Survey on Symbiotic Radio: A Paradigm Shift in Spectrum Sharing and Coexistence

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Abstract—Sixth-generation (6G) of mobile communication aims to connect this world digitally through green communication networks that provide secure, ubiquitous, and unlimited connectivity in an attempt to improve the overall quality of life. The driving force behind the development of these networks is the rapid evolution of Internet-of-Things (IoT), which has stimulated the proliferation of wireless applications in health, education, agriculture, utilities, etc. However, these applications are accompanied by the deployment of a massive number of IoT devices that require a significant radio spectrum for wireless connectivity. IoT devices usually have low data rate requirements and limited power provision but desirably a long life. Recently, the development of passive radio systems has opened new paradigms of spectrum sharing and coexistence. These systems utilize the radio resources and infrastructure of the active radio systems to perform their functionalities. By enabling the dependent coexistence, a new technology named symbiotic radio (SRad) enables the symbiotic relationships between the different radio systems ranging from mutual benefits or competition in terms of sharing the resources, in particular for IoT devices. This survey first provides the motivation for dependent coexistence and background of spectrum sharing and coexistence are defined while focusing on symbiotic communication. Lastly, we discuss research challenges, future directions, and applications scenarios.

Index Terms—6G, ambient backscatter communication, active radio system, coexistence, IoT, passive radio systems, spectrum sharing, symbiotic communication, symbiotic radio detection and ranging (Radar), symbiotic Radio.

I. INTRODUCTION

Sixth-generation has gained attention in the research and engineering community to connect this world digitally and develop future societies, where everything is working smartly such as living, healthcare, education, etc., [1]. The driving force behind this aim is IoT, which first connected the machines, then humans, and now everything to the Internet of-Everything (IoE). If the wireless devices continue to grow at this rapid pace, the number will reach approximately 12.3 billion by 2023 as predicted by Cisco [2].

Previous generations of wireless communication have offered several services such as voice, text message, multimedia, enhanced mobile broadband (eMBB), ultra-reliable low latency communication (uRLLC), massive machine type communications (mMTC), during the development period from first-generation (1G) to fifth-generation (5G) to facilitate the user with new experiences [3]. However, in 6G it is planned to go beyond the communication services and incorporate the Radar functionalities to the communication systems to achieve accurate wireless sensing and localization [4]. These services will support the development of diverse future applications such as autonomous vehicles, holographic teleportation, extended reality, industrial automation, etc. Even though a lot of research efforts are going on for the realization of these technologies, yet a major bottleneck is the limited radio spectrum, which is insufficient to support the surge of IoT devices and sensors coming along [5]. A many-fold increase in the radio frequency (RF) spectrum is needed to provide connectivity to such a massive number of devices.

Radio spectrum scarcity or the lack of spectrum issue has been coming along since the time of Guglielmo Marconi when his transatlantic transmission occupied the entire radio spectrum. As the competitors tried to use the same radio frequencies, their transmission encountered severe interference [6]. In earlier times, the radio spectrum was utilized in broadcasting, wireless telegraphy, and Radar. The evolution of technologies and standardization under strong regulations have made it possible to use it for different applications related to military, emergency services, and cellular systems, etc. However, continuously growing applications of wireless systems with changing users’ interest from frequency modulation (FM) radio, television (TV) to social media after the convergence of Internet and wireless communication technologies have changed the course of spectrum utilization. This sudden change has intensified the spectrum scarcity problem and made the electromagnetic spectrum a precious natural resource like other natural resources such as water, minerals, etc., [7]. Therefore, rules and regulations have been implemented on spectrum utilization to maximize the benefits and reduce the adverse effects, e.g., radio spectrum pollution [8].

