constraint relay nodes are equipped with multiple antennas. A set of antennas of a relay node are used for the ID and another set of antennas are used for the EH. The SWIPT based transmitters can simultaneously send information and power wirelessly.

MIMO based relay network allows serving multiple source-destination pairs simultaneously. SWIPT technique encourages the inactive MIMO nodes to act as relays to cooperate with other devices or nodes. In return, these nodes can increase their battery power by EH. So, the integration of SWIPT-CoR with MIMO will create another possibility for the network's performance improvement [84]. Discussion regarding performance comparisons of SWIPT-CoR MIMO system was provided in [19].

Amarasuriya *et al.* [139] investigated SWIPT based relay networks with massive MIMO. On their energy-rate tradeoff analysis, they revealed that needed to transmit power at each user node can be reduced if the number of relay antennas is increased. They showed that MIMO based SWIPT-CoR network gives much better performance than the conventional SWIPT-CoR network. Krikidis *et al.* [84] proposed a low complexity antenna switching scheme SWIPT-MIMO based relay network. Here, some antennas would be selected for the ID and transmitting or receiving and rest of the antenna would be used for the EH. Their proposed scheme was based on the principles of the generalized selection combiner (GSC).

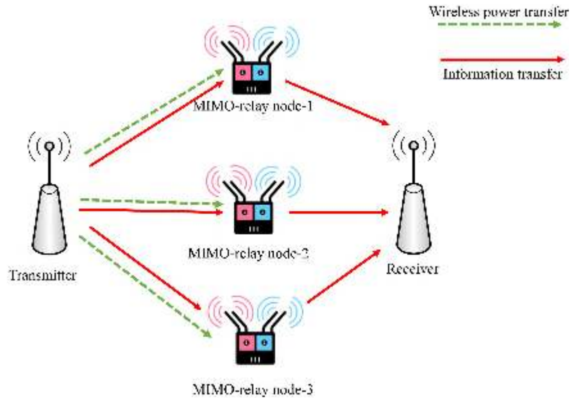


FIGURE 12. **A typical MIMO and SWIPT based relay network.**

In [12], optimal and suboptimal relay selection policies were developed for yielding the optimal tradeoff in a maximum capacity/minimum outage probability sense subjected to a pre-defined energy transfer constraint. Optimum performance boundaries of two-hop MIMO based AF relay system with multi-antenna EH receiver were studied in [140]. For data transmission, they used orthogonal space-time block codes (OSTBC) at both sources and relay nodes. The tradeoff between information rate and energy was characterized by the boundaries of the rate-energy region and the tradeoff between outage probability and energy were by outage probability-energy region. They considered two cases: i) when perfect CSI is available and ii) only the second-order statistics of CSI is available.

Liao *et al.* [141] investigated SWIPT-MIMO based PS relaying. They first considered uniform source precoding and did the optimization of the relay matrix and PS ratio to maximize the rate subject to the power constraints. After that, they did the optimization of the source covariance. Their proposed iterative schemes for two cases gave them near-optimal solutions. System achievable rate and optimization for the MIMO–OFDM DF relaying system with SWIPT were investigated in [142]. They proposed two protocols: i) TS-based DF relaying (TSDFR) and ii) PS-based DF relaying (PSDFR) protocols to enable SWIPT at the relay. On their investigation, it was found that the position of the EH-relays has great effect to the system performance, they got the worst performance when the relays are set to the middle place of the source and the destination. Other works related to MIMO-SWIPT based relay network were done in [143]–[145].

Future Research Issues: There are still lots of research works are needed for implementing the SWIPT-MIMO based relay network. Managing several numbers of antennas in a device and especially in small devices is a very big challenge both for the researchers and for the industries. Therefore, more works are needed at the hardware level to get the benefits of SWIPT-MIMO based relay network. Due to path loss and multipath fading, using this integration technique for the long-distance communication is still not in satisfactory level. More researches are needed on this. Full duplex communication can increase the overall system performance. The loopback interference issue creates an obstacle for practical implementation. Therefore, advance solutions are expected to solve the issue. Interested readers are referred to [19] for other research directions in this field.

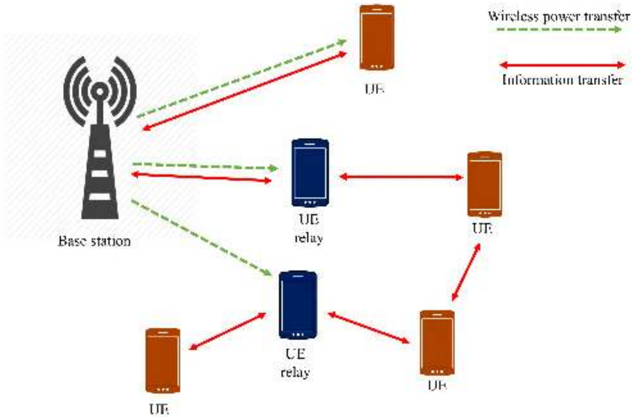


FIGURE 13. **SWIPT-relay based D2D communication.**

C. SWIPT, CoR IN D2D COMMUNICATIONS

D2D communication is one of the most advanced techniques for future communication systems. It is a candidate for the green 5th generation (5G) wireless communication, which is still under research. D2D communication can provide SE and EE, as well as improved QoS, to the users [146].

