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SURVEY

A Survey on Multiuser SWIPT Communications for 5G+

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ABSTRACT Increasing number of devices connected to the networks, applications and demands of new generation wireless communications cause very high energy consumption resulting in large amount of carbon emission. Thus, energy harvesting solutions together with accomplishing information transmission are required for energy efficient communications of new wireless communications generations such as 5G and 6G (i.e., 5G+). As such, due to the promise of energy efficient green communications, simultaneous wireless information and power transfer (SWIPT) techniques are expected to be indispensable component of 5G+. In this survey, the literature of multiuser SWIPT communications is reviewed for 5G+. Different multiuser SWIPT scenarios including multi-antenna communications, cooperative communications, network coding, communications security, and unmanned aerial vehicle (UAV)-enabled communication systems based on multiuser diversity and multiple access methods are thoroughly reviewed. The experimental studies are also discussed.

INDEX TERMS SWIPT, multiuser, multiuser diversity, multiple access, MIMO, cooperative, UAV.

LIST OF ABBREVIATIONS FREQUENTLY USED IN THE TEXT

Abbreviation	Explanation
3GPP	Third generation partnership project
ACSR	Achievable Secrecy Rate
AF	Amplify-and-forward
AHE	Average Harvested Energy
AN	Artificial-noise
AP	Access point
ARS	Artificial Redundant Signal
AS	Antenna switching
ASR	Average Secrecy Rate
BF	Beamforming
BS	Base station
CD	Code-domain
COP	Connection outage probability
CR	Cognitive radio
CSI	Channel state information
DF	Decode-and-forward
DL	Deep-learning
ECLR	Energy-constrained users with low-rate requirement
EH	Energy harvesting
EICP	Energy-information coverage probability
ESR	Ergodic secrecy rate
FD	Full-duplex
FS	Frequency splitting
H-AP	Hybrid access point
H-CRAN	Heterogeneous cloud radio access network
HD	Half-duplex
HetNet	Heterogeneous network
HRSR	High rate security requirement
ID	Information decoding
IoT	Internet of things
IRS	Intelligent reflecting surface

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LoS	Line-of-sight
LTE	Long term evolution
MAC	Medium access control
MIMO	Multiple-input multiple-output
MISO	Multiple-input single-output
MRC	Maximal ratio combining
MUD	Multiuser diversity
NOMA	Non-orthogonal multiple access
NR	New radio
OC	Opportunistic communications
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency-division multiple access
OMA	Orthogonal multiple access
PD	Power-domain
PFS	Proportional fair scheduling
PLS	Physical layer security
PS	Power splitting
QoS	Quality of service
RF	Radio frequency
SEE	Secrecy energy efficiency
SIC	Successive interference cancellation
SIMO	Single-input multiple-output
SINR	Signal-to-interference plus noise ratio
SNR	Signal-to-noise ratio
SOP	Secrecy outage probability
SWIPT	Simultaneous wireless information and power transfer
TAS	Transmit antenna selection
TDMA	Time-division multiple access
TS	Time switching
UAV	Unmanned aerial vehicle
WIPT	Wireless information and power transfer
WPCN	Wireless powered communication network
WPT	Wireless power transfer

I. INTRODUCTION

The 5G new radio (NR) features an important number of distinct signal processing algorithms to respond to the numerous requirements of the technology [1]. The upcoming telecommunications generations are further conjectured to promote continuously increasing number of different signal transforming capabilities. In addition, the innovations of new wireless communication systems (such as Internet of Things (IoT), wearable devices, ubiquitous computing, commodity sensors, smart televisions, smart buildings, smart cities, etc.) have given rise to an unprecedented scenario where the number of devices connected to the Internet is expected to rapidly exceed 50 billion with a connection density of 1 million per square kilometer [2], [3]. Moreover, the number of mobile subscribers is forecasted to exceed 7.5 billion globally in a time of a few years. The new generation communication systems with ever-increasing data rate, coverage area, connection and transmission reliability, mass connection, very low latency, spectrum efficiency requirements, growing number of networked devices, and proliferation of new applications entail an electrical energy load of about 910 TWh and cause approximately 235 million tons of carbon emissions [3]. Hence, energy scavenging solutions for energy efficient communication systems that reduce energy consumption have become imperative for 5G [4], [5] and beyond [6], [7] (in short 5G+).

Energy harvesting (EH) is the process of capturing ambient wasted or insignificant heat, sound, wind, and radio wave (radio frequency, RF) emissions and converting them into electrical energy for use in powering devices. In [8] and [9], the usability of natural energy resources for EH in wireless communication networks has been investigated and it has been concluded that these approaches are not as effective as expected due to the irregularity and unpredictability of the environmental resources. Wireless power transfer (WPT) is an EH approach that can overcome the mentioned limitations and charge the batteries of the devices in the communication network with the help of electromagnetic radiation. Green energy can be collected by WPT methods using two types of sources which rely on the signals produced by the resources already in the environment and the signals transmitted by a designated and fully controllable power source such as a base station (BS). As the distance between the BS and the end terminals in a communication network is critical for both information and power transmission, the far-field WPT techniques have been discussed in detail in the literature. In fact, the first pioneering experiment on WPT through RF signals was performed by Tesla in 1899. Since then, an important number of studies have been carried out on long-distance WPT. However, these initial works have mainly concentrated on high-power applications and the advancement of these technologies has been slow due to the health concerns and inefficiency in the implementation. Recently, many trials have been performed on the realization of self-sustainable communication systems using WPT techniques for relatively shorter distances based on inductive coupling. These approaches aim to maintain preferable quality of service (QoS) levels while supporting many current concepts such as IoT in new generation wireless networks. The need to integrate WPT approaches into wireless networks and to develop techniques that enable information and power transmission to end terminals in a concurrent fashion has led to the concept of simultaneous wireless information and power transfer (SWIPT) [10].

A. SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER

Among different energy scavenging approaches, SWIPT has gained popularity because natural energy sources such as sun and wind are not sustainable under all conditions and RF signals have the capability to carry both information and energy [2], [3], [11], [12], [13]. As making ubiquitous wireless communications possible in a self-sustainable fashion, SWIPT is an indispensable solution for 5G+ providing the necessary energy for wireless charging of energy-constrained devices and for transmitting and receiving information. It is especially helpful in charging sensor nodes at locations which are very hard (if possible) and costly to access. In [14], a novel SWIPT scheme that transports energy by a powerful unmodulated signal and transmits information by a relatively weak modulated signal is proposed. It is experimentally demonstrated that the harvested power at 4-meter distance is more than 0.5 mW, which is enough to charge many IoT devices. SWIPT concept enables simultaneous information and power transmission as in power-line communications and has the potential to provide significant gains in terms of prolonged lifetime, spectrum efficiency, interference management, and transmission delays [15], [16], [17]. Considering the fundamental pillars of 5G+, SWIPT technology is anticipated to be an important enabler in the upcoming standards. On the other hand, SWIPT brings about a paradigm shift for wireless communication networks due to the new architectural challenges. Especially, the balance between the information transmission rate and the amount of energy harvested at the end terminals is an important factor in the evaluation of the system performance [18]. In this respect, an essential trade-off exists between the information transmission rate and the amount of the harvested energy. This is designated by the so-called rate-energy region formed by all the possible combinations of the attainable information transmission rate and harvested energy levels [10]. The optimal trade-off is given by the Pareto boundary of the rate-energy region. Initially, SWIPT has been investigated for single-user, single-antenna, single-hop wireless communication systems [10], [18].

As the EH operation with RF signals disrupts the information content of the received signal, it is generally not possible to perform EH and information decoding (ID) operations on the same signal. Therefore, in order to perform SWIPT in a practical manner, it is necessary to split the received signal or to use separate antennas for ID and EH processes. Further, due to the huge gap between the sensitivity levels in ID and EH operations (depending on the application between - 140 dBm and - 85 dBm for ID circuitry and in the order of - 30 dBm for EH circuitry, i.e., no harvested power when the input power is below the sensitivity level [19]), appropriate receiver structures are needed to enable SWIPT to function effectively. To this end, time switching (TS), power splitting (PS), and antenna switching (AS) receiver designs have been developed to divide the received signal into different domains respectively as time, power, and space [13], [18], [20], [21], [22], [23]. These approaches are illustrated in Fig. 1.

In the TS structure, the receiving antenna is periodically switched between the ID and EH circuits in an alternating fashion [13]. On the other hand, the PS receiver splits the received signal into two parts with different power levels under a certain PS ratio. Subsequently, two streams are separately sent to the ID and EH units to allow simultaneous ID and EH operations [20], [21]. By modifying the PS ratio (denoted by α in Fig. 1) at the receiver, the information transmission rate and the level of harvested energy can be balanced and optimized according to system needs [21]. It has been shown in [22] that a so-called on-off PS scheme provides the best trade-off between the information rate and the amount of harvested energy for practical setups. In AS, while a subset of receive antennas are allocated for ID, EH is performed through the remaining antennas at the receiver. Hence, AS allows a simpler implementation as compared to TS and PS [23], [24]. The EH receiver circuit also known as rectenna is typically comprised of a bandpass filter, a rectifier, and a low-pass filter to convert RF energy into DC power as shown in Fig. 2 [25]. In the literature, the relation between the RF power (P_{RF}) at the input and the amount of the harvested power (P_{DC}) is commonly given by $P_{DC} = \eta P_{RF}$ where the constant $\eta \in [0, 1]$ captures the efficiency during the RF-to-DC conversion. A more practical non-linear model encompassing the effect of the saturation during the process is also provided in [26].

Multiple-input multiple-output (MIMO) techniques have been proven to increase the capacity and reliability of the system under distinct fading conditions by using multiple number of antennas at the source and/or destination [27]. In order to increase the energy and spectral efficiencies as well as the sustainability of the system, the cutting-edge smart antenna approaches such as MIMO have been combined with SWIPT under various network topologies with a single user and multiple users [17], [28], [29]. The interuser-interference plays a dominant role in the end-to-end performance of multiuser wireless networks. It is conventionally regarded as the primary hindrance in satisfying certain levels of QoS. When not harnessed suitably, the interuser-interference may considerably degrade the system performance in terms of reliability and information transmission rate. On the other hand, EH receivers can seriously benefit from the interuser-interference by converting it into useful energy. Hence, a reasonable trade-off is required to balance the harmful and beneficial effects of the interuser-interference respectively on the ID and EH processes.

In wireless networks, the source and destination pair may not be sufficiently close to each other or a direct reliable link between them may not be possible due to environmental and/or channel conditions. In this case, the transmission can be performed cooperatively through relays judiciously placed between the source and destination to expand the coverage area. Even if there is a direct path between the source and the destination, the occasional use of a relay improves performance by providing diversity [30]. In cooperative communication, the relay can function based on amplify-and-forward (AF) and decode-and-forward (DF) protocols using half-duplex (HD) or full-duplex (FD) communication protocols. The FD technique augments the spectral efficiency compared to the HD approach as it simultaneously transmits and receives data in the same frequency band and time slot. The mobile relay node with a limited battery power needs some external charging mechanism to stay active within the system [31]. For this reason, SWIPT is very important in such networks as it also enables information transmission [32], [33], [34], [35], [36], [37], [38], [39], [40], [41].

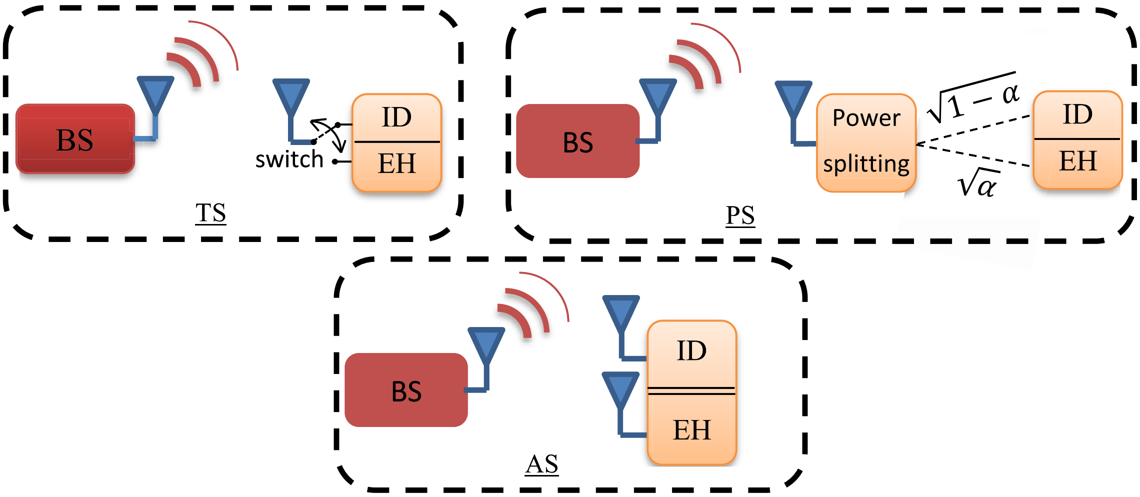

FIGURE 1. Distinct SWIPT architectures.

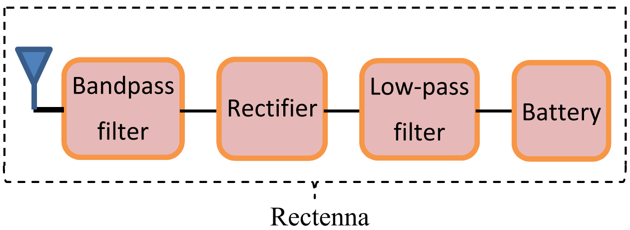

FIGURE 2. EH Receiver.

In addition to the classical store-and-forward based cooperation techniques, the use of smart processing techniques and the relay nodes may aid to increase both the spectral efficiency and the energy efficiency. One such approach is the use of network coding in wireless transmission scenarios where multiple packets of symbols can be combined at the relay, and their superposition is transmitted [42]. The benefits of the SWIPT and EH systems have hence been studied in network-coding enabled systems [43], [44], [45], [46], [47], [48], [49], [50], [51]. As one of the earliest examples, [43] presented a theoretical framework to evaluate the performance of EH in bidirectional network coded cooperative communications. A SWIPT enabled network-coded system is considered in [44] in the presence of PS and TS scenarios from an information theoretical perspective. In [45], the authors have considered an analog network coding based bidirectional relay system with multi-antenna source terminals. An optimization problem is formulated according to the TS ratio and the relay location to maximize the throughput. A SWIPT enabled multiuser multi-relay network is considered in [46] with information and energy level cooperation. Network coding is used to aid information cooperation. An optimization problem is formulated to maximize the energy efficiency under constraints of the energy causality and a predefined outage probability threshold and solved through an iterative approach. The authors in [47] have proposed an optimization framework for the joint problem of routing, network coding, and scheduling in SWIPT networks. An iterative solution is then proposed using the Lyapunov optimization algorithm. A buffer-aided two-way relay network is studied in [48], where a wireless-powered relay, which is capable of employing opportunistic network coding, as an intermediate node for data exchange. The stability region of such a network is derived for TS EH at the relay. The throughput-optimal and power-optimal policies have then been presented. The authors in [49] have considered multiuser multiple-input single-output (MISO) broadcast channels where SWIPT is used for interference management in the presence of physical layer network coding. A performance improvement due to canceling out the interference at the receivers from the aspect of data by physical layer network coding is demonstrated without eliminating the beneficial energy sources. SWIPT enabled network coded cooperation is also considered in drone applications. In [50], the authors have proposed a dynamic PS factor for harvesting the energy at nodes in a drone-assisted analog network coded system. The corresponding average rate and average outage probability expressions have been derived. Finally, [51] investigates the information freshness and EH aspects in the presence of random linear network coding. A theoretical analysis is presented to highlight the trade-off between the age of information and the EH performance considering a variation in the number of packets. Overall, the use of network coding in multiuser SWIPT network is expected to be an effective tool to improve the overall performance, and from the literature overview it can be observed that there is still a gap in the literature when combining the two techniques.