At the beginning of radio technology development, exclusive licensing was used to allocate the spectrum considering the signal interference issues. The proliferation of wireless devices and accelerating uses makes it clear that the exclusive licensing strategy is an inefficient way of spectrum utilization [9]. To ensure the efficient utilization of spectrum and avoiding the interference between radio systems; two spectrum accessing policies are defined that are static spectrum access (SSA)
and dynamic spectrum access (DSA). In SSA, the access is either licensed, rule-based or unlicensed. For licensed-based access, users buy the exclusive property rights of the radio spectrum from the regulatory authorities for specific applications or services. In the rule-based access, certain conditions must be satisfied for accessing the radio spectrum, such as fee payment, transmit power levels, and unoccupied channels. Lastly, the license-exempt or unlicensed access is initiated by the United States Federal Communication Commission (FCC) in the Industrial Scientific and Medical (ISM) bands, which allows every technology to access the spectrum with equal rights under some basic regulations [10]. On the other hand, DSA comes under the concept of cognitive radio (CR), which is defined because not all the radio spectrum is occupied all the time, and white-spaces/spectrum holes can be utilized by the secondary users (SUs) [11]. These regulations and allocations vary between countries according to their legislative bodies, geo-locations, operating conditions, and technological developments; however, the common objective is to achieve the optimum utilization and to overcome the shortfall of spectrum resources [12].

Different approaches have been considered to accommodate upcoming surge of IoT devices and high spectrum demands, including allocation of new bands (i.e., millimeter wave (mmWave) and terahertz (THz)) [45], re-allocation of legacy licensed spectrum bands [46], CR [21], and coexistence of wireless technologies [10]. The first two approaches require either innovations and technological enhancements, or transfer of property rights and clearing the existing users, which are exorbitant and time-consuming, respectively [46]. However, CR is a more convenient approach than earlier ones in terms of cost and complexity as well as in enhancing the spectrum efficiency of under-utilized bands, where the number of users using the spectrum is less than the available resources. In this case, CR users share the under-utilized part of the spectrum as SUs and enhance the spectrum utilization. However, CR systems can create unavoidable interference to the primary systems if not operated under defined regulations. Due to the interference concerns of CRs in spectrum sharing, their adoption in real-time applications is limited so far [47]. The coexistence of technologies overcomes the spectrum scarcity issue, where different wireless systems can collaborate to share and access the resources. When two or more systems can share the same band independently while not affecting the performance of the other co-existing system. Several coexistence approaches have been proposed in the literature such as wireless fidelity (WiFi) and TV in TV white space (TVWS) [11], integrated non-terrestrial and satellite systems [37], WiFi and long-term- evolution (LTE) in unlicensed 5-GHz band [42], narrow band IoT and LTE [43], and communication and radar systems [17]. However, both the CR and aforementioned wireless co-existing systems are active radio system (ARS), which require an RF source for signal generation at the transmitter. Although these systems improve the spectral efficiency; however, the active radio systems are not suitable for low power IoT devices. Active signal generation and transmission require a significant amount of power that reduces the battery life of IoT devices.

A. Motivation and Background

Unlike the ARS, there is another class of radio systems i.e., passive radio systems (PRSs), which do not require a dedicated RF source and utilize the radio waves generated by the ARS (e.g., FM/TV, WiFi, cellular systems) termed as illuminators of opportunity (also known as ambient signals). The passive communication through ambient signals is commonly known as ambient backscatter communication (ABCm) in the literature [49], [50]. Unlike the ARS spectrum sharing mechanisms, PRS can share both the unlicensed and licensed spectrum without creating significant interference [51]. Furthermore, PRS not only shares spectrum but also infrastructure of ARS i.e., RF source. Although PRS are spectrum and energy-efficient compared to ARS, their complexity is high and performance is low [52], [53]. One of the main reasons for performance limitations is that PRS can not control or modify the ambient signals according to their requirements. However, the limitations of both ARS and PRS can be overcome through interaction, and inter-specific associations within these systems for radio resource sharing [41], [47].