Fig. 13 shows SWIPT-relay based D2D communication scenario. User equipment (UE) or mobile users can communicate with each other directly. It can communicate without or with a little help of base station BS or Evolved Node B (eNodeB or eNB) [147].

Relay nodes can be used to increase reliability and to extend coverage and to solve the problems such as fading and path loss. These intermediate relay nodes are known as user equipment relays (UER) [148]. But, these UER have to expend their own energy to relay the information. SWIPT has emerged as a solution to this. SWIPT enabled BS or eNB transmits wireless power, UER receives this power and does the energy harvesting. Now, UER can relay the information by using this produced energy. Due to the broadcast nature of the wireless power transfer, any UE can also be benefitted by harvesting energy from this wireless power transfer.

This field is new to the researchers and has great potential. Yang *et al.* [149] proposed a transmission mode selection scheme and UER selection mechanism. They showed that the outage probability was far smaller in EH-relay based D2D communication compare to without EH-relay. Extensive works on security and cognitive radio aspects in SWIPT-CoR based D2D communication were done by Liu *et al.* [150].

Future Research Issues: Interference elimination between the UEs is a major challenge in SWIPT-CoR based D2D communication. Beamforming and the multi-antenna system can improve the recent performance of D2D communication. Security is one of the biggest issues in D2D,

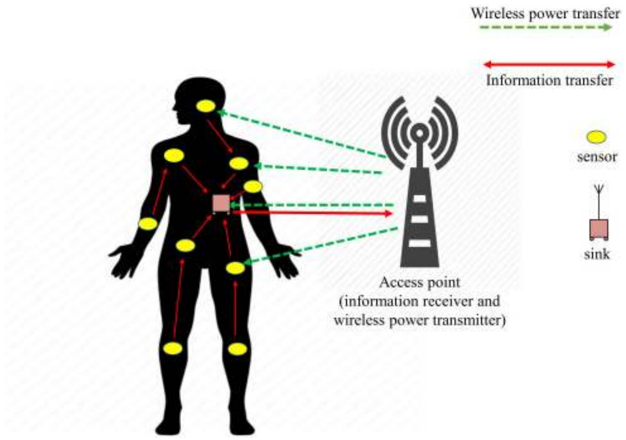


FIGURE 14. SWIPT-relay based typical WBAN.

especially authentication problem, man-in-the-middle attack, eavesdropping and so on. Extensive research on the security aspect of this communication is now the timely demand.

D. SWIPT-CoR IN WBAN

Another blessing of modern technology is WBAN. Some special purpose sensor nodes are implanted into the body (not necessarily it is a human body, but it can be non-human body also) and some devices are worn for continuous monitoring the health conditions of the patients. Patient's critical as well as non-critical conditions can be monitored from any place and at any time or on a continuous basis. WBAN is not an only a blessing for the patients but also used for the sportsperson to track his/her performance and improvement. WBAN is a system of inter-networking of the sensors, other devices, and communication networks. Advance assessment of the patients can be done and leads to take immediate actions to save the patients [151], [152].

WBAN is a special type of WSN and needs a proper system design. The latest standard for WBAN is IEEE 802.15.6 which aims to provide short distant reliable wireless communication with very low power [153].

Generally, the implantable sensor nodes' operating frequency is 400 MHz using the Medical Implantable Communication Service (MICS) band and the wearable devices at Industrial, Scientific and Medical (ISM) or Ultra-Wide Band (UWB) [154].

The lifetime of the implanted sensors inside the body depends on the battery life. Changing the battery or changing the sensor is not so easy task. To prolong the battery life i.e. the sensor's life, some external power source is needed. If the sensors can do the energy harvesting by getting the power from the external access point or the power transmitter, it can extend its battery life/ own life longer. SWIPT, in this case, plays a significant role. The SWIPT enabled access point not only to receive a signal from the sink but also can transmit the power wirelessly (Please see the Fig. 14). To be noted here that, AP is a device which is connected to the internet and act as a data receiver and a wireless power transmitter, it might work in the communication system like wi-fi, Bluetooth, 3G, LTE etc. [155]. Sensors send their data to the sink which forwards the data to the AP which forwards these data to the appropriate place like hospital or health center [156].

Some sensors inside the body send their data to the sink directly and some sensors send their data via other sensors that are acted as relay nodes. For the emergency data, direct communication is chosen and for the normal data, relaying or multi-hop is chosen. Relay nodes (sensors) are also used to mitigate path loss or fading problem [157]. So, SWIPT and relay system can provide more reliability and SE and EE to WBAN.

Combination of SWIPT, relay, and WBAN is a very new area for the researchers. Only a few works were done in this area, though the number is increasing. Ling *et al.* [158] considered SWIPT based relay in WBAN. Their solution was aimed to maximize the information throughput from sensors/sink to an AP in WBAN.

Future Research Issues: The related area of research is just flourishing. There is a lot of opportunities to work in this field. Health hazard issues related to this network can be investigated. Mitigating interference caused by multiple WBANs in close proximity is a great challenge. The positioning of the sensors and the sinks, routing, usage of cognitive radio in this field for ubiquitous communication and securing privacy of the data are few examples of future research works.