B. SURVEY STUDIES ON SWIPT

In the literature, there exist a number of survey papers each reviewing and outlining certain aspects of the EH and/or SWIPT technologies in contemporary communication systems. An overview of the recent research on both green 5G techniques and EH for communications is provided in [2]. In addition, certain technical challenges and potential research problems to accomplish sustainable green 5G networks are described. In [3], the authors present a survey on the combination of SWIPT with cooperative relaying systems which provides both flexibility in spectrum usage and energy efficiency. Distinct practical application scenarios are investigated with a broad perspective. The novel architectures and empowering technologies for SWIPT are reviewed and the technical challenges behind implementing SWIPT are specified in [11]. Additionally, the authors present a novel SWIPT-supported power allocation procedure for device-to-device communications. In [12], the authors compose an inclusive survey of the state-of-the-art SWIPT methods and present open issues stimulated by SWIPT and WPT assisted methods. Especially, potential emerging technologies due to the application of SWIPT/WPT in 5G communication systems are investigated in a detailed fashion. A comprehensive literature review on the research progress for the design of wireless networks with RF EH capability is provided in [13]. The authors present an overview on the system architecture, different RF EH techniques with existing applications, and the RF EH circuit design as well as the state-of-the-art circuitry implementations. The distinct communication protocols specifically tailored for RF EH networks are also explored. In [16], the authors provide a survey of SWIPT systems with a special focus on the hardware implementation of rectenna circuits and practical techniques for realizing SWIPT in the domains of time, power, and space. The advantages of SWIPT technologies for modern communication networks in the context of resource allocation and cooperative cognitive radio (CR) networks are also discussed. A framework is introduced for implementing SWIPT in a broadband wireless communication system with a simple SWIPT mobile architecture and different power control algorithms for single-user/multiuser systems, variable/fixed coding rates, and uplink/downlink information transfer in [24]. It is demonstrated that the power control has a critical role to improve the efficiency of SWIPT systems. In [52], the authors emphasize the fundamental challenges of RF-based EH in cellular networks. The benefits of various EH and information transmission architectures are analyzed and compared quantitatively from the view of users in the signal-to-noise ratio (SNR) outage zone. A concise survey of the contemporary SWIPT approaches is provided in [53] by introducing miscellaneous practical transceiver architectures. In addition, the most important link-level and the system-level design issues are investigated and potential solutions and research ideas are stated. In [54], the integrated wireless energy and information transfer networks are studied by providing a survey on the essential techniques from its bottom to top layers. Practical implementation, resource allocation, and protocol design issues are inspected together with the information theoretical foundations. A review of the energy efficiency optimization for cloud radio access networks (as known as C-RANs) using SWIPT is provided in [55]. The authors demonstrate an inclusive taxonomy of the miscellaneous EH sources for wireless sensor networks (WSNs) in [56] and describe certain challenges to establish cost-effective, efficient, and reliable EH systems. Input signals coming from a finite alphabet may cause an important performance degradation for SWIPT systems designed under the assumption of Gaussian distributed input signals. To this end, the modulation and coding design problems for both single-user and multiuser SWIPT systems are investigated in [57] by introducing the theoretical fundamentals and by presenting certain design guides. Differing from the preceding related works, multiuser SWIPT techniques available in the literature are reviewed in this survey study. Distinct application scenarios of multiuser SWIPT such as multi-antenna communications, cooperative communications, communications security, and unmanned aerial vehicle (UAV)-enabled communication systems are separately investigated in a comprehensive fashion. In addition, the multiuser diversity methods and the experimental studies for multiuser SWIPT are thoroughly reviewed.

C. PAPER ORGANIZATION

The remainder of this survey study is structured as follows. Section II introduces multiuser diversity and user scheduling concepts. The multi-antenna applications and the integration to SWIPT systems are respectively reviewed in Section II.A and Section II.B in a sequential fashion. In Section III, the relevant studies on the application of SWIPT with various orthogonal and non-orthogonal multiple access (NOMA) methods are rigorously reviewed. Section IV lays the foundations of the communications security in multiuser networks and the physical layer security (PLS) of multiuser schemes and multiuser SWIPT schemes are subsequently discussed in Section IV.A and Section IV.B. The UAV-enabled SWIPT systems are introduced in Section V. In the subsequent three subsections, the related studies on cooperative, multicasting, and mmWave networks are respectively reviewed under the UAV and SWIPT integration. Section VI focuses on the experimental studies on SWIPT systems. Specifically, waveform design problems and multi-antenna test systems are treated in Sections VI.A and VI.B, respectively. Section VII presents challenges, opportunities and future research directions. Finally, the conclusions are drawn in Section VIII.

II. MULTIUSER DIVERSITY AND USER SCHEDULING

Diversity methods have played pivotal roles in the design of contemporary wireless communications standards. The common feature of these methods is to assure that the replicas of a message signal are exposed to possibly distinct channel realizations such that the receiver gets multiple copies to form its decision on the transmitted message. The traditional time, frequency, and antenna diversity techniques are studied in the literature to a great extent. A relatively recent diversity scheme referred to as multiuser diversity (MUD) has been first introduced in [58] to increase the system capacity for a wireless communication system with multiple users.

It has been shown that the system capacity can be augmented by an appropriate user scheduling plan when the system resources are opportunistically allocated to the user with the best channel condition. Unlike the conventional diversity methods where the aim is to mitigate the channel fading, the MUD schemes exploit the existence of the channel fading by tracking the peak points in the random variations of the users' channel fading states towards a common entity such as a BS.

One limiting feature of MUD approaches is that the transmitter is required to possess some kind of channel information corresponding to each user to carry out appropriate user scheduling. This, on the other hand, may put a heavy burden on the system especially when the number of users is relatively large. Therefore, user scheduling approaches which function with no regard on users' channel status have been conventionally and widely adopted especially for delay-sensitive data services. The round-robin scheduling, the earliest deadline first scheduling, and the weighted fair queueing are some examples of such techniques. The round-robin scheduler gives the users service in a circular fashion. In the earliest deadline first scheduling, the user whose packet delay has the soonest expiration time is bestowed service in a prioritized fashion. On the other hand, the scheduling is performed based on a set of weights corresponding to users under the weighted fair queueing approach. These schemes are employed in the medium access control (MAC) layer with no regard on the physical layer. Although all the preceding methods are advantageous in terms of computational load and complexity, they lack the MUD gain and thus offer a limited sum throughput. Contrarily, the channel-aware scheduling techniques rely on the transmitter's partial or complete knowledge on the users' channel conditions. These methods are generally categorized under the name of opportunistic or greedy user scheduling and try to harness the MUD in a way to improve the overall system performance in terms of data rate, error probability, and QoS requirements.

The concept of opportunistic scheduling has been introduced in [58] under a scenario where a single user with the best channel condition is scheduled in every time slot. The authors have inspected MUD gain in an uplink transmission scenario where each node is assumed to be equipped with a single antenna within a single-cell system. This method, which does not take fairness into consideration and thus is appropriate for delay-tolerant applications, is generally called maximum-rate scheduling in the literature. When the network consists of a set of homogenous users, scheduling the user with the maximum instantaneous rate (or with the largest signal-to-interference plus noise ratio (SINR)) provides long-term fairness where each user has similar average throughputs. If the users form a heterogeneous network, on the other hand, the maximum-rate scheduling cannot ensure fairness among users on its own. The so-called proportional fair scheduling (PFS) tries to maintain fairness by scheduling the user whose ratio of instantaneous data rate to its own average data rate is largest [59]. It has been shown that under the PFS scheme, the data rate attained by a scheduled user is very close to its peak data rate for a scenario with a large number of users under slow fading [60]. A multiuser scheduling scheme under short-term temporal fairness constraints is investigated in [61]. The authors propose a scheduling strategy which satisfies short-term fairness constraints for arbitrarily feasible window lengths. A review of the scheduling algorithms proposed for the fourth-generation multiuser wireless networks is presented in [62] for both single-antenna and multi-antenna systems. It is concluded that a cross-layer design between the physical layer and the MAC layer, which is responsible for resource allocation and packet transmission scheduling, is of fundamental importance in order to construct the optimal scheduling scheme. In [63], a PFS method for the downlink of the Long Term Evolution (LTE) cellular communication systems is proposed. It is shown that a superior fairness performance relative to the other related works can be attained with a modest loss in throughput as long as the users' average SINRs are fairly uniform. The downlink LTE channel model is also adopted in [64] to formulate a resource allocation problem on maximizing sum throughput. In order to simplify the non-linear combinatorial optimization problem, a linearized model is developed whose solution is shown to be equivalent to allocating resources to the users with the best channel conditions. The relevant schedulers are compared in terms of achieved throughput and fairness.

One of the fundamental pillars of the 5G NR is its promise to guarantee unprecedentedly reduced latency times (around 1 ms depending on the application and deployment scenario). In order to enable the 5G NR system to satisfy the low level latency requirement, the third generation partnership project (3GPP) body has introduced the concept of grant-free scheduling [65]. Unlike grant based scheduling as in the previous generations where a user equipment is dynamically scheduled by the BS by acquiring a dedicated resource block (grant), a user demanding permission is directly granted access without undergoing any handshake process. The grant-free scheduling approach is studied in [66] over a 5G network by exploring two related access schemes. The system parameters are set such that the latency requirements are fulfilled with low resource consumption. Scheduler designs seeking solution to a dual-objective optimization problem with certain latency and data rate constraints are provided in [67] and [68] for 5G systems by adopting opportunistic scheduling mechanisms. A comprehensive survey on opportunistic scheduling methods is presented in [69] by categorizing distinct opportunistic scheduling schemes into four groups (capacity, QoS, fairness, and distributed scheduling) based on their objective functions.

A. MULTIUSER DIVERSITY IN MIMO SYSTEMS

The application of MUD methods in MIMO systems is inspected in this section. The relation between the spatial diversity and MUD gains is investigated to a great extent in the literature [60], [62], [70], [71], [72], [73], [74], [75], [76], [77]. As an example, a downlink cellular system with K

statistically homogeneous and independent users is illustrated in the sequel. The BS is equipped with N antennas and each user has M antennas such that $M \leq N$. Each user has perfect information about its own channel only and the BS is provided with only partial channel state information (CSI) of users.

In the round-robin scheduling, the channel is allocated to every user periodically and in an alternating fashion where any user informs the BS on the instantaneous throughput its current channel state can support. The BS accordingly designates the instantaneous transmission rate for the scheduled user. The average system throughput for the round-robin scheduling, C_{rr} is given by [72]. In the opportunistic scheduling scenario, the BS uses the feedback information on the instantaneous capacity of each user to allocate the channel to the user with the largest instantaneous throughput. The average system throughput for the opportunistic scheduling, C_d is given by [72]. The C_{rr} and C_d are compared for $M = N = 2$ and an average power of $P = 15$ dB in Fig. 3 as a function of K. It is important to mention that as K asymptotically increases, the average system throughput for the opportunistic scheduling exhibits a double logarithmic growth in the number of users (a $\log \log K$ scaling in K) [76].

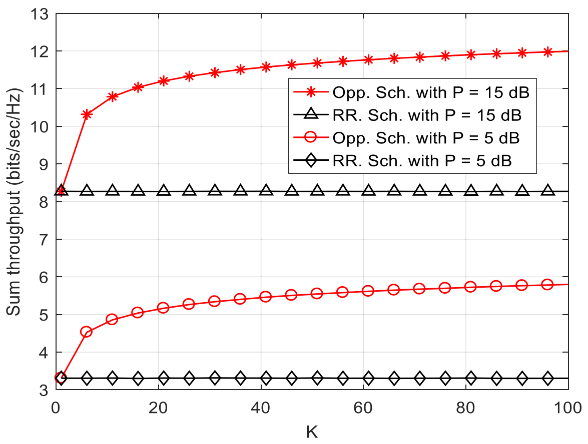

FIGURE 3. Comparison of the sum throughput values for the round-robin scheduling and the opportunistic scheduling schemes for $M = N = 2$.

The use of spatial diversity in MIMO systems has an effect of lessening randomization in the channel fluctuations. This, on the other hand, has a negative impact on the amount of MUD gain, which mainly depends on the random nature of the users' channels. The application of opportunistic scheduling into MIMO systems is first studied in [70] where it is demonstrated that the utilization of spatial diversity has a consequence of decreasing the variations in the channel fading. A similar result is also concluded in [71] where the gain due to MUD is shown to get rapidly reduced as the number of antennas increases. The authors term this effect as channel hardening. An opportunistic beamforming scheme is proposed in [60] based on a random beamforming technique at the transmitter. The aim is to increase the dynamic range of the channel fluctuations for the scenarios with little scattering and/or slow fading such that the MUD gain is augmented. When there exist a sufficient number of users, this scheme is shown to achieve the coherent beamforming gains only with quite limited channel feedback. A downlink multiple antenna multiuser wireless system is investigated in [72]. The authors propose a novel scheduling scheme that exploits both spatial diversity and MUD gains available in the channel. It is shown that the decrease in the MUD gain due to the increase in the number of antennas can be circumvented partially by properly designing user scheduling mechanism.

A random beamforming technique that achieves MUD, spatial multiplexing, and array gains simultaneously is proposed in [73] for multiuser MIMO downlink systems. The transmitter is required to have partial CSI (effective received SINR values) only corresponding to all the users. It is demonstrated that the throughput of the introduced scheme approaches to that of the eigen-beamforming technique when there exist sufficiently many users within the network. In [74], a cross-layer analytical framework is presented to concurrently study the MUD gain, the spatial diversity gain, and the array gain over a generalized Nakagami-m fading channel. The interplay among these and the fading parameter is investigated for a multiuser MIMO downlink scenario.

Several multiuser scheduling schemes with limited feedback are investigated in [75] over MIMO broadcast channels. It is demonstrated that the introduced scheduling algorithms have the potential to attain large MUD gains with a greatly reduced feedback load. Note that a similar conclusion is also drawn in [60] for a broadcast channel with a multi-antenna BS and single-antenna users. In [76], a multiuser multi-antenna downlink system under partial channel knowledge at the transmitter is studied. It is shown that in order to fully benefit from spatial multiplexing and MUD gains simultaneously, feedback quantization at the users must be based on the users' SINR values rather than the channel magnitudes. The trade-off among the number of feedback bits, the number of users, and the operational SNR is determined. A unified error rate analysis of a downlink multiuser scheduling system is presented in [77] with imperfect CSI at the BS. Three distinct transceiving schemes are adopted by assuming that all the nodes are equipped with multiple antennas. It is shown that as a result of the imperfect CSI, the diversity level is reduced differently for the three transceiving techniques. Scheduling in relaying networks has also been studied in [78] and [79] for multi-hop and two way cases, respectively.