In a biological ecosystem, dissimilar organisms share an environment and interact in different ways. Anton de Bary noticed this behavior and called it ‘symbiosis’ means ‘living together’ [54]. He defines symbioses as “associations between two different species of organisms for food, shelter, or protection.” The different ways of interspecific association for resource sharing between organisms are defined by the symbiotic relationships, and each organism is called a symbiont. Furthermore, symbiosis can be obligatory or facultative based on the dependence of the organisms. If two symbionts are so close to each other that one or both cannot live without each other then the symbiosis is obligatory. Otherwise, if both can survive independently but can also be in symbiosis by choice then this type of symbiosis is facultative [47].

A similar analogy can be applied to radio ecosystem for resource sharing between two dissimilar systems, i.e., ARS and PRS, where symbiosis represents the coexistence, symbiotic relationships define the ways of radio resource sharing between systems and the relevant radio system is called symbiotic radio (SRad) [47]. Moreover, coexistence between radio systems can be dependent (obligatory) or independent (facultative) according to the dependence of systems. If one radio system cannot survive without the other, then this type of coexistence may be termed as dependent coexistence, e.g., the coexistence of ARS and PRS. On the other hand, independent coexistence, the radio systems can perform their functions independently but choose to coexist, e.g., WiFi and licensed assisted access long term evolution (LAA-LTE) [55]. Besides, SRad systems can achieve collective objectives as well as individual objectives through mutualistic or competition-based symbiotic relationships. Thus, SRad can enhance the performance of both ARS and PRS through dependent and independent coexistence with efficient radio resource sharing [51], [53], [56].
### TABLE I
**LIST OF ABBREVIATIONS**

| Abbreviation | Description |
|--------------|-------------|
| 1G | First-Generation LTE |
| 5G | Fifth Generation LTE |
| 6G | Sixth Generation |
| ABCm | Ambient Backscatter Communication |
| ABCmS | Ambient Backscatter Communication System |
| ACS | Active Communication System |
| APSC | Active-Passive Systems Coexistence |
| AR | Active Receiver |
| ARDS | Active Radar System |
| ARS | Active Radio System |
| AT | Active Transmitter |
| BCC | British Broadcasting Corporation |
| BBCmS | Bistatic Backscatter Communication System |
| BD | Backscatter Device |
| CDRL | Centralized Deep Reinforcement Learning |
| CR | Cognitive Radio |
| CSI | Channel State Information |
| DDRL | Distributed Deep Reinforcement Learning |
| DSA | Dynamic Spectrum Access |
| eMBB | Enhanced Mobile Broadband |
| FCC | Federal Communication Commission |
| FD | Full-Duplex |
| GPS | Global Positioning System |
| IoE | Internet-Of-Everything |
| IoT | Internet-Of-Things |
| ISM | Industrial Scientific and Medical |
| LAA-LTE | Licensed Assisted Access Long Term Evolution |
| LIS | Large-Intelligent Surface |
| MBCmS | Monostatic Backscatter Communication System |
| MIMO | Multiple-Input Multiple-Output |
| mMTC | Massive Machine Type Communications |
| mmWave | Millimeter Wave |
| NOMA | Non-Orthogonal Multiple Access |
| OOK | On-off Keying |
| PCS | Passive Communication System |
| PRDS | Passive Radar System |
| PRS | Passive Radio System |
| PU | Primary |
| RDR | Radar Detection and Ranging |
| RF | Radio Frequency |
| RFID | Radio Frequency Identification |
| RIS | Reconfigurable Intelligent Surfaces |
| SCm | Symbiotic Communication |
| SINR | Signal-to-Interference-Plus-Noise-Ratio |
| SRad | Symbiotic Radio |
| SSA | Static Spectrum Access |
| SU | Secondary User |
| THz | Terahertz |
| TV | Television |
| TVWS | TV White Space |
| uRLLC | Ultra-Reliable Low Latency Communication |
| WiFi | Wireless Fidelity |
| Wireless Fidelity |