E. SWIPT BASED COOPERATIVE RELAY IN CRN

Cognitive radio is the concept of the efficient utilization of the limited spectrum resource. The main concept of cognitive radio is to use the under-utilized spectrum opportunistically by changing its transmission parameters learned from the surrounding environment. The learning or cognitive process includes acquiring information regarding communication parameters and obtaining any unused spectrum by sensing the environments. Adaptive and dynamic reconfiguration of the transmission parameters like transmission power, the value of SNR, modulation scheme etc. allows achieving increased utilization of the spectrum [159]. This revolutionary concept was first introduced by Mitola and Maguire [160] and Mitola [161]. Later Haykins [162] extended the concept and provided an excellent insight of CR which is treated as an intelligent wireless communication system.

In the CRN system, unlicensed users or secondary users (SUs) sense the licensed frequency whether it is unoccupied from its allowed users or primary users (PUs). If SU finds any vacant frequency from the licensed frequencies, then it uses this by giving a guarantee that it will release the frequency when any PU intends to use the same frequency. SU has to use a certain level of transmitting power so that interferences cannot disturb the PU [163].

In SWIPT-CoR based cognitive radio, a PU provides wireless power and spectrum to an SU and in return, the SU relays the PU's data (see Fig. 15). This cooperation provides better system performance. PU gets the benefits like large coverage

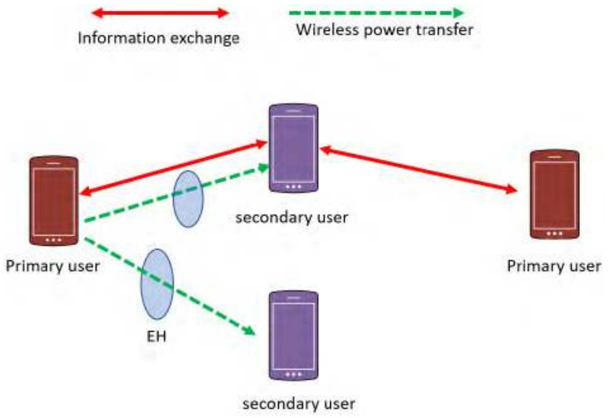


FIGURE 15. SWIPT-CoR based CRN.

and improved throughput, on the other hand, SU can harvest energy to boost up its battery power or the required power for its transmission if it is battery-less [164], [165].

There are several works have been done in this field. Al-Habob *et al.* [166] investigated the SWIPT-CoR based CRN consists of multiple primary receivers. They considered single source which communicates via a DF relay node which utilizes PS protocol to do EH and ID from the same received signal. Yang *et al.* [167] analyzed outage performance of SWIPT-CoR based CRN. Similar outage analysis was done in [165] for SWIPT-CoR based two-way CRN. They analyzed the impacts of power splitting factor for SWIPT and relay location while analyzing the system outage performance. The performance of opportunistic relay selection (ORS) in a cognitive radio was analyzed in [168] over flat Rayleigh fading channels. El Shafie *et al.* [164] proposed cooperative access schemes for SWIPT transmission in CRN.

Zheng *et al.* [169] investigated energy cooperation between PU and SU in CRN along with existing information cooperation. An opportunistic relaying scheme along with dynamic EH in SWIPT-CoR based CRN was proposed in [170]. They made a framework that can merge direct transmission, relay transmission, and energy harvesting. They solved two non-convex problems by using the dual Lagrangian method. A new TSR protocol for multi-destination dual-hop underlay SWIPT-CoR based CRN was proposed in [171].

Future Research Issues: Though lots of works have been done, still there are huge potential research problems to solve in this research area. Full duplex relaying in SWIPT based CRN is an interesting topic to do the research [172]. Further investigations are needed on the interference issues created by the SU and the relay. The whole concept is still challenging for the devices that are in mobility. MIMO implementation in this field can provide more benefits. It is expecting that the SWIPT-CoR based CRN would be more intelligent (for faster spectrum sensing issue, whether relaying has to choose or not, faster relay selection and power allocation) in near future. Machine learning approaches can be applied in this regard. Integration of UAVs into this SWIPT-CoR based CRN is another dimension to do the research. UAVs can be used to exchange the spectrum sensing information, intermediary relay nodes, and source of wireless power.

F. SWIPT BASED CoR IN VANET

VANET is a member of Mobile Ad Hoc Network (MANET) family. It is especially featured for the vehicles that communicate with other vehicles via a wireless link. They generally exchange safety information and infotainment.

VANET is assumed to first appeared in 2001 as ‘‘car-to-car ad-hoc mobile communication and networking applications’’ where cars can form network and relay information among them [173].

It is mainly motivated by Intelligent Transportation System (ITS) and Wireless Access in Vehicle Environment (WAVE) [174].