B. MULTIUSER DIVERSITY AND SWIPT

In terms of SWIPT integration, multiuser communication systems have certain differences in comparison with single user (point-to-point) communication systems. An appropriate user scheduling procedure that satisfies certain QoS levels (in terms of data rate, amount of harvested energy, fairness, complexity, etc.) should be adopted under multiuser SWIPT. In addition, signals of different links are superimposed in multiuser SWIPT systems. This brings about the existence of interuser-interference as an additional dimension to the optimization problem, which is not applicable under single user SWIPT systems. A multiuser downlink SWIPT system is depicted in Fig. 4 where a certain set of scheduled users are chosen as the ID (wireless information transfer) users, the EH (wireless power transfer) users, and SWIPT users. The distinguishing feature of the multiuser scheduling problem in an SWIPT based network (SWIPT-N) is that it extends the problem by an additional dimension represented by the harvested RF energy constraint. The conventional multiuser scheduling schemes aim at achieving the best usage of the available resources among multiple users such that certain QoS criteria in terms of throughput are satisfied under a definite fairness requirement. For instance, the user whose channel gain is in its peak is selected for information transmission in the opportunistic scheduling technique. However, such a scheduling model is not convenient for the SWIPT-Ns as it may fall short of achieving the harvested RF energy requirement. The rationale behind this is that the best channel states are tracked and designated for the ID users in a way limiting the amount of the RF energy harvested at the EH users. Some of the notable works on MUD SWIPT systems are listed in Table 1 with their distinctive features.

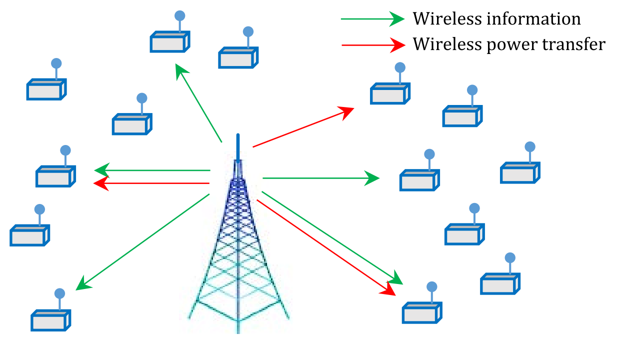

FIGURE 4. A multiuser downlink SWIPT system.

In an early work, downlink multiuser scheduling problem has been studied for a time-slotted system with SWIPT over fading channels [80]. Assuming that a single user is scheduled for ID and the remaining users opportunistically harvest the ambient RF energy in every time slot, new scheduling schemes have been devised to control the trade-off between the achieved throughput and the amount of the harvested energy. The multiuser scheduling is investigated for SWIPT-Ns in [52] and a concise survey on the existing solutions addressing certain inherent challenges is provided. In [81], the authors treat a downlink multiuser scheduling scenario with SWIPT. Optimal scheduling techniques maximizing the long-term average system throughput are proposed under an average harvested energy constraint and distinct fairness requirements. The spectral efficiency of an uplink RF-powered network is investigated in [82] by adopting the so-called harvest-then-transmit protocol where the scheduled user transmits in the uplink channel based on the energy it harvests from its administrator BS through the downlink channel. The conventional greedy and round-robin user scheduling schemes are modified such that the system performance is enhanced. In [83], a novel SWIPT scheme based on opportunistic communications is introduced for an interference alignment network where both user and antenna selection scenarios are studied. An EH cooperative network model with multiple source-destination pairs and one relay is considered in [84] where the relay schedules only some set of user pairs for transmission. It is shown that when an EH relay is employed, the max-min criterion incurs a loss in diversity gain. In [85], the authors inspect a SWIPT system with an HD hybrid access point (H-AP) regulating the information transmission to a scheduled downlink user and power transfer to an uplink user. The link scheduling and power allocation problems are jointly formulated in order to maximize the sum throughput under a power causality requirement. It is numerically demonstrated that the proposed approaches yield considerable performance improvements as compared to the conventional schemes. With the aim of maximizing the average total harvested power, a joint scheduling and power allocation scheme is suggested for a multiuser SWIPT scenario in [86] by embracing a realistic non-linear EH model. In [87], the outage probability performance of a cooperative relaying scheme in a two-user NOMA system is analyzed where SWIPT is adopted at the near terminals to power their relaying operations. A best-near best-far user scheduling algorithm is introduced. User scheduling problem is considered in [88] for a multicell SWIPT system employing the static PS receiver. An α-adaptive scheduling scheme is introduced such that any certain trade-off constraint between maximizing achievable rate and maximizing harvested energy of the scheduled user is achieved by adjusting the corresponding α factor. The performance of the proposed approach is compared with those of two conventional scheduling schemes namely random scheduling and max-SNR scheduling. In [89], the downlink outage performance of opportunistic scheduling is analyzed in dual-hop cooperative networks comprised of one source, multiple RF EH relays, and multiple destinations. Two low-complexity relay-destination selection techniques are suggested where the first one is based on opportunistic CSI whereas the second scheme relies on partial CSI. It is shown that the former approach attains full diversity gain of $(M+K)$ while the latter achieves a diversity order of $(M+1)$ where M and K respectively represent the number of destinations and the number of relays. The authors of [90] investigate an EH underlay CR system consisting of multiple cognitive users with EH capability, a common cognitive BS, and multiple passive eavesdroppers. A novel energy-aware multiuser scheduling technique is proposed to improve the PLS of the system. It is demonstrated that the introduced scheme outperforms the round-robin scheduling and the conventional multiuser scheduling approaches. In [91], two multiuser scheduling schemes are presented for an FD wireless-powered IoT system. The authors model the charging and discharging processes of the battery at each wireless-powered node as a finite-state Markov chain. The proposed methods are shown to outperform the round-robin scheduling and the random scheduling techniques in terms of throughput and fairness. An adaptive PFS algorithm is studied for SWIPT-enabled multi-cell downlink networks in [92]. The recommended scheduling algorithm is demonstrated to accomplish better fairness measure in comparison with the miscellaneous other scheduling algorithms. A multiuser downlink communication system with SWIPT is considered in [93] and [94] by assuming that while the BS transmits information to a single user, the remaining ones opportunistically replenish energy from the received RF signals. Power allocation and user scheduling policies are proposed for the throughput maximization problem under the average power limitation of the grid and a constraint on the amount of the harvested energy. In [95], the performance of a wireless powered communication network (WPCN) is studied by assuming that multiple batteryless devices harvest RF energy from a dedicated energy transmitter and a single device is selected for information transmission to a common information receiver. The authors inspect various selection approaches depending on distinct CSI requirements and implementation complexities. An intelligent reflecting surface (IRS)-aided FD WPCN scenario is investigated in [96] and [97] where an FD H-AP transmits RF energy to multiple devices in downlink and meanwhile receives information from the devices in uplink through an IRS. In [96], assuming multiple antennas at each node, the time allocation for downlink/uplink, precoding and transmit covariance matrices, and phase shifts have been jointly optimized to maximize the sum throughput of the IRS-aided MIMO FD-WPCN. Three types of IRS beamforming architectures for the IRS-aided FD-WPCN are proposed in [97] to obtain a balance between the system performance and signaling overhead as well as implementation complexity. The performance of multiuser SWIPT-enabled IoT relay networks in the presence of transceiver hardware impairments is inspected over Nakagami-m fading channels in [98]. Both TS and PS architectures of SWIPT are considered at the relay terminal. The dependence of the system performance on the number of IoT users, fading severity parameter, TS factor, PS factor, and energy conversion efficiency is demonstrated. In [99], an EH relay network is considered where multiple sources communicate with a destination through multiple EH PS-based DF relays. An optimal PS and joint source-relay selection method is proposed such that the main link capacity is maximized.

III. MULTIPLE ACCESS TECHNIQUES AND SWIPT

The number of devices to be connected in IoT networks is projected to skyrocket in a few years' time. As such, efficiency in energy and spectrum usage has become particularly important in the contemporary communication systems. In quest of a solution to this, SWIPT technology has recently been combined with distinct multiple access methods. The conventional orthogonal multiple access (OMA) approaches rely on orthogonal resources in either time, frequency, or code domain. Thus, they offer only a limited spectrum efficiency. In NOMA, the data multiplexing is carried out in the power domain and successive interference cancellation (SIC) is performed at the receive sides yielding superior spectral efficiency and user fairness by allowing multiple users simultaneously to access the same spectrum [5], [100]. Due to its advantages, a downlink NOMA technique called multiuser superposition transmission has been recommended for the 3GPP LTE advanced (3GPP-LTE-A) networks [101]. In addition, NOMA is envisioned to evolve into next generation multiple access in order to satisfy the stringent challenges of next generation wireless networks [102]. With their inherent advantages, SWIPT and NOMA approaches can be combined to present a promising solution for 5G+ and IoT communication systems. In this section, the relevant studies on the application of SWIPT with various orthogonal and non-orthogonal multiple access methods are reviewed. Some of the prominent studies on MAC SWIPT systems are tabulated in Table 2 with their distinctive features.

The work in [103] focuses on the transfer of information and energy in multiple access and multi-hop channels. Using an information-theoretic approach, it is shown that the constraints on the energy flow and information transfer have central effects on the design of wireless networks with multiple nodes. In [104], a WPCN scenario where an H-AP with constant power supply regulates the wireless energy and information transmissions to/from a group of dispersed users with no other energy sources is considered. Each user initially harvests wireless energy over the downlink channel and then sends its information to the H-AP over the uplink channel by means of time-division multiple access (TDMA). As the far users can replenish less energy than the near users, the sum throughput is maximized by allocating considerably more time to the near users than the far users leading to a significantly unfair scenario in terms of users' data rates [104]. In order to tackle with this doubly near-far phenomenon, the authors in [104] introduce a new objective function with an additional constraint such that all the users have the identical data rate. Due to its spectral efficiency and its capacity in tackling frequency-selective fading, orthogonal frequency-division multiple access (OFDMA) has become very popular as an air interface technique and been adopted in a number of modern transmission technologies such as WiMAX, WiFi, LTE-A, 5G NR. Accordingly, OFDMA systems with SWIPT capability have been studied extensively in the literature. In a pioneering work, a novel framework is presented to realize SWIPT in single-user and multiuser broadband systems [24]. The authors of [21] study the resource allocation problem for OFDMA systems with SWIPT. PS-based receivers, which divide the received signals into two power streams for simultaneous ID and EH, are adopted with the aim of maximizing the energy efficiency of data transmission in terms of bits/Joule delivered to the receive nodes. The resource allocation optimization for a multiuser downlink SWIPT system is investigated in [105] by using two transmission techniques given by TDMA-based information transmission with TS implemented at each receiver and OFDMA-based information transmission with PS implemented at each receiver. The obtained results reveal that the TDMA-TS scheme can attain the same data rate as the traditional TDMA systems while every user is still able to harvest a fair amount of energy and the TDMA-TS system outperforms the OFDMA-PS system under certain scenarios. On the other hand, if the constraint on the harvested energy level at the users is proportionately high, the OFDMA-PS approach performs better than the TDMA-TS method. In [106], the resource allocation problem for a WPCN is inspected. An H-AP transfers wireless energy to a group of users in the downlink and simultaneously receives independent information from the users based on TDMA in the uplink. A novel protocol is introduced to satisfy the system constraints. A combination of SWIPT and NOMA techniques is studied in [107] by proposing a new cooperative SWIPT NOMA protocol where the near users function as EH relays to assist the far users. It is analytically demonstrated that the diversity gain of the system is the same as the conventional NOMA approach without SWIPT. In [108], a wireless powered uplink communication system comprised of one BS and numerous EH users is considered with NOMA. The system is optimized in terms of user data rates and fairness among users. The numerical results reveal that in terms of throughput and fairness, the introduced approach outperforms a baseline scheme where EH nodes employ TDMA. NOMA is studied for the uplink of WPCNs in [109]. In order to deal with the doubly near-far effect, a decoding order that is inversely proportional to the users' distances to the transmitter is adopted and it is shown that in comparison with the TDMA-based schemes, the introduced approach results in considerable rate improvement for the cell-edge EH users, thus improving system fairness. The outage performance of a two-user cooperative NOMA system is investigated in [87] where SWIPT is adopted at the near users to provide necessary energy for their relaying operations. The authors recommend a best-near best-far user selection algorithm. In [110], a cooperative NOMA network with SWIPT is considered where a transmitter communicates with two users by means of an EH relay. The impact of the power allocation is inspected on the system performance. It is demonstrated that the introduced NOMA schemes can noticeably decrease the outage probability as compared to the traditional cooperative SWIPT networks with OMA. The work in [111] inspects a wireless powered communication IoT network scenario where multiple energy-limited nodes first harvest energy over the downlink channel and subsequently transmits information through the uplink channel. The time allocation is optimized by respectively adopting TDMA and NOMA approaches such that the spectral efficiency is maximized under both cases. By taking into account the circuit energy consumption of the IoT devices, it is shown that the NOMA-based scheme is neither spectral efficient nor energy efficient in comparison with the TDMA-based scheme. However, this result is obtained with no regard on the user fairness. The communication security is studied for a MISO NOMA CR network with SWIPT in [112]. Adopting a practical non-linear EH model, an artificial-noise-aided cooperative jamming method is introduced. The results reveal that the NOMA-based technique outperforms its counterpart with OMA. In [113], with the aim of obtaining a trade-off between spectrum efficiency and energy efficiency, the authors offer to use SWIPT for hybrid precoding based mmWave massive MIMO-NOMA systems. The numerical results demonstrate that the proposed scheme can attain higher spectrum and energy efficiency as compared to a similar method based on OMA. NOMA with SWIPT is studied in [114] where an AP concurrently conveys information and power to two users. It is proven that in terms of the information-energy trade-off, NOMA outperforms OMA when the decoding energy consumption is negligible. In addition, if the decoding energy consumption is not negligible and the channel power gains of the two users are not distinct enough, OMA may perform better than NOMA. In [115], the energy efficiency optimization problem for a SWIPT NOMA system is addressed. Compared to the traditional OMA, it is shown that an important energy efficiency gain can be attained by appropriately combining SWIPT with NOMA. The resource optimization for NOMA heterogeneous small cell networks with SWIPT is studied in [116]. A low-complexity subchannel matching algorithm is proposed based on the merits of channel conditions. In [117], the authors consider PLS for a downlink orthogonal frequency-division multiplexing (OFDM) SWIPT IoT system with multiple legitimate IoT nodes. In order to manage multiuser communications, OFDMA and TDMA are separately adopted by using PS-SWIPT and TS-SWIPT architectures at the IoT objects, respectively. It is shown that in terms of secrecy rate, the OFDMA system with PS-SWIPT always outperforms the TDMA system with TS-SWIPT. A new resource allocation and relay selection method is proposed for cooperative multiuser multi-relay OFDMA networks with SWIPT in [118]. The authors demonstrate that the introduced approaches yield important performance gains in comparison with a semi-random resource allocation and relay selection technique. Also, the achieved performance converges to the optimal solution when the number of OFDMA subcarriers is large enough. In [119], the outage probability of a SWIPT-based cooperative NOMA system with a transmitter, a near user, and a far user is analyzed by assuming that the near user relying on PS for EH and ID processes serves as a relay to assist the far user. It is revealed that the introduced technique considerably improves the near user's performance and yields a larger system throughput. The authors of [120] inspect EH capability at the users for a hybrid combination of NOMA, TDMA, and SWIPT approaches. The numerical results show that the introduced scheme outperforms the conventional TDMA technique in terms of transmit power consumption. Energy efficiency resource allocation optimization for cooperative CR networks with SWIPT is studied in [121] by adopting TDMA for information transmission. The authors provide a number of comparisons with existing resource allocation algorithms and show that the introduced technique attains higher energy efficiency.