### TABLE II
**COMPARISON WITH SURVEYS IN LITERATURE**

| Reference | Active Systems | Passive Systems | Spectrum Regulations | Coexistence |
|-----------|---------------|----------------|----------------------|-------------|
| This survey | ✓ ✓ | ✓ ✓ | ✓ ✓ | ✓ ✓ |
| [13], [14] | ✓ ✓ | ✓ ✓ | ✓ ✓ | ✓ ✓ |
| [9], [10], [15]–[18] | ✓ ✓ | ✓ ✓ | ✓ ✓ | ✓ ✓ |
| [19], [20] | ✓ ✓ | ✓ ✓ | ✓ ✓ | ✓ ✓ |
| [21]–[35] | ✓ ✓ | ✓ ✓ | ✓ ✓ | ✓ ✓ |
| [36]–[38] | ✓ ✓ | ✓ ✓ | ✓ ✓ | ✓ ✓ |
| [39]–[44] | ✓ ✓ | ✓ ✓ | ✓ ✓ | ✓ ✓ |

### B. Related Prior Literature

Some several tutorials and surveys exist in the literature on spectrum sharing and coexistence. A classification of previous surveys based on system types i.e., active or passive, spectrum band regulations i.e., licensed or unlicensed, and co-existing systems is provided in Table I. For the explanatory purpose, active and passive systems are sub-categorized into communication and radar systems. While considering the coexistence scenarios, only active-passive systems coexistence (APSC) is considered, where one system is active and the other is passive, irrespective of whether it is for communication or radar. In [13], [14], authors review the coexistence of active communication and passive radar systems in licensed and unlicensed bands. Overview of active communication and radar systems in both licensed and unlicensed bands is in [9], [10], [15]–[18], and only in the unlicensed band is discussed in [19], [20]. Considering the active communication systems coexistence in both licensed and unlicensed, only licensed and only unlicensed bands is discussed in [21]–[35]; [36]–[38]; and [39]–[44], respectively. Although surveys considering all the scenarios are presented in Table I for completeness, the studies relevant to this work are given in [13], [14]. The authors in [13] provide a survey on joint communication and radar systems from wireless communication and radar sensing perspectives. Further, they discuss three techniques namely coexistence, codesign, and cooperation for the development of a joint radar communication system considering both active as well as passive radars. The overview of waveform design and signal processing techniques for joint radar and communication is given in [14]. The differences between active and passive radar systems and their coexistence mechanism are also discussed along with their applications and use case scenarios.

### C. Contributions

The contributions of this survey to the literature are listed below:

- To the best of the authors’ knowledge, this is the first survey on SRad systems that study the spectrum sharing
concept in wireless radio systems, leveraging the symbiosis concept. In line with this, the history of symbiosis is described along with applications in wireless systems.

- The dependence of PRSs on ARSs is highlighted and the different types of symbiotic relationships are explored ranging from mutual benefit for both to competition for the sharing of the radio resources, in particular the RF spectrum.
- We investigate the symbiotic communication (SCm) and SRad paradigms for IoT devices and networks through symbiosis between PRS and ARS.
- Lastly, we explore the applications of SRad systems for 6G from human and machine-centric perspectives and highlight open research problems to direct future research in this area.

D. Survey Structure

The organization of the survey is outlined in Fig. 1. Section II provides an overview of the active and passive radio systems. Details on symbiosis are provided in section III, and different symbiotic radios for spectrum sharing with detailed discussions on symbiotic communication and symbiotic radar are given in section IV. Section V presents the potential applications of SRad systems. The critical challenges and future directions for further research and development of SRad are provided in section VI. Lastly, the conclusion is provided in section VII. A complete list of abbreviations is given in Table II.

II. AN OVERVIEW OF RADIO SYSTEMS

This section gives a general overview of active and passive radio systems. Starting from the definition and brief overview of ARS, then discuss the PRS and its different types. Additionally, communication and radar systems are discussed as use case scenarios for both systems, which are shown in Fig. 2.