There are different communication modes available in VANET. They are [175], [176]:

a. *vehicle-to-vehicle (V2V) communication*
b. *vehicle-to-infrastructure (V2I) or infrastructure-to-vehicle (I2V) communication*
c. *infrastructure -to- infrastructure (I2I) communication*
d. *Vehicle-to-person or vehicle-to-pedestrian (V2P) communication.*

VANET is already using the cooperative relay technique for relaying data among the vehicles. A car can send its information to the RSU or to the BS or AP via another car (V2V) which acts as a relay. Incorporation of SWIPT can make this VANET greener. This integration will give the SE and the EE and can also help to reduce the carbon footprints. RSUs or the vehicles (OBU: Onboard Unit) can take wireless power transmitted by the SWIPT enabled BTS/BS. By doing energy harvesting, RSUs or the vehicles can increase their power level [177]. A Contemporary survey regarding EH issue in VANET can be found in [178]. The authors investigated the feasibility of EH in VANET, discussed its different challenges confronting its applicability in vehicular environments and open research problems and directions. Wang *et al.* [179] proposed joint power allocation and power splitting for SWIPT based vehicular network to maximize the achievable data rate with constraints on the delivered energy.

Future Research Issues: This SWIPT based cooperative VANET is a new area for the researchers. The high speed of the vehicles is one of the major challenges in this network. Traditional mobility models of MANET like Random Walk or Random Waypoint are not sufficient to cover the issues in vehicular networks. Though for these networks, few models like Manhattan mobility model and Freeway mobility were introduced but there is still on needs of more practical models to adapt [180]. Cognitive radio system can be integrated with this network to maximize the benefits in terms of SE and ubiquitous communicability. Proper relay selection and power allocation is another direction. More extensive researches are needed for the proper antenna design for this network. Clustering based VANETs along with SWIPT-CoR is another dimension for the research.

G. SWIPT-CoR WITH BEAMFORMING TECHNIQUES

Beamforming is one the most promising technologies for the next generation wireless network. It is all about focusing RF signal in a specific direction that provides linear spatial filtering. This technique is one of the candidates for 5G to provide interference less signal to the specific users who are even in the very dense network. An array of smart antennas is used to achieve this. It is used for both transmitting and receiving sides for obtaining the spatial selectivity. To obtain a higher data rate and interference-less or interference-free communications, beamforming technique is used [181].

To achieve a higher data rate, SWIPT based beamforming relay was designed to support multiple source-destination communications in [182]. Li *et al.* [183] proposed three solutions to overcome from the optimization problems of EH-constrained relay beamforming system in SWIPT based two-way relay network. An iterative algorithm based on constrained concave-convex procedure (CCCP) to secure relay beamforming in SWIPT based cooperative network was proposed in [113]. Other relevant works of beamforming in SWIPT-based CoR network were done in [184]–[186].

Future Research Issues: There are lots of scopes to work with beamforming in SWIPT-CoR networks. More researches are needed for the practical implementations. Distributed beamforming is a direction for future researches. Proper synchronization between timing, synchronization between carrier frequencies and information sharing are needed. New cross-layer protocols and the physical layer can be designed. Beamforming for the devices that are in mobility is a very challenging job. Hybrid beamforming (integration of digital circuits with analog phase shifters) is another dimension to work with it.

H. SWIPT-CoR WITH NOMA

Another emerging technology for the NGWNs is NOMA (non-orthogonal multiple access). In NOMA, the signals have significant differences in power level. It is used to improve the SE of the network by superposing multiple users in a power domain (that means by using NOMA, more users can be supported in a network at a time). It is a new technique for 5G (not used before in 3G or 4G) [187].

In general, the near NOMA users relay information to the far NOMA users who have poor channel conditions. Near NOMA users are energy-constrained but still, they have to expend their own battery power for relaying. As a result, this relaying shortens their lifetime. Again, SWIPT in this scenario helps those near NOMA users (relays) to generate the required power for the relaying by doing EH. Therefore, the combination of SWIPT, CoR and NOMA would play significant roles in SE and EE [187].

There are several types of research have been done in the field of SWIPT-NOMA based CoR network. To maximize data rate, Xu *et al.* [188] proposed multiple-input-single-output (MISO) based SWIPT-NOMA protocol in DF-CoR network.

Do *et al.* [189] analyzed the performance of transmit antenna selection (TAS) schemes. They considered a two-user MISO-NOMA based CoR network where the near users are SWIPT enabled. They considered DF relaying. Liu *et al.* [120] proposed a cooperative SWIPT NOMA protocol with three different user selection criteria.

Yang *et al.* [190] investigated two types of power allocation policies: i) NOMA with fixed power allocation (F-NOMA) and ii) cognitive radio inspired NOMA (CR-NOMA) in a SWIPT based CoR network. Their policies significantly reduced the outage probability compared to the conventional networks.

Performance analysis for SWIPT-NOMA based CoR networks with TAS and MRC over Nakagami-m fading was done in [191]. They considered multi-antenna and AF relay for relaying the information. In transmitting end, every source user had multiple antennas. Among those antennas, a single antenna was selected which could give the maximum channel gain. The relay does the PS-EH by using the signals received. By using this harvested energy, the relay broadcasts the superposed signals to the receiver. Due to having multiple antennas in the receiving end, MRC rule was imposed on the received signals for decoding the information.