Another potential application of SWIPT lies in the field of heterogeneous networks (HetNets), where multiple frequency bands are used in an overlapped manner. Especially as the number of users increases and the HetNet becomes ultra-dense (as expected in the literature such as the joint use of microwave and millimeter wave bands [122]), the potential of SWIPT to benefit from both the power efficiency and the frequency diversity aspects will become more apparent. In line with the vision, there are some works in the literature that considers the use of SWIPT in HetNets. In [123], the authors consider a downlink resource allocation problem for a two-tier HetNet, where both TS and PS approaches are considered for SWIPT. It is shown that the co-tier interference signals can provide significant harvesting gains, and the trade-off in achievable throughput and EH rate depends on the selected harvesting approach. [124] has considered the use of power beacons in a HetNet with the goal of increasing energy efficiency. The weighted sum of harvested energy and information rate is maximized in a multiuser MISO configuration. The cross tier and co-tier co-channel interference has been exploited to improve energy efficiency in [125] in the absence of perfect CSI. The power allocation problem is modeled as a non-cooperative game and an iterative approach has been proposed for power optimization and subchannel allocation in SWIPT enabled transmission scenario. The authors in [126] have considered a heterogeneous cloud radio access network (H-CRAN) where EH is used to alleviate the power consumption of the grid. The authors have proposed a mixed integer non-linear programming problem to increase energy efficiency. The impact of cell load of a SWIPT system in a HetNet is studied in [127]. A number of different user association and network deployment scenarios have been considered, and the SWIPT performances have been quantified numerically. A robust energy efficiency maximization problem is formulated in [128], and a practical min-max approach is proposed for iterative power allocation. A two-tier heterogeneous SWIPT network has been studied in [129] in the presence of Nakagami-m fading channels. Outage probability expressions are derived by making use of the stochastic geometry theory in the presence of a non-linear EH model. Non-linear EH model is also considered in [130] for HetNets in the presence of multi-carrier transmission. In [131], the authors have considered an IoT HetNet in a densely deployed transmission scenario where uplink and downlink transmissions are decoupled to increase the target utility. Finally, the authors in [132] consider a SWIPT enabled multi-tier network with a cooperative NOMA transmission scenario where BS distribution follows a Poisson point process model. Expressions for outage probability and throughput are derived, and the benefits of the interference components are highlighted from an energy efficiency perspective. Overall, it is clear that as the number of users increases and the number of tiers are layered, the complex interference nature of SWIPT-enabled wireless networks is expected to be beneficial from an energy efficiency perspective.

IV. COMMUNICATIONS SECURITY OF MULTIUSER SWIPT SCHEMES

Due to the drastically increased number of connected wireless equipments within the same or neighbor service area of the state-of-art and forthcoming communications applications/standards, the communications secrecy has been constituting a major and challenging issue from the implementation and scheduling perspectives. The open transmission media of the wireless communications applications allow room for the unauthorized access of the eavesdroppers' on the content of a legitimate communications link. Former approaches on this communications security problem have mainly concentrated on employing several cryptographic protocols in the network layer [133]. However, detailed researches on the multiuser communications secrecy have revealed that security measures at higher communication layers would be overcosting and extremely fragile to attacks [134], [135].

On the other hand, despite being a widely-used PLS approach in military applications, direct jamming technique (i.e., performed in order to degrade the signal quality at an intended receiver) has not been of considerable importance. However, several researches on the practical usage of interleaved jamming signals have proposed and investigated the artificial-noise (AN) injection technique as another efficient perspective to combat wiretapping techniques in fading environments [136], [137], [138]. AN-based approaches have been shown to achieve enhanced communications security against eavesdroppers in the presence of Gaussian noisy channels whereas their efficiencies vanish for the case of multiuser interference channels [139]. Additionally, these approaches typically aim to insert a fractional AN into the null space of the channel matrix related to the legitimate receiver, which only deteriorates the eavesdropping capability, but not the reliability at the legitimate receiver. Hence, they lead to increased signal processing complexities at the transmitter terminals that might complicate their physical implementation [139].

Alternatively, PLS has emerged as a novel and efficient tool instead of the traditional cryptographic key-based and AN-based schemes those lack to fulfill the power-efficiency and latency requirements of forthcoming (5G+) wireless systems. By taking the advantage of the stochastic characteristics of the communications channels, PLS techniques have been shown to enhance the data security of the legitimate users while successfully preventing the eavesdroppers (i.e., unauthorized terminals) to intercept the others' data over the open wireless medium [140].

A. PHYSICAL LAYER SECURITY OF MULTIUSER SCHEMES

The literature related to the communications security problem of multiuser wireless networks have been consisting of detailed investigations on miscellaneous techniques for different antenna configurations (single-antenna

TABLE 1. List of various eminent studies on MUD SWIPT approaches.

Ref.	Scheduling	Number of Scheduled Users	Channel Model	Antenna Setting	Relaying	Distinctive Features
[80]	Order-based SNR scheduling and order-based equal throughput scheduling	Single for ID with remaining users harvesting RF energy	Quasi-static flat Rician, Nakagami-m, Weibull, and Rayleigh fading	Single antenna at each node	No	Novel scheduling schemes are introduced to control the trade-off between the sum rate and the amount of harvested energy.
[81]	Maximum throughput, proportional fair, equal throughput scheduling	Single for ID with remaining users harvesting RF energy	Block flat Rayleigh fading	Single antenna at each node	No	User scheduling methods for SWIPT systems are studied under distinct definitions of fairness.
[82]	Greedy, round-robin, and harvesting-constrained scheduling	Single	Quasi-static generalized composite fading	Single antenna at each node	No	Performance of user scheduling schemes in RF-powered uplink networks is investigated.
[83]	Opportunistic	Multiple for ID with remaining users harvesting RF energy	Block flat Rayleigh fading	Multiple antennas at each node	No	A SWIPT system with opportunistic communications is proposed for interference alignment networks.
[84]	Greedy scheduling	Multiple	Quasi-static flat Rayleigh fading	Single antenna at each node	Cooperative with an EH relay	It is shown that the max-min scheduling leads to a loss in diversity level when an EH relay is used.
[85]	Opportunistic and link scheduling	Single	Quasi-static flat fading	Single antenna at each node	No	Link scheduling, user scheduling, and power allocation are jointly optimized.
[86]	Online scheduling	Single for ID with remaining users harvesting RF energy	Slow flat Rician fading	Single antenna at each node	No	Resource allocation for multiuser SWIPT systems is investigated for a realistic non-linear EH model.
[87]	Best-near best-far user scheduling	Two	Block flat Rayleigh fading	Single antenna at each node	Multi-hop with an EH relay	Three relaying policies as DF, AF, and hybrid DF/AF are considered.
[88]	α-adaptive scheduling	Single	Block flat Rayleigh fading	Single antenna at each node	No	α-adaptive scheduling is introduced by jointly considering information transmission and EH with an adjustable weight factor.
[89]	Direct links plus opportunistic CSI-based selection and direct links plus partial CSI-based selection	Single	Block flat Rayleigh fading	Single antenna at each node	Dual-hop cooperative with relay selection	Three relaying policies as DF, variable-gain AF, and fixed-gain AF are used.
[90]	Energy-aware multiuser scheduling	Single	Quasi-static flat Rayleigh fading	Single antenna at each node	No	A novel scheduling scheme is introduced to enhance the physical-layer security in an EH underlay CR system.
[91]	Throughput-oriented and fairness-oriented scheduling	Single for ID with remaining devices harvesting RF energy	Quasi-static flat Rician fading	Two antennas at H-AP and single antenna at IoT devices	No	Two user scheduling methods are proposed for FD wireless-powered IoT systems.
[92]	Adaptive proportional fairness scheduling	Single	Block flat fading	Single antenna at each node	No	In comparison with various conventional scheduling schemes, the introduced approach attains better fairness measure.
[93]	Policy iteration and R-learning scheduling	Single for ID with remaining users harvesting RF energy	Finite state Markov channel chain	Single antenna at each node	No	BS can set a trade-off between the data rate and the amount of harvested energy at users by applying the introduced techniques.

TABLE 1. ***(Continued.)*** **List of various eminent studies on MUD SWIPT approaches.**

[95]	Opportunistic based on SNR, amount of harvested energy, transmission rate, and max-min selection	Single	Block flat Rayleigh fading	Single antenna at each node	No	The selection procedure relies on several novel selection/scheduling techniques corresponding to distinct implementation complexities and CSI requirements.
[96]	Opportunistic with the largest SNR of the HAP-device link	Single	Quasi-static flat-fading with HAP-IRS and IRS-device links following Rician fading and HAP-device link following Rayleigh fading	Multiple antennas at each node	No	The advantage of employing an IRS increases when a dynamic IRS beamforming strategy is adopted for both downlink power transfer and uplink information transmission.
[97]	Opportunistic with the largest SNR of the HAP-device link	Single	Quasi-static flat Rician fading	Two antennas at H-AP and single antenna at each device	No	Three types of IRS beamforming architectures for the IRS-aided FD-WPCN are proposed.
[98]	Opportunistic with the largest signal-to-noise-and-distortion ratio	Single	Quasi-static flat Nakagami-m fading	Single antenna at each node	A SWIPT-enabled AF relay	A diversity order that is equal to the product of the fading severity parameter and the number of IoT users is achieved.
[99]	Opportunistic with the largest main link capacity	Single	Quasi-static flat Rayleigh fading	Single antenna at each node	Multiple SWIPT-enabled DF relays	The proposed scheme is shown to outperform the traditional PS-based and the round-robin scheduling methods in terms of outage probability performance.

or multi-antenna cases), cooperation types (e.g., single-hop, cooperative or multi-hop schemes), multiple access types (e.g., code-, frequency- or time-division-based, orthogonal/non-orthogonal) and channel characteristics (e.g., Rayleigh, Rician and Nakagami-m fading). In order to enhance the network security against the attacks of multiple eavesdroppers, different relay and user pair selection strategies have been proposed in [141] for multiuser cooperative relay networks with multiple AF relays in Rayleigh fading channels. The authors of [142] have provided on the investigation of AN-aided secure beamforming (BF) scheme for multiuser MISO broadcast channel with confidential messages.

The PLS examination of two-way untrusted relay schemes within Sparse Code Multiple Access networks has been provided in [143] where the relationship between the security capacity and the number of users, the power coefficients for users and the power allocation of cooperative interference in the two-way network is also investigated. The authors of [144] have focused on the PLS of a dual-hop uplink CR network over Nakagami-m fading channels.

By jointly considering interference power constraints and the total transmit power constraint, an extensive study on the optimization of the secrecy rate of multiuser MIMO wiretap channel has been carried out in [145]. This study has provided rigorous information and useful outcomes from the optimization perspective.

On the other hand, several researches have focused on the multiuser communications schemes with non-orthogonal type of access. Exact expressions for the average secrecy outage probability (SOP) performance of NOMA AF-relayed network where the transmitter employs transmit antenna selection (TAS) / maximal ratio combining (MRC) scheme through cooperation with untrusted EH relays is provided by [146]. The investigation in [147] has focused on a NOMA-based massive machine-type communications (mMTC) uplink scenario where each terminal conveys its confidential signal to the BS while a passive eavesdropper has been operating to steal information. Opportunistic scheduling schemes employed within multiuser MIMO-NOMA systems have been examined in [148] where the multi-antenna BS is dedicated to communicate with multiple single-antenna cell-center and cell-edge users while multiple single-antenna eavesdroppers strive to access the users' information. Another NOMA-based investigation has been done in [149] on the PLS of CR networks with multiple primary and secondary users under Nakagami-m fading conditions. The study provided by [149] has focused on a multiuser massive MIMO scheme that promises improved PLS performance due to its ability to steer the transmission

TABLE 2. List of relevant works on MAC techniques for SWIPT systems.

Ref.	MAC	Channel Model	Antenna Setting	Relaying	Key Aspect
[21]	OFDMA	Quasi-static block, frequency selective, Rician fading	Single antenna at each node	No	Resource allocation problem for SWIPT OFDMA systems is studied.
[24]	OFDMA	Quasi-static block, frequency selective, Rician fading	Multiple antennas at BS, two antennas at each user	No	An antenna array at BS is utilized to compensate for the propagation loss by directing beams towards designated users.
[87]	NOMA	Block flat Rayleigh fading	Single antenna at each node	Multi-hop with an EH relay	A best-near best-far user selection scheme is introduced by adopting three distinct relaying protocols.
[103]	General	Additive white Gaussian noise (AWGN)	Single antenna at each node	Multi-hop with an EH relay	Information-theoretic tools are used to obtain capacity-energy region.
[104]	TDMA	Quasi-static flat Rayleigh fading	Single antenna at each node	No	A harvest-then-transmit protocol is adopted.
[105]	TDMA and OFDMA	Slow frequency selective fading, a power delay profile with exponentially distributed taps	Single antenna at each node	No	For EH, the TDMA-based approach relies on TS at each receiver whereas the OFDMA-based scheme adopts PS at each receiver.
[106]	TDMA	Quasi-static flat Rayleigh fading	Two antennas at H-AP and single antenna at each user	No	The H-AP operates in FD mode by simultaneously broadcasting wireless energy to a set of users in the downlink and receiving independent information from the users in the uplink.
[107]	NOMA	Quasi-static flat Rayleigh fading	Single antenna at each node	Multi-hop with EH relays	A new SWIPT NOMA protocol is introduced to enhance the reliability of the far users by the help of the near users.
[108]	NOMA	Quasi-static flat Rayleigh fading	Single antenna at each node	No	A harvest-then-transmit protocol is embraced.
[109]	NOMA	Block flat Rayleigh fading	Single antenna at each node	No	Compared to OMA-based schemes, significant rate enhancement for cell-edge EH users is attained.
[110]	NOMA	Quasi-static flat Rayleigh fading	Single antenna at each node	Multi-hop with an EH relay	The impact of power allocation on cooperative NOMA systems with SWIPT is studied.
[111]	TDMA and NOMA	Quasi-static flat Rayleigh fading	Single antenna at each node	No	A harvest-then-transmit protocol is exploited where the devices first harvest energy from a power beacon and then transmit information in the uplink.
[112]	NOMA	Quasi-static flat Rayleigh fading	Multiple antennas at the primary and cognitive BSs. Other nodes have single antenna.	Cooperative	Primary and cognitive BSs cooperate for enhancing security and give access to the secondary network.
[113]	NOMA	Quasi-static flat Rician fading	mmWave massive MIMO. A multi-antenna BS communicates with multiple single-antenna users.	No	To reduce the number of required RF chains, the beamforming at BS is performed by means of analog and digital precoders.
[114]	OMA and NOMA	Quasi-static flat fading	Single antenna at each node	No	Depending on the amount of decoding energy consumption, OMA and NOMA based approaches may perform quite differently.
[115]	NOMA	Quasi-static flat Rayleigh fading	Single antenna at each node	No	TS is used at each user to accomplish ID and EH in two orthogonal time slots.
[116]	NOMA	Slow frequency selective fading	Single antenna at each node	No	Subchannel allocation and power optimization are investigated for heterogeneous networks with

TABLE 2. ***(Continued.)*** **List of relevant works on MAC techniques for SWIPT systems.**

					NOMA SWIPT.
[117]	TDMA and OFDMA	Slow frequency selective fading	Single antenna at each node	No	It is shown that, in terms of secrecy rate, the OFDMA system with PS-SWIPT outperforms the TDMA system with TS-SWIPT.
[118]	OFDMA	Slow frequency selective Rician fading	Single antenna at each node	Two-hop with multiple AF relays each operating in HD mode	Resource allocation and relay selection problems are inspected by assuming that end nodes support SWIPT.
[119]	NOMA	Quasi-static flat Rayleigh fading	Single antenna at each node	Two-hop with the SWIPT-enabled near user assisting the far user	A SWIPT-based cooperative NOMA system is analyzed in terms of outage probability.
[120]	TDMA and NOMA	Slow flat fading	Single antenna at each node	No	Each group of users is served with a distinct time slot and NOMA is used inside a group.
[121]	TDMA	Slow frequency selective fading	Single antenna at each node	No	Optimal energy efficiency resource allocation problem is studied. The non-convex problem is split into two convex subproblems.

beams through the direction of the intended users. Additionally, a long short-term memory (LSTM)-based channel prediction approach has been proposed with the aim of mitigating the degrading effects of imperfect CSI due to high mobility conditions [150]. By mentioning the fact that NOMA networks would face substantial security risks due to the distributed nature of the employed SIC mechanism, the investigation in [151], the secrecy performance of a multi-antenna cooperative NOMA scheme has been examined for both DF and AF relaying cases. Here, in addition to the conventional metric i.e., SOP, the authors have also focused on a different performance metric called strictly positive secrecy capacity (SPSC). The detailed investigation in [152] has focused on the effects of external and internal eavesdropping scenarios on the PLS performance of a unified NOMA framework for the case of stochastically-located multiple user terminals.