A. Active Radio Systems

A radio system that generates RF signals at the transmitter for information transfer and extracts the information from the transmitted signal at the receiver. A general system for radio signal transmission consists of two parts: transmitter A and receiver B. A sends the information by transmitting a radio signal in the air, where B receives the signal and extracts the information. The radio signal can be an information modulated signal or a continuous wave signal depending on the application. For instance, an ACS modulates the carrier i.e., RF signal, to send the information to the receiver as shown in Fig. 2(a). On the other hand, ARDS shown in Fig. 2(b), which contains an ARDS transceiver that radiates the radio wave in the air to detect the presence of the target and its related information. ARDS can be considered as a special case of ACS, where the target sends its information unknowingly by reflecting the radio wave radiated by the ARDS transceiver. Furthermore, active signal generation and transmission are necessary for ARS either it is a communication system or a Radar system.

B. Passive Radio Systems

A radio system that reflects/backscatters RF signals at transmitter for information transfer and extracts the information from the reflected/backscattered signals at the receiver. The use

Fig. 1. The organization of survey.

The architecture of the Radar system is different from the communication systems because an ARDS is a monostatic system, in which the transmitter and the receiver are collocated and a single antenna is used for transmission of RF signals and reception of reflected signals. The common examples of ARS in communication are FM, TV, cellular, WiFi, unmanned aerial vehicle (UAV) etc., and in Radar systems are mapping, earth monitoring, navigational, etc.
of PRS based on backscattering principle can be dated back to the development of passive radar technology used in World War II. When passive radio reflector was mounted on the allied aircraft to backscatter the signal transmitted by the home radar with better illumination than enemy aircraft [57]. Afterward, the idea of reflected power communication was proposed by Harry Stockman in 1948, who contributed to the development of radio frequency identification (RFID) technologies [58]. However, a completely passive RFID system that is operated and controlled by the illuminated signals, was demonstrated by Alfred Koelle in 1975 [59]. Since then, the RFID technology has been deployed in various fields such as medical, business, logistics, and so on [60].

PRS can be a PRDS used in military applications or a PCS to provide the connectivity to a simple IoT device or sensor. A PRDS is shown in Fig. 2(c), where Radar receiver utilizes the radio waves radiated by ambient ARS for target detection instead of generating a dedicated signal [52]. On the other hand, in PCS, the ambient signals of ARS are remodulated and backscattered by a backscatter device (BD) i.e., tag to send the information to the receiver as shown in Fig. 2(d). Furthermore, PRSs can utilize the ambient signals of RF sources belong to ARS, from the Bluetooth device through to space-based satellites as well as everything and anything in between. However, in practice, only a few ambient sources are favorable for the PRS because they are not designed to support these systems [61].

1) Passive Radar Systems: The first PRS was a PRDS designed in 1935 by Robert Watson-Watt, which was able to detect the aircraft at a distance of 12 km using the radio signals of British Broadcasting Corporation (BBC) shortwave transmitter [62], [63]. After world war II, long-lasting research on PRDS started for its advantages that include covertness, ability to operate in the lower frequency bands, the capability of anti-stealth detection, spectral efficiency, and so on [61]. PRDS are bistatic radars, and they detect their target of interest exploiting ambient RF signals reflected by the target. Thus, additional spectrum resources are not needed for PRDSs, which makes them spectral efficient compared to ARDSs. However, the ambient radio signals are generated by ARSs and unknown to the passive radar receiver. The ambient signal has to be measured initially to cross-correlate with the target
reflected signal to detect and track the target. The bistatic range and Doppler shift are measured from the time difference of arrival and frequency difference between the direct signal (also called reference signal) coming from ARS and the signal reflected off the target. A PRDS can also have multiple ambient ARS sources or multiple receivers for reception, these types of radars are called multi-static radars. Although RF sources of several ambient ARS are available, whose signal can be used in PRDSs, a good RF source is the one that provides the continuous signal for a longer time duration [61].