Future Research Issues: Most of the works done in SWIPT-NOMA based CoR networks considering the ideal assumptions. But for the practical implementations of SWIPT-NOMA based CoR networks, there are several obstacles the researchers have to face. Some of them are hardware impairments, the nonlinear characteristic of EH, energy consumption by circuit etc. More researches are needed to secure SWIPT-NOMA based CoR networks. Researches on the mobility issues of the devices and the usage of mmWave are also further needed.

I. SWIPT AND CoR IN IoT

IoT is an ever-growing next generation internetworking system which will connect almost ‘everything’ like vehicles, households or home appliances, sensors, animals, machinery and so on. As mentioned earlier, around 46 billion IoT devices will be connected by 2020 according to the Bell lab’s calculation (while according to Cisco and Gartner the number is 39 billion and 26 billion respectively) [7]. In general, 1 W (watt) or less power is needed by a single IoT device to operate. So, the cumulative requirement would be around 1 W multiplied by the total number of IoT devices (maybe 46, 39 or 26 billion). This power requirement is much more than the current total power consumption which is around 12 billion W by the cellular networks available worldwide [192]. Therefore, the upcoming biggest challenge is to provide this huge amount of power to the IoT devices. Moreover, carbon emission by this huge number of devices and e-wastes are another threat to obtain the greener future. To solve these issues, EE must be ensured. Relaying is a great technique to provide such EE to the network. As the relay nodes are also energy constrained and therefore they must be powered up either by the external dedicated power source or EH process by using the ambient RF signal. SWIPT in this regard can be the optimal solution. As providing information and power simultaneously, SWIPT is only a source of power but also provides SE to the network. Nevertheless, SWIPT and CoR will play a very major role in the deployment of massive IoT devices to ensure the EE and SE.

Needs of SWIPT-CoR in IoT were elaborated in [192]. The authors investigated the scopes and opportunities of SWIPT-CoR in IoT network. The reliability performances of SWIPT-CoR were done in [193].

Future Research Issues: Massive M2M communication in IoT networks has eventually opened several doors for the researchers. Incorporating SWIPT and CoR in IoT is relatively new in this area to explore. New energy modeling is needed to develop by considering energy consumptions by both transmitters and receivers [192]. A relay node's mode switching scheme, as well as advanced relay selection mechanisms, are to be developed. Discontinuous transmission (DTX) or receiving (DRX) can be developed for the relay nodes to save energy. In DTX or DRX, the relay node will be on silent mode while it has nothing to send or receive or to relay. Mobility issues of the IoT devices should be taken into care, the Doppler effects of the mobile IoT devices can be considered for further researches.

Table 16 reviews some of the papers presented on Section IV and V.

VI. OPEN ISSUES, CHALLENGES, AND FUTURE RESEARCH DIRECTIONS

In the previous sections, we have reviewed some aspects of the combined use of SWIPT and CoR. We have also mentioned the future directions of the researches of these integrated techniques. Together both these techniques provide several common research issues in different SWIPT-CoR enabled emerging communication technologies. In this section, we highlight some of the future research issues and challenges in SWIPT-CoR based communication networks.

A. SWIPT-CoR FOR HIGH-SPEED MOBILITY

One of the major concern in wireless networks is the high-speed mobility of the nodes, power source, and the information gateway. As time-varying nature of EH and information transmission, the resource allocation scheme has to be real-time and adaptive for mobile nodes. A node's power level decreases due to mobility and it affects the relay selection methods. Moreover, mobility issue affects the availability of the CSI of the network. This situation creates a big challenge for the researchers. Advanced beamforming technique can be integrated to mitigate the issue [194]. Few investigations [195] on the mobility models were done but need more attention to this area to develop more sophisticated models. In summary, further researches are needed to be carried out in this mobility issue.

B. HARDWARE LIMITATIONS

Extensive researches on the practical hardware related to SWIPT-CoR are on timely demand. For the practical implementations of the SWIPT-CoR, hardware impairment is one of the vital obstacles. For example, some researchers suggested to use MIMO and massive MIMO in SWIPT-CoR for massive improvement of the network performances, but it is still a great challenge to put an array of antennas into a device especially if it is small sized like small sensors. Moreover, embedding RF-EH components (like antenna, rectifier and matching network) into a small device is a very big challenge. Other issues of the RF-EH components are impedance mismatch, quadrature imbalance and oscillator phase noise. Attentions are needed to develop new circuit and antenna design to solve these issues.

C. HEALTH ISSUES

There are several types of research were done to investigate the effects on health through wireless communication. Masao and Soichi [196] showed several concerns and effects of RF signal into our health. They concluded that extensive RF signal could damage human health seriously. They found neurological effects due to the RF signal. One experiment [197] showed that due to the presence of the RF signal, physical response time and memory reaction speeds getting slower compared to the normal scenario (absence of RF signal). Moreover, in SWIPT-CoR network, more RF power will be transmitted. So, there are some chances of possible health hazards by this power. Therefore, some intensive researches and investigations need to be carried out to ensure the safety issues related to health.

D. SECURITY ISSUES

Section III has discussed the security issues in SWIPT-CoR network. Though lots of works were done in this area, still there are huge potentialities to work on it. Authentication issue for the relay nodes, special security concern while choosing the best relay, trade-off analysis between delay and security, cross-layer security implementations are some of the potential dimensions on this field. In summary, more attention is needed to develop more dynamic and adaptive security mechanisms in this emerging SWIPT-CoR network.