The authors of [153] have provided the PLS examination for the data of the weak user where this data have been considered to be intercepted by the strong user in a NOMA network. By employing the directional modulation technique [154], [155], the proposed NOMA scheme allows access of the intended symbols at the weak user while giving access to a different but valid lower order symbol alphabet to the strong user for performing SIC. Due to its distributive nature at the decoding steps, SIC technique brings along with serious security risks for the far-end users' signals in the presence of near-end users. The security designs for 5G NOMA systems are examined in [156] for firstly the two-user case that has been extended to the multiuser case. After adjusting the order of SIC and employing a cooperative jammer, an optimal power allocation problem has been built subject to users' data rate and total power constraints.

B. PHYSICAL LAYER SECURITY OF MULTIUSER SWIPT SCHEMES

In systems employing wireless information and power transfer (WIPT), both information and power signals are carried by the same RF wave. Afterwards, information packets are decoded by ID receivers, while electromagnetic energy is collected by power receivers and converted into electrical energy [158], [159]. However, due to the open (unguided) nature of wireless communication channels that has been demonstrated in Fig. 5, information signals may also reach power harvesters and unwanted receivers, thus creating the potential for information leakage.

In particular, in WIPT-based systems, a power beacon assigned to wireless power transmission can be exploited to improve communication privacy by scrambling eavesdropper terminals. In addition, an information sign can also be used as a power source to increase the energy collected in power receivers. Therefore, PLS techniques offer natural solutions to improve the security of communication systems using the WIPT approach. While increasing the channel capacity provided to main users in classical systems that only transfer information, in addition to the aim of reducing the capacity of infiltrating channels to users making malicious / unauthorized listening to minimum levels, with the inclusion of WIPT techniques, the aim of maximizing wireless power transmission efficiency is also coming onto the agenda.

Accordingly, the combined optimization of the privacy and power efficiency performances of communication systems using SWIPT techniques constitutes a dual-objective optimization problem in which communication reliability and power efficiency phenomena that constitute trade-off between each other are input. For this reason, it is necessary to establish a good balance between information transmission security and power transmission efficiency.

A brief categorization of the research studies on the communications security of SWIPT-based schemes has been provided in Table 3 with respect to their network structure, transmission & reception strategy, EH mechanisms, channel model & system imperfections, and performance metrics evaluated.

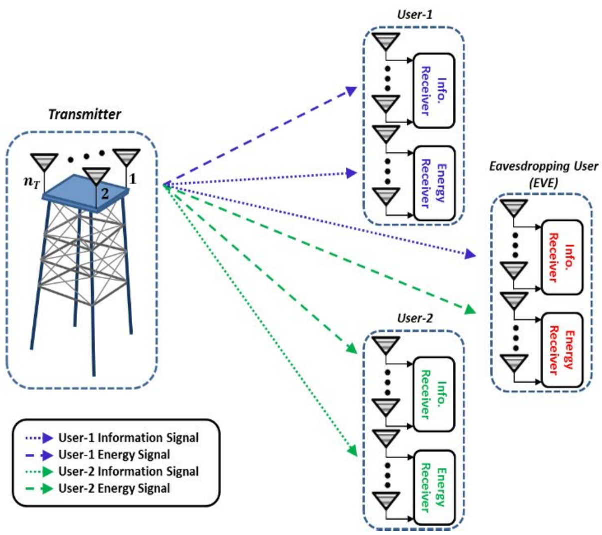

FIGURE 5. Open nature of multiuser schemes that sketches the main infirmity in communications security.

In study [160], the authors has projected the trade-off between information transmission security and power efficiency on two distinct problems: the first problem has focused on maximizing the privacy rate, provided that the minimum energy level collected for each of the users, while the other problem has aimed to maximize the energy level collected by the users under a specified secrecy constraint. In this study, while designing spatial BF structures for information and power signals in a multi-antenna BS, both problems are tried to be solved jointly. The secrecy performance of the MISO-SWIPT scheme has been examined when the CSI of the wireless channels between the BS and the information and power receivers is incorrect / uncertain, and a robust BF scheme has been designed in [161].

Recently, thanks to the identification of new attributes of interference effects, research interest has focused on the beneficial use potential of interference in wireless systems rather than avoiding or suppressing interference. Accordingly, it is evaluated that traditional suppression techniques are no longer optimum and the use of more innovative interference comes to the fore. Thus, it has been revealed that the reliability, privacy and accessible data rates of wireless communication systems can be improved when interference is utilized. In the modern communication concept, interference is of great importance in both information and power transmission in wireless communication systems [162].

In the literature, there are studies in which SWIPT techniques using the approach to exploit interference effects in multiuser systems have been studied extensively [163], [164], [165], [166]. The interference effects, although seen as detrimental to the ID process, can be beneficial for the EH process. On the other hand, a trade-off between ID and EH processes is existing for effective implementation of the SWIPT approach in multiuser systems. The idea of BF optimization achieves a remarkable gain by collecting signals in constructive / supportive interference scenarios. The references [167] and [168] suggest a multiuser symbol-level precoding approach, positioning the effects of multiuser interference at the point of common use of CSI and information. In some specific cases, interference effects between data packets can be transformed into useful signals that have the potential to improve the SINR of the downlink signal. Using a similar setup, with the help of the experience of CSI and data packets at the transmitter, the effects of constructive / supportive interference have been studied in [169]. Recently, by proposing a hybrid analog / digital precoding structure, a number of BF strategies have been proposed to take advantage of the concept of mutual coupling between transmitting antennas with the help of adjustable antenna loads [168].

In study [170], it has been shown that interference does not limit the capacity of the broadcast channel. However, in many studies, SIC approach has been proposed and used. The use of SIC technique in communication networks including the SWIPT approach has been examined in [162]. In the study, it was shown at what level each receiver in the network could perform WPT using the SIC technique without affecting the decoding process of the information packets. In addition, the results of the study revealed that the SIC technique is considerably useful for communication systems using SWIPT. A SWIPT scheme based on opportunistic communications (OC) has been proposed in [83] for networks conducting interference alignment (IA). In this study, in order to apply the SWIPT technique, OC-based antenna and user selection approach has been used. The reference [171] has analyzed the improvements in the performance of both EH and ID processes with the aid of constructive interference in a MISO downlink transmission scenario. In addition, it has been proposing a new precoder design for the SWIPT scheme, which can significantly reduce transmitter power values for cases with fewer transmit antennas than the number of users. Besides, in study [172], the effects of residual self-interference (RSI) in MIMO channels have been discussed. In [157], implications for the use of SWIPT techniques in broadband wireless systems aiming to create a set of parallel sub-channels that simplify the resource allocation mechanism by using OFDM and beam shaping techniques together are presented. Here, the authors propose power control mechanisms for the SWIPT approach in a multiuser multi-antenna OFDM infrastructure, including electronic circuit power constraints. Whereas, in the study, subcarriers allocated to a particular user are used for EH-purpose by assuming a fixed-number of subcarriers.

Moreover, the study in [21] brings the performance of the SWIPT approach to the literature in a multiuser OFDM-based system consisting of single-antenna users using a PS technique. Here, it has been shown that system energy efficiency can be improved by using RF-based EH techniques in interference-limited regime. The use of multi-antenna receivers has been stated to be beneficial in improving system capacity rather than improving system energy efficiency. The performance of SWIPT techniques in multiuser OFDM-based wireless systems has been examined in [105] for the scenario of transmission from a fixed access point to distributed user terminals. Within this study, two multi-access techniques such as TDMA and OFDMA are discussed. When using the TDMA technique, the TS approach has been employed within such a layout in which the information packet receiver of a particular user will be active during the scheduled time channel of that user, and in all other time channels, the receiver (energy receiver) serving the EH process will be active. However, when using OFDMA technique, the PS approach is operated assuming that all sub-carriers use the same PS ratio in each receiver. In the SWIPT approach, in order to facilitate the EH process by utilizing the RF signal, the transmitter unit must be able to emit a highly reinforced signal. This, in turn, can lead to high vulnerability to eavesdropping due to the high level of data leakage potential if the receiver unit is malicious. In this context, a new QoS-oriented paradigm has been introduced for communication systems using the SWIPT approach. In particular, privacy and authorization have increasingly been the main fields of study for wireless communication technologies. Besides, the concept of physical layer privacy has been introduced as a new layer of defense in order to provide a considerable level of communication secrecy without cryptography.

Cooperative relay systems that provide secure transmission through physical layer privacy / security enhancements have attracted great attention [173], [174]. In studies [175], [176] the secrecy rate has been maximized for AF-type relays using SWIPT. By using a dedicated receiver mode (e.g., a scheme where one of the receivers is conducting a highly confidential ID process while the others participate in the EH process), SWIPT-assisted PLS has been investigated in [177] and [178]. In study [160], AN has been used both to confuse the eavesdropping system and to increase information confidentiality and as the primary power source for receivers that support the EH process (non-ID-oriented). This method has been thought to be not suitable for co-located antennas where users simultaneously receive information packets and conduct EH. In the references [179] and [180], the resultant power received by all users was optimized to meet the privacy requirements for each user scheduled with OFDMA access method. Secrecy performance for SWIPT-based single-input multiple-output (SIMO) system using MRC has been analyzed over SOP and secrecy capacity criteria in [181]. A similar system configuration based on MISO using TAS has been examined in [182] for the case of imperfect CSI.

The secrecy probability performance of a SWIPT scheme supported by a large number of multiple-antenna relays has been examined in [183] when the imperfect CSI information available at the relays and non-linear EH equipment are employed. The authors have brought detailed investigation to the literature on selecting the relay that maximizes instantaneous secrecy capacity when relays are operated in DF-type data transmission mode. In the case of non-ideal (erroneous) channel estimation, an energy-efficient resource allocation mechanism for multiuser massive MIMO systems based on the SWIPT approach is proposed in [184]. The PLS performance of a multiuser downlink OFDM-IoT system to be observed in the presence of a large number of eavesdropping equipment while communicating with a large number of legitimate IoT equipment has been studied in [117]. For the scenario in which a large number of users are scheduled using OFDMA and TDMA access techniques, assuming that IoT equipment could jam the wiretapper systems using power signals based on the SWIPT technique, the secrecy performance analysis has been conducted in terms of extensive simulation studies.

The communications security of a multiuser MISO downlink scheme employing SWIPT has been investigated in [20] by considering passive and potential eavesdroppers. Here, receiver equipments have been considered to employ the PS scheme in order to decode information and harvest energy simultaneously. A resource allocation algorithm that aims to minimize the total transmit power for EH receivers by combining the usage of AN and energy signals has been proposed. The study has shown that the proposed algorithm could provide secure communications and efficient energy transfer capabilities. The application of SWIPT scheme within a MIMO downlink scenario has been examined in [185] via Monte Carlo simulations by considering the case that the information aimed to the legitimate receiver might be wiretapped by the intruding EH receivers (i.e., the potential eavesdroppers). In the case that the CSI of EH receivers is not perfectly known at the transmitter, the worst-case communications secrecy is tried to be optimized by jointly taking the precoding matrix, AN covariance matrix, PS ratio into accounts. A transmit BF power minimization scheme has been proposed in [186] for a multiuser MIMO SWIPT scheme where PSs are employed by the receivers. The authors have extended their investigation by including robust secrecy transmission designs by incorporating deterministic channel uncertainties. For both perfect and imperfect CSI cases, the study has introduced a sequential parametric convex approximation (SPCA)-based iterative algorithm, and illustrated the average transmit power of the information signal in terms of different target secrecy rates. The authors of [187] have introduced a SWIPT IoT network system that employs selection-combining (SC) technique at two legitimate user terminals with two-antennas in Rayleigh fading channels. By assuming that the network suffers from the non-collaborating passive single-antenna eavesdropping nodes,

TABLE 3. Brief description of research studies on communications security of SWIPT-based schemes.