2) Passive Communication Systems: Similar to PRDS, the signals of opportunity (also known as ambient signals) have been used to enable passive communication for low-power sensors and IoT devices. These systems are known as ambient backscatter communication systems (ABCmSs), where BD modulate its data over the ambient signals by switching its antenna [64]. Although PCS term has not been used particularly for ABCmS but we prefer to use it due to its generality and similarity to PRDS. The terms PCS and ABCmS are used interchangeably throughout the paper. The main idea of ABCmS comes from the backscatter communication systems, where a BD modulate and scatter the incident signal to transmit its data [57]. Backscatter communication systems are designed with three configurations of RF signal source and receiver: a) monostatic backscatter communication system (MBCmS); b) bistatic backscatter communication system (BBCmS); c) ABCmS [50].

A PRS system in which communication is done by reflecting the continuous wave signal transmitted by a dedicated RF source, which is located with the receiver in the same device. An RFID is the most common example of a MBCmS, which consists of a reader and an RFID tag i.e., BD. Both the RF source and the backscatter receiver (BR) are located in the reader when the reader wants to communicate to the tag, RF source transmits the RF signals to activate the tag. Then, the tag backscatters the signal to the reader. Where the receiver gets the information from this signal. Besides, tags are battery-less devices, which harvest the energy from the received signals before transmission. Besides, semi-passive tags with batteries are also used in RFID to perform internal functions but not RF signal generation or transmission.

In MBCmS, as the RF source and receiver are collocated, the signal suffers from round trip path loss. Consequently, the performance of the system degrades due to the doubly near-far problem especially when the distance between the tag and the reader is large [64]. Several techniques have been proposed to enhance the performance of MBCmS such as multi-antenna [65], channel modelling and estimation [66], anti-collision schemes [67], coding schemes [68] etc. Although MBCmS have a wide range of applications such as positioning, patient identification, tracking, etc., [69]. Yet, its applications are limited in long-range and high data rate applications.

A PRS in which communication is done by reflecting the continuous wave signals transmitted by dedicated RF source located separately from the receiver is termed as BBCmS. A simple BBCmS consists of an RF source, a BD, and a BR. The RF source generates a signal to enable the communication in BBCmS, which is located at a distance from the BD but separated from the receiver. The isolation of RF source helps in reducing the round-trip path loss as in MBCmS, leading to the long-range communication [70]. However, the increase in the range comes at the additional cost for the deployment of RF sources. BBCmS have applications in IoT, wireless sensor networks, surveillance and security [71]–[73].

In an ABCmS system communication is done by remodulating and backscattering the modulated ambient RF signals, transmitted by ARSs such as WiFi access points, cellular base stations, TV towers, etc. Different terms have been used in the literature for ABCmS such as FM backscatter, WiFi backscatter, BackFi, HitchHike, etc., [74]–[76]. Nonetheless, all the aforementioned backscatter systems share the common principle of using the ambient radio signals for communication as shown in Fig. 3. In ABCmS system cost is reduced, which is required for the deployment of dedicated RF sources in BBCmS. Allocation of the frequency spectrum is also not
required in ABCmS as it shares the same spectrum with the ARSs [49]. To transmit the data, BD first harvests the energy from the RF signal then remodulates it as a carrier by switching its antenna to reflecting and non-reflecting states to transmit 1 and 0, respectively, or otherwise. On the other hand, the BR receives two signals: one is reflected signal from BD and the second is direct link signal from the RF source. The direct link signal is strong compared to BD signal and creates the interference. Besides, an ambient radio signal is unknown to BR, which makes the BD signal detection a challenging problem for ABCmS. Different methods have been proposed in the literature to efficiently detect the BD signal in the presence of interference from direct link RF signal [77]–[81]. Further, several other works have been proposed to improve ABCmS performance through system design [49], coding [82], and application of multiple antennas [83], [84].