E. SWIPT-CoR WITH NETWORK CODING TECHNIQUES

Wireless signal suffers from noise, interference, fading etc. that lead the received signal corrupted. Hence proper coding technique is needed. There are several works were done to face these challenges. Mekikis *et al.* [198] did the performance analysis of network coding in EH based CoR network. Their proposed coding scheme along with EH increased the lifetime of the network significantly. That means proper network coding can be used to increase the EE of the network [199]. For SWIPT-CoR network, two coding methods can be very useful i) Polar codes [200], [201] and ii) LDPC (low-density parity-check) codes [202]. Still, there are lots

TABLE 16. Review of Some articles presented in Section IV and V.

Application	Paper	Brief description	Performance metrics	EH	SWIPT	CoR	Results/Findings	*Research direction*
5G Network	[116]	Surveyed the existing cell association and power control schemes used in 5G networks.	---	✓	✓	✓	Outlined the challenges for interference management in 5G multi-tier networks.	*Combining hybrid cell association methods with the prioritized power control scheme for the 5G network.*
	[117]	Surveyed user association schemes used in 5G. Heterogeneous networks, massive MIMO networks, mmWave scenarios, EH and CoR have been surveyed.	---	✓	✓	✓	Highlighted the inherent features of the user association corresponding 5G enabling technology.	*Self-Organizing Networks (SON), Cloud radio access network (C-RAN) and full-duplex communication.*
	[123]	Sub-carrier allocation based SWIPT algorithm was proposed for 5G OFDM communication systems considering AF relay.	Convergence performances.	✓	✓	✓	Information decoding rate improves with the increase of total transmit power for the fixed threshold of harvested energy. Cooperation gives higher information decoding rate than the direct transmission case.	*The scheme can be applied with wireless caching and PHY layer security.*
WSN	[125]	Optimal power allocation and relay selection for energy efficient clustered WSN.	Convergence performances. Energy efficiency vs maximum allowed transmit power.	✓	✓	✓	Power splitting ratio plays an important role in relay selection but depends on minimum harvested energy requirement. 29bits/mJ from 25dB	*Issues related to the mobility of the sensor node, choosing the cluster head based on the battery power level, the positioning of the sensors and fading of the channels. Works on energy storage capability and PHY layer security. Mobile wireless charging system, proper positioning of it and mobile relaying.*
	[126]	Propose a cooperative transmission scheme based on distributed space-time block coding for clustered WSN.	Overall energy consumption vs packet error rate, number of a cluster member, inter-cluster distance.	✓	×	✓	Having more nodes in a cluster may not be more energy efficient. Total energy consumption can be minimized by optimally adjusting the transmit energy levels.	
	[130]	Proposed a charging-aware routing protocol (J-RoC) and charging scheme to prolong WSN lifetime	Network lifetime	✓	×	✓	Proactive guide on the routing activities of the charging system can prolong more lifetime of WSN	
	[131]	Considered the mobile charging vehicle periodically traveling inside the WSN for charging each sensor node's battery wirelessly.	Total cycle time, and individual charging time at each node.	✓	×	✓	Introduced a new concept called renewable energy cycle.	
	[19]	The article focused on the application of advanced smart antenna technologies to MIMO based SWIPT-CoR.	Harvested energy vs achievable sum rate. Outage probability.	✓	✓	✓	The combination of these techniques exploits spatial diversity and significantly enhances the system's EE. The stronger the co-channel interference, the stronger the rate gain.	*Hardware-level research to accommodate a large number of antennas into small devices to*
	[84]	Investigated SWIPT in MIMO based relay network. Proposed dynamic antenna switching between decoding and rectifying.	Outage probability	✓	✓	✓	Increases in the number of antennas increase the SE and improve the outage probability of the system.	

TABLE 16. *(Continued.)* Review of Some articles presented in Section IV and V.