Ref.	Network Structure	Transmission & Reception Strategy	EH Mechanisms	Channel Model & Imperfections	Performance Metrics
[20]	• MU-MISO	• Transmit BF & AN	• PS	• Rayleigh Fading	• ASR • AHE
[117]	• MU-SISO IoT Downlink OFDMA/TDMA	• OFDM	• PS • TS	• Rayleigh Fading w/ Imperfect CSI	• SSR
[160]	• MU-MISO Downlink	• Transmit BF & AN	• Steering Multiple Beams through ERs	• Rayleigh Fading	• ASR • WSET
[161]	• SU-MISO Downlink w/ WR	• Transmit BF	• Transmit BF through ERs	• Rayleigh Fading with Uncertainties	• AWCSR
[162]	• Bipolar Ad Hoc Network w/ SISO Terminals	• SISO w/ SIC	• PS	• Rayleigh Fading	• ECP • AHE
[164]	• MU-MIMO	• Transmit BF	• Rank-One Energy BF	• Rayleigh Fading w/ MU-IFC	• AHE • SLER
[165]	• 2-D Large-Scale (Bipolar Ad Hoc) Network	• SISO	• PS	• Partial (Rayleigh) Fading	• OP • AHE • SINR
[166]	• SU-MIMO	• mmWave Transmit BF	• PS	• Rayleigh Fading	• ECP • AHE
[175]	• SU-SISO Two-Hop Relaying	• AF and CJ BF by Multiple Relays	• TS	• Rayleigh Fading w/ local CSI at each relay	• ASR
[176]	• SU-SISO Two-Hop Relaying	• AF and CJ BF by Multiple Relays	• TS • PS	• Rayleigh Fading w/ local CSI at each relay	• ASR
[177]	• MU-MISO Full-Duplex System	• Transmit BF	• Transmit BF through ERs	• Rayleigh Fading w/ Residual Self Interference	• SINR • ILR
[178]	• SU-MIMO Two-Hop AF Relaying	• Transmit BF and Receive MRC	• TS • PS	• Rayleigh Fading	• Effective Secrecy Capacity (ESC) • Max. Achievable ESC
[179]	• MU-SISO Downlink	• OFDM	• PS	• Rayleigh Fading	• ASR • WSET
[180]	• MU-SISO Downlink	• OFDM w/ AN	• PS	• Rayleigh Fading	• SSR
[181]	• MU-SIMO Downlink	• MRC at IRs	• PS	• Rayleigh Fading	• SOP
[182]	• MU-MISO Downlink	• Single TAS	• PS	• Rayleigh Fading w/ Imperfect CSI	• SOP
[183]	• SU-SISO w/ Power Beacon	• DF Relay Selection	• TS	• Rayleigh Fading w/ Imperfect CSI at Relays	• SOP
[185]	• MU-MIMO Downlink	• Transmit BF & AN	• PS	• Rayleigh Fading w/ Imperfect CSI	• AWCSR
[186]	• MU-MIMO Downlink	• Transmit BF & AN	• PS	• Rician Fading w/ Imperfect CSI	• ASR
[187]	• SU-SISO Downlink	• SISO w/ CJ	• PS	• Rayleigh Fading w/o CSI	• SOP
[188]	• MU-SISO Downlink	• SISO at LUs • SIMO at WR	• PS	• Rayleigh Fading	• Secrecy Rate Region
[189]	• MU-SISO Downlink OFDMA	• OFDM	• PS	• Rayleigh Fading	• OP • MASR
[193]	• MU-MIMO Two-Way AF Relaying	• Relay Transmit BF	• PS	• Rayleigh Fading w/ CSI Uncertainties	• MASR
[194]	• MU-SISO Two-Way AF Relaying	• Bidirectional SISO Transmission	• PS • TS	• Rayleigh Fading	• ASR • SEE
[195]	• MU-MIMO Two-Way AF Relaying w/ NOMA Down.	• Relay Transmit BF	• PS	• Rayleigh Fading	• ACSR
[196]	• Two-Tier HetNet • MISO Macrocell	• Transmit BF & AN	• PS	• Rayleigh Fading w/ Imperfect CSI	• SEE

TABLE 3. ***(Continued.)*** **Brief description of research studies on communications security of SWIPT-based schemes.**

	• MISO Femtocells				
[197]	• MU-MISO Downlink	• Massive MIMO Transmit BF	• PS	• Rayleigh Fading	• ASR
[198]	• MU-MISO Downlink	• Transmit ARS	• PS	• Rayleigh Fading w/ Imperfect CSI	• ASR
[199]	• MU-SISO UAV Network	• SISO mmWave LoS • OMA/NOMA	• PS	• Rayleigh Fading w/ Imperfect CSI	• SOP • EST • COP
[200]	• mmWave Cooperative NOMA Downlink	• Half-Duplex DF Two-Hop Relaying	• PS	• Rayleigh Fading	• EICP • EST
[201]	• MU-SISO Satellite NOMA Downlink	• UAV-Assisted Transmission	• PS	• Shadowed Rician • Nakagami-m Fading	• SOP
[202]	• MU-MISO IoT Network Downlink	• Transmit BF & AN	• PS	• Rayleigh Fading w/ Imperfect CSI	• ASR
[203]	• MU-SISO NOMA Network Downlink	• DF Relay selection	• PS	• Rayleigh Fading	• SOP
[204]	• SU-SISO IoT Network Downlink	• SISO Transmission under Cooperative Eavesdropping	• PS	• Rayleigh Fading	• SEE
[205]	• MU-MIMO CSTN Downlink	• Transmit BF	• PS	• Rayleigh Fading w/ CSI Uncertainties	• ASR
[206]	• MU-MIMO Downlink	• Transmit BF & AN under Cooperative Jamming	• Non-linear PS	• Rayleigh Fading w/ CSI Uncertainties	• AHE
[207]	• Cell-Free Massive MIMO Network	• Transmit BF & AN	• PS	• Rayleigh Fading w/ CSI Uncertainties	• AHE
[209]	• IRS-Assisted SU-SISO Network	• SISO and AI-Based Passive Beamforming	• PS	• Rician Fading w/ CSI Uncertainties	• ASR
[211]	• IRS-Assisted SU-SISO Network	• SISO Transmission w/ IRS Jamming	• PS	• Rician Fading w/ CSI Uncertainties	• ASR
[212]	• IRS-Assisted HetNet	• Transmit BF & AN • Passive Reflection via IRS	• PS	• Rician Fading	• ASR
[213]	• SU-SISO Network Downlink	• SISO Transmission	• PS	• Rayleigh Fading	• ASR

AWCSR (Average Worst-Case Secrecy Rate)
CJ (Cooperative Jamming)
CSTN (Cooperative Satellite Terrestrial Network)
ECP (Energy Coverage Probability)
ER (Energy Receiver)
ESC (Effective Secrecy Capacity)
EST (Effective Secrecy Throughput)
IFC (Interference Channel)
ILR (Information Leakage Rate)
IR (Information Receiver)
LU (Legitimate User)
MASR (Max. Achievable Secrecy Rate)
MU (Multi-user)
OP (Outage Probability)
SISO (Single-Input Single-Output)
SLER (Signal-to-Leakage-and-Harvested Energy Ratio)
SSR (Secrecy Sum Rate)
WSET (Weighted sum energy transferred to ERs)
WR (Wiretapping receiver)

the zero-forcing (ZF) BF scheme has been employed at the jamming node with the aim of confusing the eavesdroppers. After deriving closed-form expressions for the SOP and secrecy throughput, the investigation has indicated that increasing the EH efficiency conversion has a positive impact on the system's secrecy performance. The secrecy rate region of wiretap interference channels that employ multi-antenna passive eavesdroppers has been studied in [188] under EH constraints of PS receivers. Lower-bounds for secure communication rate have been derived without imposing any limitation on the eavesdropper processing. The authors have discovered that the Pareto boundary of the secrecy rate region might be achieved via the reasonable adjustment of transmit power and PS coefficients. An optimization procedure on maximizing the minimum downlink secrecy throughput of the multiuser OFDMA network with SWIPT that is composed of a BS and several receiver users has been carried out in [189] by considering the subcarrier allocation and PS ratio as inputs of the objective function. The secrecy rate of the weakest user has been aimed to be maximized in case that every user could wiretap all other users' subcarriers. In order to jointly allocate subcarriers and determine the PS ratios for all users, a particle swarm optimization has been performed. The results of the investigation on the average total instantaneous secrecy rate of the weakest user indicate that the total transmit power should be high enough to overcome the minimum operating energy. Whereas, for higher values of the total transmit power beyond a threshold, the average total instantaneous secrecy rate has been shown to be saturated.

Recently, HetNets have been considered as novel network structures that have been promising enhancements in the spatial resource reuse opportunity and the users' QoS by providing coverage via smaller cell deployments [190]. Under the wiretapping scenario of a single eavesdropper in a heterogeneous macro-pico network has been studied in [191] where the sum-rate of macrocell users is examined with the optimization purpose from both subcarrier and power allocation perspectives. A secure HetNet scheme has been proposed in [192] by considering an energy efficiency-based resource allocation problem. The investigation provided in [193] has been focusing on the secure relay beamforming problem for SWIPT in an AF two-way relay network that employs a multi-antenna relay node in order to serve single-antenna end users. By considering both the conditions that the CSI related to the eavesdropper channels are available or not available, the achievable secrecy sum rate has been tried to be optimized under transmit power constraint and energy harvesting constraint. The authors of [194] have provided an investigation on the communications security of two-way untrusted AF relay networks with SWIPT. With the objective of maximizing the secrecy rate and SEE, the PS- and TS-based SWIPT relaying strategies have been examined for single-antenna user and relay nodes under Rayleigh fading channel conditions. In [195], an AF-based two-way MIMO relay-assisted CR NOMA network that employs the SWIPT technology in order to enhance network energy efficiency has been analyzed. In this study, the authors have focused on a scenario in which a pair of primary users and two pairs of secondary users (SUs) exchange information with the help of a MIMO two-way relay. Here, the edge SU of each pair is considered an untrusted node that tries to wiretap the central SU's information. By jointly optimizing the power allocation at all users, PS factor and relay beamforming under the constraints on the QoS, EH and transmit power, the sum achievable secrecy rate (ACSR) metric has been aimed to be maximized for communications security purposes. The authors of [196] have focused on the robust secrecy energy efficiency (SEE) optimization in a wirelessly-powered HetNet by considering ellipsoid-bounded CSI uncertainties. Here, the network is considered as to consist of a macrocell BS that covers multiple femtocell BSs. By the time, the macrocell BS has been dedicated to serve multiple users in the presence of a wiretapping multiple-antenna user while each femtocell BS serves a pair of ID and EH receivers with multiple antennas, where the EH receiver attempts to wiretap the information of ID receiver in the same femtocell. In order to enhance the secrecy performance, the macrocell and femtocell BSs have injected AN within the downlink signal, and the problem of maximizing SEE has been formed in a cross-tier multi-cell AN-aided transmit BF design. The reference [197] has studied the secure downlink transmission of a massive MIMO SWIPT system. A BS with massive number of antennas conveys both the energy and the information signals to the legitimate users in the presence of an active eavesdropper. The legitimate and malicious users all perform a PS approach with the aim of simultaneously harvest energy and decode information. With the effective and precise beam-steering advantage of massive MIMO, the BS is considered to focus energy to the intended users while preventing the leakage through the wiretappers. The study has focused on the ACSR and provided a closed-form lower bound. In order to assign secure multiuser communications, the authors have carried out with an optimization process to maximize the ACSR based on the constraints on the minimum harvested energy by the user and the maximum harvested energy by the wiretapper. The outcomes of the study have exhibited the effectiveness of using massive MIMO in providing PLS in SWIPT systems. The system model examined by the reference [197] has been also at the focus of reference [198] where the authors have investigated the robust joint design of hybrid analog-to-digital (A/D) BF matrices and the artificial redundant signal (ARS) covariance matrix at the BS while the main purpose is shifted to the maximization of the worst-case sum secrecy rate of the ID users with a transmit power constraint, a non-linear EH constraint and a unit-modulus constraint on the entries of the analog BF matrix. By using the penalty-concave convex procedure within the optimization problem, the study has introduced the simulation results of the proposed design, and afterwards exhibited that the robust joint hybrid BF design achieves considerable improvements when compared to the conventional hybrid BF benchmark.

Studies focusing on the investigation of SWIPT schemes with NOMA in mmWave frequencies have been provided in [199], [200], and [201]. Being motivated by the potential of millimeter wave (mmWave) systems from abundant available bandwidth and line-of-sight probability perspectives, the analysis provided by [199] has developed a framework to examine security, reliability and energy coverage performance of downlink mmWave SWIPT systems consisting of UAV networks employing both NOMA and OMA. Under the consideration that a UAV serves two types of authorized IoT devices in the presence of multiple passive eavesdroppers, the directional modulation scheme has been employed in order to enhance the PLS performance. After deriving the analytical expressions for COP, SOP, and effective secrecy throughput (EST) of the users with high rate security requirement (HRSR) under NOMA and OMA schemes using stochastic geometry, the active antenna selection of directional modulation using adaptive genetic simulated annealing (AGSA) algorithm is optimized to further improve the secrecy performance based on the obtained analytical results. Consequently, the authors have obtained the closed-form expressions for the COP and energy-information coverage probability (EICP) of the energy-constrained users with low-rate requirement (ECLR) under NOMA and OMA schemes. Useful insights for the effect of various parameters on the trade-off between the reliability and security for the HRSR user, and the trade-off between the reliability and energy coverage for the ECLR user have been provided. Moreover, the analysis has shown that the EST of the NOMA scheme outperforms OMA at low transmit power and high codeword transmission rate.

The EICP metric corresponding to the IoT systems with the help of relay selection has been analyzed in [200] in the presence of multiple eavesdroppers. The authors of [201] have derived the average SOP and probability of strictly positive secrecy capacity related to the UAV-assisted satellite-terrestrial SWIPT scheme by considering shadowed Rician fading and Nakagami-m fading effects in satellite-to-UAV and UAV-to-users links, respectively. In [202], the secrecy rate optimization is performed for IoT systems employing PS-based SWIPT schemes with the help of AN-assisted transmission for both the perfect and imperfect CSI conditions. The average SOP performance of SWIPT scheme has been examined in [203] for the cooperative NOMA scheme with Min-Max User Selection. In [204], the SEE metric of the relayed communications scenario constructed by SWIPT-based IoT nodes in the presence of cooperative eavesdroppers. The research in [205] focuses on the coexistence case of the primary satellite networks in the mmWave bands and the secondary multiuser terrestrial networks with SWIPT. The authors have investigated robust secure BF and PS for the case of a BS equipped with a uniform planar antenna array and a secondary user employing a PS-type receiver. By relying on an angle-based CSI error model, the minimal value of the worst-case secrecy rate among all secondary users have been tried to be maximized while the QoS constraints for each secondary user, the interference limit for a primary satellite earth station, and the power consumption limit for the BS are satisfied. The numerical results of the extensive study have provided comparisons to the existing approaches and useful insights into different robust designs. Another study on the robust BF design for multiuser MIMO secrecy IoT networks with SWIPT has been presented in [206]. Here, the user terminals have been harvesting energy via a non-linear EH model with the help of a cooperative jammer. In order to facilitate efficient wireless energy transfer and secure transmission, the BS employs AN. An optimization process has been performed in order to maximize the minimum harvested energy among users subjected to secrecy rate constraint and total transmit power constraint in the presence of channel estimation errors. The authors of [207] have focused on the secure SWIPT scenario in cell-free massive MIMO systems where a massive number of randomly located access points (APs) are considered. Here, the Poisson-distributed APs have been serving multiple ID receivers and an information-untrusted active EH receiver. The EH and the wiretapping processes have been assumed to be performed through the spatially separate antennas. Hence, the dual-antenna active EH receiver has dedicated its first antenna for EH purposes while the other for eavesdropping information. The analysis has provided closed-form expressions for the average harvested energy (AHE) and a tight lower bound on the ergodic secrecy rate (ESR). The lower bound for the ESR metric has taken into account the information users' knowledge attained by downlink effective precoded-channel training. The comparison provided by the study has shown that the cell-free massive MIMO outperforms the co-located massive MIMO case over the interval in which the AHE constraint is low. Besides, the cell-free MIMO has been found to be more immune to the increase in the active eavesdropping power than the co-located MIMO case. The extensive study in [208] has stated that the employment of SWIPT approach promises to prolonging the battery life of mobile terminals and enhancing the overall system energy efficiency within especially in NOMA cases which enables the EH receivers to exploit the inter-user interference. The achievable data rate for the downlink multi-carrier NOMA network supported by PS-based SWIPT has been optimized by involving deep-learning based approaches by satisfying the limitations on the available power budget and the requirement for EH. The simulation results of the examination have demonstrated the superiority of the combination of PS-based SWIPT with multi-carrier NOMA over SWIPT-aided single-carrier NOMA and SWIPT-aided OMA.