**Fundamentals of PCS:** A simple PCS such as ABCmS consists of a transmitter i.e., BD, and a receiver i.e., BR. Different from other backscattering communication systems, ABCmS does not have a dedicated RF source and utilize ambient signal transmitted by an ARS. The ARS can be any ambient system with its own transmitter and receivers e.g., an indoor WiFi system to provide the internet connectivity to cell phone users. For ease of understanding, we denote the RF source and receiver of ARS as active transmitter (AT) and active receiver (AR), respectively. As in Fig. 3 the channel gains of the links between AT and BD, AT and BR, and BD and BR are represented as \( h_0 \), \( h_1 \), and \( h_2 \), respectively. The AT transmits an information modulated signal \( x \), and the signal received at the BD represented as \( y_{bd} \) is given by

\[
y_{bd} = \sqrt{p}h_1x + n,
\]

where \( p \) is the transmit power and \( n \) is the noise, which is negligible if the BD only uses the a passive components [85]. However, an active load can also be used at the BD for the amplification of incident signal, in that case the contribution of noise is not negligible [86]. When BD receives the signal transmitted by AT, it switches the antenna between different reflecting states to re-modulate the signal with its information bits \( b \). Each reflecting state defined by a reflection coefficient \( \Gamma_j \) is expressed as

\[
\alpha_j = \frac{Z_j - Z_{sc}^*}{Z_j + Z_a} \tag{2}
\]

where \( z_j \) is the load impedance, \( Z_{sc}^* \) is the antenna impedance due to structural component, \( j \) represents the number of reflecting states, and * is complex conjugate. Thus, time varying \( \alpha_j \) can be obtained by changing the load impedance as given by \( \phi(t) = \alpha_j \). Furthermore, the \( \alpha_j \) can be used to design the constellation set of a modulation scheme for BD. For instance, in case of on-off keying (OOK) two states are required to represent ‘0’ and ‘1’ i.e., reflecting and non-reflecting states. The signal at the output of the BD \( z_{bd} \) is given by

\[
z_{bd} = \alpha_jy_{bd}, \tag{3}
\]

where \( \alpha \) is the reflection efficiency of the BD antenna and its value if between 0 and 1.

Suppose the BR samples the signal at Nyquist-information rate of the AT signal, which are given by

\[
y_{br}[m] = x_a[m] + x_b[m] + w[m], \tag{4}
\]

where \( y_{br}[m] \) are the samples of the received signal, \( x_a[m] = \sqrt{p}h_1x[m] \) is the signal coming directly from AT, \( x_{bd}[m] = \sqrt{p}\alpha_jh_1z_{bd}[m] \) is the modulated BD signal, and \( w_{br}[m] \) represents the noise. The average power of the \( M \) received samples can be computed at the BR as follows [49]:

\[
\frac{1}{M} \sum_{i=1}^{M} |y_{br}[m]|^2 = \frac{1}{M} \sum_{i=1}^{M} |x_a[m] + x_b[M] + w[m]|^2 \tag{5}
\]

The signal \( x[m] \) is uncorrelated with noise \( w[m] \) and \( z_{bd} \) can take only two values \( j=0 \) and \( j=1 \) in the case of OOK. Then, (5) can be rewritten as follows:

\[
\frac{1}{M} \sum_{i=1}^{M} |y_{br}[m]|^2 = \frac{1}{M} \sum_{i=1}^{M} |x_a[m]|^2 + \frac{1}{M} \sum_{i=1}^{M} |w[m]|^2 \tag{6}
\]

where the average power of received AT signal is \( P_{at} = \frac{1}{M} \sum_{i=1}^{M} |x[m]|^2 \), when BD is in reflecting state i.e., \( z_{bd} = 0 \) and non-reflecting i.e., \( z_{bd} = 1 \) states, then the average power at BR is \( P_{at} \) and \( 1 + \alpha z_{bd} |^2 P_{at} \), respectively. Now, BR can decode the BD data based on the average power of the signal using a common digital receiver. However, an analog-to-digital converter is required at BR to sample the received signal, which consumes a significant amount of power and not suitable for low power systems [80].