MIMO	[139]	Investigated SWIPT in massive MIMO AF multi-way relay networks using PSR and TSR.	Harvested energy vs achievable sum rate	✓	✓	✓	The presence of co-channel interference can be potentially exploited for boosting the energy harvesting at the relay.	*get the benefits of SWIPT-MIMO based relay network. More works needed in MIMO based SWIPT-CoR network for long-distance & full duplex communication. Loopback interference should be reduced.*
	[140]	Investigated two-hop MIMO based AF relay system with a multi-antenna energy harvesting (EH) receiver. Orthogonal space-time block codes used at relay and maximum-ratio combining at the receiver.	Harvested energy vs achievable sum rate. Outage probability.	✓	✓	✓	Energy transfer improves when correlation increases. Outage probabilities improve with the increase of information decoder receiver.	
	[142]	Proposed two protocols: i) TS-based DF relaying (TSDFR) and ii) PS-based DF relaying (PSDFR) protocols to enable SWIPT at the relay.	Achievable rate vs source transmit power, number of antennas and carriers	✓	✓	✓	The position of the EH-relays has a great effect on the system performance, they got the worst performance when the relays are set to the middle place of the source and the destination.	
D2D communication	[146] [147]	Both papers gave detail insight into D2D for energy saving networks.	Survey-based papers focused on energy efficiency.	✓	✗	✓	EH, and relays can be used along with D2D to achieve energy efficient network.	*Interference elimination, usage of beamforming and the multi-antenna system for the improvement of D2D communication. Security issues in D2D, especially authentication problem, man-in-the-middle attack, eavesdropping and so on.*
	[149]	Proposed a transmission mode selection scheme and user equipment relays selection mechanism. Harvest energy from BS of the cellular network.	Outage probability	✓	✗	✓	D2D communication improves outage probability for EH cellular network. This performance becomes more significant when the density of BSs is small.	
	[150]	Proposed and analyzed the PHY layer security in an energy constrained D2D communication under a power constraint of BSs. Used power beacons for EH.	Outage probability. Secrecy throughput.	✓	✓	✗	Secrecy performance improves with increasing densities of power beacons and D2D receivers. Collaborative power beacons achieve better secrecy performance than schemes.	
WBAN	[157]	Proposed link-aware and EE protocol for WBAN and cooperative link-aware and EE protocol for WBAN routing schemes. Focused on collaborative learning and path loss.	Stability period. Residual energy. Network lifetime. Throughput. Delay spread. Path-loss.	✓	✗	✓	Each sensor would share each other's distance and residual energy information for selecting the best route from a given sensor to sink. Cooperative learning reduces the redundant transmission and maximizes the network throughput.	*Health hazard issues, interference caused by multiple WBANs in close proximity, the positioning of the sensors and the sinks, routing, usage of cognitive radio in this field for ubiquitous communication and securing privacy.*
	[158]	Considered PS protocol in normal circumstance and TS protocol in the abnormal circumstance at the sensor. The objective was to maximize the information throughput from the sensor to the AP.	Throughput.	✓	✓	✓	Optimal power-splitting ratio and fixed ratio have a different impact on throughput performance. Under the optimal time switching ratio, information throughput is greater compared to other time switching ratio.	

TABLE 16. ***(Continued.)*** **Review of Some articles presented in Section IV and V.**

CRN	[164]	Investigated joint information and energy cooperative schemes in a slotted-time CRN. Proposed a three-stage cooperative transmission protocol and five different schemes for secondary access and powering the primary transmitter.	Average secondary sum-throughput and average primary throughput.	✓	✓	✓	Cooperative distributed beamforming increases the energy harvested at the primary transmitters and hence the achievable primary throughput (25% more).	*Full duplex relaying in SWIPT based CRN. Interference issues created by the SU and the relay. The whole concept is still challenging for the devices that are in mobility. MIMO implementation in this field. Machine learning approaches can be applied in SWIPT-CoR based CRN to make it more intelligent (for faster spectrum sensing issue, whether relaying has to choose or not, faster relay selection and power allocation). UAVs can be used to exchange the spectrum sensing information, intermediary relay nodes, and source of wireless power.*
	[165]	Used DF and PSR relaying protocol at SU to obtain closed-form expressions for outage probability of PU and SU.	Outage probability vs PSR factor, relay location. SE and EE.	✓	✓	✓	In terms of SE and EE, two-way EH DF-relay protocol is found to outperform the corresponding one- way protocol. With moderately high values of transmit power, DF relay performs better than an AF relay, while at its very high values, they have similar SE performance.	
	[166]	Studied multi-destination dual-hop underlay CRN with multiple primary receivers and DF relay based secondary users.	Outage probability.	✓	✓	✓	Applying the SWIPT technique in CoR based CRN affects the diversity order and makes it equal to one.	
	[167]	Considered underlay CRN with one primary receiver, one cognitive transmitter-receiver pair, and one EH DF relay	Outage probability.	✓	✓	✓	the use of SWIPT deteriorates outage performance but a diversity gain of 1 is achievable.	
VANET	[177]	Investigated the problem of scheduling the downlink communication from renewable energy-powered RSUs toward vehicles aimed to maximize the number of served vehicles.	Harvested energy vs the percentage of served vehicles. Number of RSUs and vehicle speed vs the service delay. Convergence time.	✓	×	✓	EH could reduce the deployment cost of RSU while maximizing the number of vehicles served and decreasing the service delay in VANETs.	*The high speed of the vehicles is one of the major challenges. Random Walk, Random Waypoint, Manhattan, Freeway or new mobility model should be developed.*
	[179]	Proposed joint power allocation and splitting (JoPAS) for SWIPT-based vehicular network.	Achievable rate-energy regions. Average rate vs. relative speed. Average rate vs. window length.	✓	✓	✓	Their proposed scheme achieved a better result than dynamic power splitting. The average rate increases while longer window length is employed in the power allocation and splitting optimization. 8.9 Mbps rate at 80 km/h speed while 9.01 Mbps rate at 120 km/h.	*Integration of machine learning and cognitive radio system in VANET to maximize the benefits in terms of SE, EE and ubiquitous communicability.*

TABLE 16. *(Continued.)* Review of Some articles presented in Section IV and V.