By inserting concept of the IRSs, which is also termed as reconfigurable intelligent surfaces (RIS) and is one of the emerging wireless communication applications, into SWIPT-based schemes, several researches have canalized on the communications security performances [209], [210], [211], [212]. The secrecy analysis of SWIPT scheme that incorporates the assistance of IRSs in the presence of an eavesdropper has been investigated in [209]. The computational complexity burden is aimed to be reduced with the help of deep-learning (DL)-based optimization approach. The authors of [210] have considered the joint transmit/reflect beamforming and power-splitting SWIPT scheme where the transmit sum energy of IRS-aided secondary transmitter is minimized subject to the QoS requirements of secondary receivers and the interference constraints of the primary receivers. In [211], a two-phase communication scheme under the passive eavesdropping in Rician fading channels has been examined by also considering the IRS as a tool to convey the information signals to the legitimate user. An optimization procedure has been handled in [212] that has focused on the secrecy rate corresponding to a beamforming scheme enhanced by the IRS employment.

The literature related to the multiuser SWIPT schemes also includes several researches that focus on the DL-based optimization approaches promising to efficiently reduce the computational complexity burden and processing time [209], [213]. The secrecy rate of PS-based SWIPT schemes has been investigated in [209] by utilizing the feasible point pursuit (FPP) and the successive convex approximation (SCA) methods. Additionally, a DL based solution has been introduced to solve the optimization problem. The authors of [209] have extended their DL-based analyses through the assistance of IRSs and provided the outcomes in [213].

V. UAV-ENABLED SWIPT SYSTEMS

UAVs, owing to their prominent attributes such as maneuverability, adaptive altitude, low cost, and deployment flexibility, play a paramount role in establishing and/or enhancing ubiquitous and seamless connectivity of communication devices as well as improving the capacity of future wireless networks. Furthermore, UAVs channel characteristics show significant differences, particularly offering a higher chance of line-of-sight (LoS) connectivity to ground users. The reader can refer to [214], [215], [216] for more details about air-to-ground channel models.

UAVs can be categorized, based on their altitudes, into high altitude platforms (altitudes above 17 km and typically quasi-stationary) and low altitude platforms (altitudes of up to a few kilometers, quickly move, and a flexible deployment), while based on type, into fixed-wing (e.g. small aircrafts) and rotary-wing (e.g. drones and quadcopter) [216]. In UAV-based wireless communications, these vehicles require a sufficiently high energy resources for the propulsion, management and stabilization due to their mobility as well as communications purposes. Energy-constraints of UAVs can be supported through several EH techniques from ambient resources. UAV-assisted SWIPT, as an upsurge of recent research topic, has gained momentum rapidly. The existing UAV-enabled SWIPT literature can be broadly divided into three categories, which are cooperative SWIPT networks [217], [218], [219], [220], [221], [222], [223], [224], [225], [226], [227], [228], [229], multicasting SWIPT networks [230], [231], [232], [233], [234], [235], [236], [237], [238], [239], [240], [241], [242], [243], [244], [245], [246], [247] and millimeter-wave (mmWave) SWIPT networks [199], [248], [249], [250], [251], [252], [253]. Apart from these, there are a few works in the literature that facilitate disaster aware clustering and association [254], and secure information and power transmission [255].

UAV-enabled SWIPT systems are vulnerable to malicious attacks because of the higher chance of LoS transmission link and the broadcast nature of the wireless channel, and hence need secure designs. Also, this gets more hectoring as smart wireless devices become cheaper and more accessible by malicious users or attackers.

A. UAV-ENABLED COOPERATIVE SWIPT NETWORKS

Cooperative communication can be basically expressed as the collaboration of the devices in a communication network with each other in information transmission to ensure the efficient use of the available network resources. UAV-assisted cooperative communication with its inherent attributes that enable a higher chance of LoS links to ground users, reveals an exciting great potential, especially for the cases where the channel condition of the direct link between the source and the destination is undesirable and unable to afford transmission with acceptable performance. A conceptual UAV-enabled cooperative SWIPT communication system is illustrated in Fig. 6.

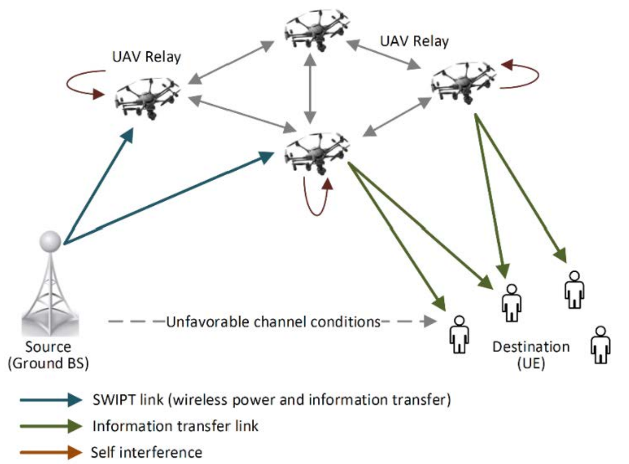

FIGURE 6. UAV-enabled cooperative SWIPT communication system with ground BS, multi-UAV relay and multiuser.

The current literature has reported several UAV-aided cooperative SWIPT studies [217], [218], [219], [220], [221], [222], [223], [224], [225], [226], [227], [228], [229], which are summarized in Table 4. In [217] and [218], a UAV-assisted cooperative communication network with PS SWIPT has been investigated, in which the UAV serves as a mobile relay for both AF and DF protocols, and its transmission capability is powered by radio signal from the source. The authors in these studies examined the cooperative throughput maximization problem by jointly optimizing the UAV's decision profile, power profile and trajectory. These works have been revised for the time sharing mechanism in [219] and [220]. The articles [221], [222] examined FD-enabled UAV-assisted cooperative communication system, where the UAV is used as an aerial relay with DF protocol. Here, the transmission capability of the UAV is powered exclusively by a dedicated WPT link and a radio signal transmitted from the source via TS SWIPT policy. Self-interference on the UAV is also utilized as an EH source since the UAV in [221] and [222] is equipped with two antennas for ensuring simultaneous reception and transmission in FD mode. The authors revised these studies by considering Nakagami-m air-to-ground channels in [223]. The paper [226] presented a cache-assisted UAV-enabled cooperative network with a dynamic TS SWIPT mechanism, in which the UAV as an intermediate mobile relay node ensures backscatter communication through a backscatter circuit. Apart from these studies [217], [218], [219], [220], [221], [222], [223], [226] (considers a source-destination pair, and a UAV relay with SWIPT technology), the literature provides a few studies that envisage multiuser [227], and multi-relay [228] cooperative communication system. The authors of [227] introduced a UAV-enabled cooperative network that includes a multi-antenna ground BS and an HD-enabled UAV with AF relay protocol, and multiple single-antenna ground users with PS SWIPT. This work strives to maximize the sum harvested energy of users. In [228], a UAV-aided multi-relaying system has been investigated, where IRSs deployed on two UAVs and a building act as relay nodes, and a ground user (IoT) conducts PS SWIPT policy. Here, the maximization of the average achievable rate is examined.

Motivated by the importance of the security in UAV-assisted communication systems, the article [224] envisaged a cooperative secure and energy-efficient transmission scheme, that a source delivers confidential information to a destination through an AF-based UAV relay in the presence of a ground eavesdropper. This work considers PS SWIPT mechanism and Rician fading channel model. As a similar work, in [225], a mobile relay UAV-assisted secure SWIPT network has been investigated in the presence of a legitimate source-destination pair and multiple eavesdroppers with imperfect locations. The UAV utilizes both PS and TS schemes. Here, the devices are equipped with a single antenna, apart from FD destination that has dual antenna, one for signal transmission and the other for signal reception. The article [229] presented a cooperative secure communication scheme in UAV-aided NOMA network that embodies a source, an artificial jammer, an AF-enabled mobile UAV relay with PS SWIPT, and two destinations.

A point worth mentioning here is that the devices, i.e., the source (except [227], [228]), the destination (except [228]), and the UAV (except pointed out above), have a single antenna and thus these studies can be viewed as single-antenna single-user (except [227], [228]) communication systems.

B. UAV-ENABLED MULTICASTING SWIPT NETWORKS

Multicasting implies in the most general sense that of sending a common message from a BS to a group of users. As an exemplified in Fig. 7, it is highly favorable for WPT, and hence in recent years UAV-aided multicasting SWIPT systems have gained a lot of research interest [230], [231], [232], [233], [234], [235], [236], [237], [238], [239], [240], [241], [242], [243], [244], [245], [246], [247]. An overview of these works is provided in Table 5.

In [230], trajectory design and resource allocation issues by maximizing minimum average achievable rate have been studied for a UAV-assisted multicasting SWIPT system, where a single UAV as an aerial BS simultaneously sends common information and wireless power to multiple

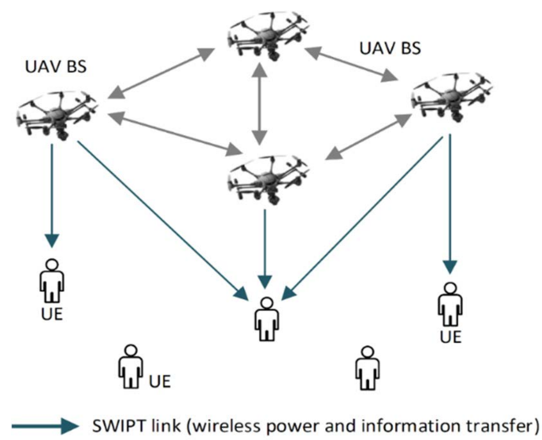

FIGURE 7. UAV-enabled multicasting SWIPT communication system with multi-UAV BS and multiuser.

ground users (with PS receiver architecture). A similar work in [239] has been conducted with dynamic PS policy. As similar researches, the article [231] performed except grouping ground users as a single information receiver and multiple energy receivers, while [240] as only information receivers and both information and power receivers. The papers [232], [241] investigated (joint) information (and) or energy coverage performances by considering a UAV-enabled SWIPT system that include multiple UAVs as aerial BSs and multiple ground users adopting either PS or TS schemes. The authors revised these works by deploying a single directional antenna on each UAV in [242]. Here, these studies consider both linear and non-linear EH models.

Security is the main challenge in all UAV-assisted systems as mentioned earlier. This surely further increases when the multicasting is considered. In [233], a UAV-enabled secure SWIPT NOMA network has been studied in which a single UAV as an aerial BS equipped with a multi-antenna sends both wireless energy and information to multiple passive ground users equipped with a single antenna. These passive users adopt PS receiver architecture. This work proposed a joint precoding optimization scheme by applying a non-linear EH model that guarantees the security via artificial jamming, as well as verified the effectiveness of the corresponding scheme via simulations.

There are several UAV-enabled multicasting SWIPT studies that customize ground users as IoT devices [234], [235], [236], [237], [238], [243], [244], [245]. (We here remind that even if IoT is not specifically emphasized in these studies, they can be adapted to IoT in terms of their network structure.) The authors of [234] handled the trajectory design and resource allocation problems for a UAV-aided SWIPT with PS in IoT network. This work is extended to multiple UAVs in [235]. The article [236] examined a single UAV-enabled multiuser SWIPT IoT network, in which the UAV delivers power and information that covers both common and private streams. In [237], SWIPT in UAV-assisted cellular IoT network has been studied. Except these works, the available literature has presented a few SWIPT studies in IoT networks with a focus on device-to-device (D2D) communication perspectives [243], [244], [245]. In [243] and [244], energy efficiency optimization issue has been tackled for a UAV-enabled SWIPT system in an industrial IoT network, where an aerial UAV BS with antenna array, and multiple D2D transmitter and receiver pairs with a single antenna. Here, the UAV transmits information and power to D2D-transmitters utilizing NOMA, and the transmitters send information to D2D-receiver by using harvested energy via PS SWIPT. The authors of [245] envisaged a UAV-aided hybrid communication scenario that consists of a cellular user, and an IoT network including a low-power IoT-hub and a sensor node. Here, the UAV BS exploits NOMA for serving the cellular user and IoT-hub, while the hub exploits SWIPT for serving to the sensor node.

We here note that in the aforementioned works the UAV(s) are considered as aerial BS(s) and only the ground users exploit SWIPT technology, as well as all devices except the UAV in [233], [243], and [244] are equipped with a single antenna.

Unlike the aforementioned studies, by considering UAVs as users, the authors of [246], [247] introduced federated learning based joint scheduling and resource allocation solution for SWIPT-enabled micro UAV swarm networks.

C. UAV-ENABLED mmWAVE SWIPT NETWORKS

Millimeter-wave bands give key enablers for the revolutionary facilities with the wide swaths of unused and unexplored spectrum. Towards this, the available literature has presented a few mmWave UAV-enabled SWIPT studies that can be basically grouped as single-user communication [248], [249], [250], [253] and multiuser communication [199], [251], [252]. These studies are summed up in Table 6. A similar work [253] has been studied an FD-enabled AF-based UAV-aided cooperative SWIPT communication system over fluctuating two-ray fading model that well characterizes the wireless channels in a wide range of frequencies, i.e., millimeter waves. The authors, in [250], investigated a downlink secure mmWave UAV-aided SWIPT system, where the UAV as an aerial BS exploits the directional modulation scheme based on a random frequency diverse array.

The article [199] considers a mmWave SWIPT network with an aerial UAV BS serving two authorized users with different communication requirements (i.e., one of the high rate private information, the other of energy-constrained with low-rate) in the presence of multiple ground eavesdroppers. Herein, the security, reliability, and energy coverage performance have been analyzed for NOMA and OMA schemes. We notice that all devices in these works, only apart from the UAV of [199], [250] are equipped with a single antenna. The authors of [251] studied a downlink mmWave NOMA SWIPT network that a UAV aerial BS delivers simultaneously wireless information and energy to multiple single-antenna ID devices and EH devices. These devices are clustered via two different unsupervised learning approaches. In [252], a joint downlink SWIPT and uplink information transmission in a UAV-aided mmWave cellular network has been studied. The users' locations in this work are modeled by Poisson cluster process, and the results show that as the cluster size becomes smaller, the network performance is enhanced.

Albeit a number of UAV-enabled SWIPT studies as mentioned above has been reported in the current literature, there are still lots of issues to be researched and addressed. These can be exemplified as the multi-antenna systems, the consideration of distinct (or even hybrid) power sources, and the utilization of more realistic channel characteristics.

VI. EXPERIMENTAL STUDIES ON SWIPT

Experimental activities on EH have started with the extensive experiments of Nikola Tesla on 1890's [256]. Ever since then, the remote energy transfer topic has been investigated and currently there is an extensive literature on EH and associated test-bed based studies. The survey paper [257] provides a detailed description of the components of EH circuits. The energy efficiency of harvesting modules has been also listed recently in [258]. Although closely coupled, this survey aims to highlight the experimental activities of EH with information transfer. As one of the most comprehensive studies on SWIPT systems, Section 5 of [259] briefly explains on the associated testing activities. Below we provide a more detailed list of the research works. There are three different implementation approaches for SWIPT systems; TS, PS [53], and the recently proposed frequency splitting (FS) [260]. Extensive experimental analyses for TS and PS architectures are given in [261] along with the signal designs. Experimentation activities have started with a TS approach. [262] is a leading study that demonstrated the operation of a battery-free wireless sensor network in the microwave band. An output DC power of 50 mW is observed with an efficiency of 49.7%, highlighting the potential of SWIPT systems. The transmission of power is considered from one node to another, and communication is enabled in the reverse direction. The communication performance of the SWIPT system is investigated through experimentation in [257]. The received signal strength, packet loss rate, and the harvested power have been quantified.