								Proper relay selection and power allocation is another direction. Clustering based VANETs along with SWIPT-CoR is another dimension for the research. Security enhancement in SWIPT-CoR based VANET.
Beamforming	[182]	Proposed a new beamforming scheme to achieve high data rate in SWIPT AF EH-enabled relay networks. Schemes were to support multiple source-destination nodes simultaneously (instead of serving one information transmitter at a time) in addition to the EH receiver.	Average sum rate. Convergence rate.	✓	✓	✓	Sum-rate of the increases when the number of the source-destination pairs is increased from 1 to 2 but decreases when it is from 2 to 4 due to the result of the interference between communications pairs. They found their scheme with fast convergence, that means with low complexity.	*Extensive research on practical implementations, distributed beamforming, proper synchronization between timing, synchronization between carrier frequencies and information sharing and needs to design new cross-layer protocols and the physical layer protocol. Beamforming for the devices with high speed mobility, co-channel interference mitigation, hybrid beamforming (integration of digital circuits with analog phase shifters) are some dimensions of future works.*
	[183]	Studied the optimal beamforming design problem for SWIPT in a non-regenerative two-way relaying network consisting of two source nodes, a relay node equipped with multiple antennas, and an RF energy harvester.	Average sum rate. Convergence rate.	✓	✓	✓	While having the highest computational complexity, the global optimal solution achieves the global optimum. While having lower complexity, the local optimal solution performs a little bit worse than the global optimal solution.	

of scopes for further improvement of the network coding for SWIPT-CoR network.

F. AMBIENT BACKSCATTERING

Wirelessly powered relays, in general, get lesser time to generate adequate harvested energy before transmission and they also face the problem of CCI. Ambient backscattering technique has been emerged to solve these limitations. It is also used to overcome from the limitations of the conventional backscatter communication techniques such as RFID. This technique is still in its early stage. Integration of ambient backscattering technique with SWIPT based CoR would be an interesting research direction. This hybrid relay node consisting of both prominent techniques would provide much better performance and applicability than the traditional relay node. This hybrid relaying can be further investigated in multi-hop and full-duplex scenarios.

G. USAGE OF MACHINE LEARNING METHODS

There is a huge scope to work with the machine learning (ML) methods in SWIPT-CoR. ML improves the overall performance of the relay nodes. ML can be used to detect malicious users' activities and several security threats such as jamming attack. By using ML, the pattern of the attacks by the harmful nodes in a relay network can be detected. The neural network can be used to map the CSI for the optimal transmission. Reinforcement learning, a type of ML, can be applied in the relay nodes to learn about the surrounding environment for taking proper and faster routing decision. ML can also be used in proper scheduling (switching between relaying, EH or silent mode), secured antenna selection, optimum resource allocation and so on. Nevertheless, more extensive researches should be conducted on this domain for further improvements of SWIPT-CoR network.

H. INCORPORATION WITH OTHER PROMINENT TECHNOLOGIES

SWIPT based CoR can be merged with some other prominent technologies. Few aspects of them already discussed. SWIPT-based CoR can be used with CR- based VANETs. Satellites and UAVs can be incorporated with SWIPT based CoR to provide energy and communication gateway to the remote nodes or devices or the users. QoS improvement can be done in SWIPT-CoR by utilizing a single SWIPT based relay for the multiple sources or destinations concurrently. Though few works [87], [203], [204] were done on the SWIPT based full-duplex relaying, still there are lots of opportunities to explore this area.

I. MISCELLANEOUS ISSUES

Most of the recent works done considering the transmission energy in SWIPT-CoR network, but merely focused on the energy consumption of receiving which can't be ignored while making proper scheduling scheme. When to switch the relay as receiver or conveyer and when to keep silent are needed for proper investigations. Researches of SWIPT-CoR system mainly focused on the short distance communication, but it needs to focus also on the long-distance communication. In SWIPT-CoR, a relay's battery might be overflowed by EH for longer time. On the other hand, a relay might be in shortage of power for the relaying as it has not done enough EH. Therefore, there should be adaptive switching between EH and ID of the SWIPT based system so that a relay is not getting overflowed or facing a shortage of power.

VII. CONCLUSION

This paper has surveyed simultaneous wireless information and power transfer (SWIPT) system with cooperative relaying (CoR) system. The joint usage of these two prominent techniques provides more spectrum and energy efficient wireless networks. This paper has started the discussions with the basics overview of CoR and its various types along with their advantages and disadvantages and some benefits of it. After that, the paper has focused on the energy harvesting issues, from its fundamental overview to operational overview and with types. Then, it has discussed regarding SWIPT, its basic overview, taxonomies and receiver architectures. On the following section, the operational frameworks of SWIPT-based CoR protocols and its classifications have been presented. Then, the paper focused on the resource allocation and relay selection issues of SWIPT-based CoR network along with their performance metrics. The roles of SWIPT and CoR and their integration to 5G have been elaborated. Various combined usages of SWIPT and CoR into various wireless networks have been described. The paper explored a broader perspective and the applications of SWIPT-based CoR in WSN, MIMO system, D2D, WBAN, CRN, VANET, beamforming, NOMA techniques and IoT in details with their future research directions. Research on SWIPT-based CoR is very comprehensive and lots of opportunities and challenges are coming ahead. Some of those have been mentioned. But still, more attention and researches are needed to fully explore these two prominent techniques for the further improvements of the next generation wireless networks.

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