As a different perspective a digital receiver is proposed for SWIPT in [263], where the nodes transmit data by counting the number of activations of the energy harvesters' control signals. A data rate of 400 bps has been transmitted. The use of inductive coupling has also been considered for short range SWIPT systems in [264] for FSK modulated signals. The unwanted harmonics are being exploited in [265], where a diplexer-based six port receiver is designed and tested by the use of the proposed multiport power recycling method.

[14] proposes a fresh new approach to transmit wireless power using an unmodulated high-power continuous wave and information using a small modulated signal. On the receiver side, the signal is rectified and then split between power and information signals. The FS approach presented in [260] makes use of circulator and filters for the receiver

TABLE 4. Overview of UAV-enabled cooperative SWIPT systems.

Ref.	Network structure	Relay properties	EH mechanisms	Channel model	Research interests
[217], [218]	• S – UR – D • Single antenna	• AF & DF protocol • Time-division HD	• PS SWIPT • On UAV	• LoS (Free-space path loss)	• Throughput maximization
[219], [220]	• S – UR – D • Single antenna	• AF protocol • Time-division HD	• TS SWIPT • On UAV	• LoS	• Throughput maximization
[221], [222]	• S – UR – D • S and D with single antenna • UAV with two antennas	• DF protocol • FD	• TS SWIPT • WPT • SI EH • On UAV	• Log-distance path loss • Rayleigh fading	• Outage probability • Achievable average throughput
[223]	• S – UR – D • S and D with single antenna • UAV with two antennas	• Soft information relaying or SAM for low SNR (converges DF for high SNR) • FD	• PS SWIPT • SI EH • On UAV	• Log-distance path loss • Nakagami fading	• Outage probability
[226]	• S-UR-D	• Time-division duplexing	• Dynamic TS SWIPT • On UAV	• Log-distance path loss • Rician fading	• Backscatter communication • Caching technology • Throughput maximization
[227]	• BS – UR – multiuser • BS and UR with multiple antennas • Users with single antenna	• AF protocol • HD	• PS SWIPT • On users	• Probabilistic free-space path loss • Rician fading	• Multiuser cooperative communication
[228]	• BS – two URs and one ground R – IoT device • BS with multiple antennas • IoT device with single antenna • Relays with IRS	• IRS	• PS SWIPT • On IoT device	• Log-distance path loss • Rician fading	• Multi-relaying cooperative communication • Achievable rate
[224]	• S – UR – D and a ground eavesdropper • Single antenna	• AF protocol • HD	• PS SWIPT • On UAV	• Probabilistic log-distance path loss • Rician fading with elevation angle dependent rice parameter	• Secure and reliable communication • Outage probability • Secrecy rate
[225]	• S – UR – D and multiple ground eavesdroppers • S, UR and eavesdroppers with single antenna • FD D with a dual antenna	• AF protocol • Time-division duplexing	• PS & TS SWIPT • On UAV	• LoS	• Secure and reliable communication • Artificial noise • Secrecy rate
[229]	• S – UR – two Ds and a ground jammer • Single antenna	• AF protocol • HD	• PS SWIPT • On UAV	• Nakagami fading	• Secure cooperative communication • NOMA • Outage probability
S (Source), UR (UAV Relay), D (Destination) SI (self-interference) SAM (soft angular modulation)					

design. Power and data symbols are split in the frequency domain, and a higher performance is absorbed in terms of the harvester power and SNR.

The majority of SWIPT test-beds rely on physical layer prototyping. As the only counterexample, [266] considers a full protocol stack over Zigbee that is used with directional

TABLE 5. Overview of UAV-enabled multicasting SWIPT systems.

Ref.	Network structure	Key points	EH mechanisms	Channel model	Research interests
[230]	• Single UAV as BS • Multiple users	• Not specified	• PS SWIPT • On users	• LoS (Free-space path loss)	• Resource allocation • Trajectory design
[239]	• Single UAV as BS • Multiple sensor nodes	• FDMA	• Dynamic PS SWIPT • On sensor nodes	• Log-distance path loss	• Trajectory design • Power allocation
[231]	• Single UAV as BS • Multiple users	• Group users as single information receiver and multiple energy receivers • Energy receivers may eavesdrop UAV-information receiver communication	• Not specified	• LoS	• Resource allocation • Trajectory design • Secure communication
[240]	• Single UAV as BS • Multiple users	• Group users as multiple information receivers and multiple both information and power receivers	• TS SWIPT • On information and power users	• Log-distance path loss	• User grouping • Trajectory design
[232], [241]	• Multiple UAVs as BSs • Multiple users	• Serve each user by its nearest UAV • Consider linear and non-linear EH model	• TS or PS SWIPT • On users	• Log-distance path loss • Rayleigh fading	• Coverage analysis
[242]	• Multiple UAVs as BSs • Multiple users	• Equip each UAV with a directional antenna	• TS or PS SWIPT • On users	• Log-distance path loss • Rayleigh fading	• Coverage analysis
[233]	• Single UAV as BS with multi-anntena • Multiple passive receivers with single antenna • Single eavesdropper	• NOMA	• PS SWIPT • On receivers	• Probabilistic free-space path loss • Rician fading	• Secure communication • Throughput maximization
[234]	• Single UAV as BS • Multiple IoT nodes	• IoT network	• PS SWIPT • On IoT nodes	• Log-distance path loss	• Trajectory design • Power allocation
[235]	• Multiple UAVs as BSs • Multiple IoT nodes	• IoT network	• PS SWIPT • On IoT nodes	• Probabilistic log-distance path loss	• User association • Power allocation
[236]	• Single UAV as BS • Multiple IoT nodes	• IoT network • Classify data streams as common & private	• PS SWIPT • On IoT nodes	• LoS	• Rate analysis
[237]	• Multiple UAVs as aerial BSs • A ground cellular BS • Multiple IoT nodes	• Hybrid communication system with cellular and IoT networks • Consider three dimensional antenna pattern for ground BS	• PS SWIPT • On IoT nodes	• Probabilistic log-distance path loss • Nakagami fading	• User association • Coverage analysis
[243], [244]	• Single UAV as BS with antenna array • Multiple D2D pairs (a transmitter & a receiver) with a single antenna	• Industrial IoT network • D2D communication • NOMA	• PS SWIPT • On D2D-transmitter	• LoS	• Resource allocation
[245]	• Single UAV as BS • Two ground users (a cellular user and an IoT network with an IoT-hub & a sensor node)	• Hybrid communication system with cellular and IoT networks • D2D communication • NOMA	• PS SWIPT • On IoT-hub	• Log-distance path loss • Nakagami fading	• Capacity analysis
[246], [247]	• A ground BS • Multiple UAVs as users	• Micro UAV swarm network • OFDMA	• Not specified	• Not specified	• Federated learning • Joint scheduling and resource allocation

antennas. This is a promising study considering the future products with SWIPT features.

A. WAVEFORM DESIGN FOR SWIPT SYSTEMS

Impact of the high peak-to-average power ratio on the EH efficiency has been first investigated in [267], where the authors consider OFDM, white noise and chaotic waveforms. A high peak-to-average power ratio is shown to provide a higher RF-DC efficiency. The authors of [268] considered the use of QAM and PSK modulated multisine signals in the SWIPT system while also regarding the power and data transfer efficiency and the transmitter distortion. It has been shown that PSK modulated multisine signals are more resistant to distortion than QAM modulated signals. [269] introduces the FSK based modulation schemes to improve the wireless power transfer efficiency. The transmission of 18 Mbps data rate has been experimentally verified. [270] considers the design of an integrated rectifier receiver with the goal of reducing the associated power consumption. Magnitude ratio modulation, ratio phase modulation, and ratio amplitude phase modulation techniques are proposed and tested. Given the impact of the used modulation on the performance, the authors of [271] implemented a system that selected the communication mode adaptively among single-tone and multi-tone signals according to the duty ratio of EH and ID.

A class F rectifier-based scheme that supports low input power levels and wide bandwidth is designed for 2.4 GHz band in [272], where the authors have reached 54.3% maximal RF-DC conversion efficiency. Software defined radio based measurements are presented in [273], by considering the use of rectangular pulses and cyclic prefix OFDM. A biased amplitude modulated OFDM waveform is proposed and tested for low power SWIPT receivers in [274]. An extension to wearable antennas is given in [275], where the authors present a textile antenna for dual-band SWIPT with a 2.4 GHz off-body communications antenna and a sub-1 GHz (785–875 MHz) broad-beam rectenna. This work highlights the potential of SWIPT systems to a wide variety of sensor networks.

B. MULTI-ANTENNA TEST SYSTEMS

A multi-antenna system has been designed and implemented in [276]. Power transmission and data communication has been carried out independently similar today time suturing scenario. The impact of the sleep cycles of the sensor modes have also been investigated. Through measurements, it has been observed that a distance of 2.5 m can be supported. [277] makes use of a multi-antenna test-bed and measures the performance of the joint beam-splitting and energy neutral control method proposed by the authors. The coupling between the duty cycle and the performance of the SWIPT system has also been highlighted. [278] describes the prototype of a wireless powered sensor network with an antenna array of 64 elements that functions up to 50 m, highlighting the practical relevance of the investigated systems.

Overall, although there are limited studies considering prototyping of SWIPT systems, the promise of battery free sensor networks is appealing both to researchers and industry. What does high potential it is expected that in the future the practical aspects will be more thoroughly examined and the advanced antenna techniques, such as massive MIMO, will be investigated further in the system deployments.

VII. CHALLENGES, OPPORTUNITIES, AND FUTURE RESEARCH DIRECTIONS

Since 5G+ communication systems and standards are promising to serve the vastly increased number of connected terminals, complicated computational burden related to the optimization with respect to power allocation, subcarrier allocation, and communications security metrics would be encountered, especially in the case of multiuser SWIPT structures being incorporated into real-time downlink and uplink operations. Hence, in order to exploit their benefits, artificial intelligence-oriented state-of-the-art approaches might be better adapted to the multiuser SWIPT communications scenarios that target communications secrecy.

In multi-tier multiuser wireless networks, it would be possible to improve privacy and reliability performances by managing the beamforming and beam tracking tools at the transmitter much more effectively in cellular scenarios, thanks to the multi-dimensional analysis and determination of spectrum sources from the CR perspective and the angle-of-arrival estimations for the eavesdropping users. Hence, the cooperation of simultaneous threat estimation and beamforming mechanisms would be of great importance in future applications.

Preliminary studies on the usage of IRSs in both indoor and outdoor communications scenarios have shown the potential of these passive but useful surfaces through providing additional increments on the received signal quality by continuously manipulating their scattering characteristics. Hence, employing IRSs within the multiuser SWIPT schemes would also promise considerable QoS enhancements despite the programming and optimization complexity required for the equipped tunable elements (i.e., photodiodes). Further research on the optimization of the states of the tunable elements, and the locations of IRSs through both traditional signal processing-based or artificial intelligence-based approaches would be of great importance to pave the way of IRS deployments in next generation mobile communication systems.

Future UAV-enabled SWIPT studies can include channel modeling and estimation, which is one of the leading issues as wireless air-to-ground channel characteristics suffer from many external parameters such as the position and altitude of users and UAVs, etc. Another notable issue on UAV-enabled SWIPT networks is multi-antenna systems that enhance superior data rate and reliability. As a similar research area from the perspective of improving data rate, IRSs reveal great potential for such networks since they can reflect or refract the signals in the desired manner. As energy consumption

TABLE 6. Overview of UAV-enabled mmWave SWIPT systems.

Ref.	Key points	Network structure	Relay properties	EH mechanisms	Channel model	Research interests
[248], [249]	• Single-user • Cooperative secure communication	• S – UR – D and multiple eavesdroppers • Directional beamforming antenna array	• AF & DF protocols • Time-division duplexing	• PS SWIPT • On D	• Log-distance path loss • Nakagami fading	• Secure and reliable communication • Coverage analysis • Secrecy rate
[250]	• Single-user • Secure communication	• Single UAV as BS with multiple antennas • Single user and multiple eavesdroppers with single antenna	• No relay	• PS SWIPT • On D	• LoS	• Secure and reliable communication • Secrecy rate
[253]	• Single-user • Cooperative communication • TDMA	• S – UR – D • Single antenna	• AF protocol • FD	• PS SWIPT • WPT • SI EH • On UAV	• Fluctuating two-ray fading	• Outage probability
[199]	• Multiuser • Secure communication • IoT network • NOMA • OMA	• Single UAV as BS with multiple antennas • Two users (energy-constrained low-rate user and high rate security user) • Multiple eavesdroppers	• No relay	• PS SWIPT • On energy-constrained low-rate user	• Probabilistic log-distance path loss	• Secure and reliable communication • Outage probability
[251]	• Multiuser • NOMA	• Single UAV as BS with multiple antennas • Multiple ID and EH users with single antenna	• No relay	• Not specified	• Multipath	• User clustering • Unsupervised learning
[252]	• Multiuser • Hybrid communication system with cellular and IoT networks	• Multiple UAVs as aerial BSs • Ground cellular BSs • Multiple IoT devices	• No relay	• PS SWIPT • On IoT devices	• Probabilistic log-distance path loss • Nakagami fading	• Coverage analysis • User association

has a vital factor for the overall performance of UAV-aided networks, one of the open challenges is EH based on distinct (or even hybrid) power sources.

Due to the pragmatic nature of the research process, the literature most likely exhibits the advantages and drawbacks of proposed schemes, techniques and algorithms under several stringent assumptions. Hence, for a while, the research studies lack to mention the practical achievements of the proposed schemes and systems under realistic operating conditions. Nevertheless, from the emerging communications standards and systems perspective, the feasibility of the investigated schemes under miscellaneous hardware and computation imperfections is of critical importance. Hence, the literature related to multi-user SWIPT schemes need rigorous and extensive examinations addressing the variations of QoS metrics under practical system impairments (e.g., IQ imbalance, phase noise, amplifier non-linearity, channel estimation errors, outdated feedback, pilot contamination) specified to the next generation communications use cases.

Another conventional but critical issue that deserves to be treated refinedly is the channel coding process for especially the wirelessly-powered low-budget transceiver terminals. Any additional signal processing burden at these systems would result in additional energy consumption that threatens the knife-edge equilibrium between EH and consumption. Hence, novel channel coding techniques proposed by further researches should be strictly tailored due to the solid energy restrictions of wirelessly-powered terminals (e.g., constrained run-length limited codes, unary coding). Thanks to the low-complexity novel channel coding approaches, the communications reliability of the emerging critical applications such as e-Health IoT would be able to be enhanced.

Future wireless communications systems are strongly envisioned to include energy-eager technologies such as orthogonal time frequency space modulation, IRS, NOMA, massive MIMO, and satellite or high altitude platform based communications. To this end, the integration of SWIPT within the upcoming standards renders an essential challenge and opens up new research directions.

VIII. CONCLUSION

In this survey paper, as an effective way of energy efficient green communications, expected to be an inevitable part of 5G+, SWIPT communication systems are reviewed in detail for multiuser case. Using multiuser diversity and multiple access techniques, diverse multiuser SWIPT communication scenarios comprising multi-antenna communications, cooperative communications, network coding, communications security, and UAV-based communications are comprehensively reviewed, indicating the state-of-the art studies and related open issues.

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