**Discussions:** In the conventional design, ABCmS share the spectrum with ARS without any cooperation which results in major problems, few of them are outlined below:

- As ABCmS share the spectrum with ARS, the signal that comes directly from AT is a strong signal compared to BD signal and treated as interference at BR signal. Consequently, the transmission rate performance of ABCm degrades severely due the direct link interference [87], [88].
- Due to lack of cooperation between the ABCmS and ARS channel estimation information is unknown at the BR, alongside the synchronization is also not possible. Therefore, blind signal detection algorithms are adopted to decode the signal at BR but these algorithms are not suitable for low power BR due to their high complexity issues [80].
- The ambient signals transmitted by ARS are designed independently from the ABCmS and have signal characteristics not suitable for passive BD. For instance, passive BD requires a power-optimized waveform that transmits a maximum amount of power during energy harvesting [89].

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**III. SYMBIOSIS AND SYMBIOTIC RADIO**

In this section, we give a brief overview of the radio ecosystem and its relevance to biological symbiosis. Then, we discuss the symbiotic radio along with its types. Lastly, symbiotic relationships are discussed for resource sharing between different radio systems in symbiosis. A general diagram of symbiosis in the radio ecosystem is shown in Fig. 4.
A. Biological Symbiosis

A natural ecosystem consists of two types of components, namely biotic and abiotic. Biotic components include all the living organisms such as animals, plants, bacteria, etc., and abiotic components refer to non-living physical resources that affect the ecosystem such as water, soil, minerals, etc. In a biological ecosystem, multiple biotic components live together and have different associations while sharing physical resources that can be for survival or facultative. In 1879, a pathologist named Anton de Bary coined the term ‘symbiosis’ which means ‘living together for interspecific associations or interactions among dissimilar organisms’ [90]. He defines symbiosis as “interspecific associations, or symbioses, occur when two different species of organisms depend on each other for food, shelter, or protection.” The organism that takes part in the symbiosis is called symbiont and the ways in which two or more symbionts interact for resources sharing are defined by symbiotic relationships. The symbiosis can be facultative and obligatory as per the dependence of the symbionts on each other. If one or two of the symbionts completely depend on each other and cannot survive without symbiosis, this type of symbiosis is called obligatory symbiosis. On the other hand, if both symbionts can survive independently but also engage in symbiosis, then this type of symbiosis is termed facultative or optional symbiosis. In each symbiosis, symbionts can have different symbiotic relationships either to achieve the common objectives or individual objectives. The possible symbiotic relationships include but are not limited to mutualism, commensalism, parasitism, neutralism, amensalism, and competition [91].

B. Radio Symbiosis

The radio ecosystem is somehow not different than the biological ecosystem. It has biotic components, i.e., radio systems, and abiotic components, i.e., radio resources. Radio systems are categorized into ARS and PRS, which utilize the radio resources such as frequency, space, time, etc., to perform their functionalities e.g., communication, Radar. The current radio ecosystem is evolving rapidly with the proliferation of wireless applications; however, the radio resources particularly the spectrum is limited and insufficient to accommodate the needs of radio systems. Even the ARS with exclusive spectrum access, e.g., the ones with licensed spectrum, are unable to meet their stringent requirements. Therefore, they are trying to access the other radio spectrum resources, available to everyone on an equal basis, i.e., unlicensed spectrum. This
solution is not feasible because the unlicensed spectrum is becoming populated with wireless devices in each passing and going to face drastic interference issues in the near future.

In order to meet the radio resource requirements, different radio systems can engage in symbiosis for intelligent radio resource sharing. Symbiosis is analogous to the coexistence between two dissimilar systems, where each radio system called SRad, have inter-specific associations and interaction with other SRads for sharing the resources. According to the dependencies of SRads, the coexistence can be categorized as dependent or independent, similar to obligatory or facultative symbiosis, respectively. In dependent coexistence, one or both SRads depend on each other for sharing the radio resources e.g., coexistence between PRS and ARS, where PRS depends on ARS for radio resources and cannot survive alone [50], [61]. However, the example of independent coexistence is the coexistence between two ARSs, where both can also survive separately. As the radio systems provide a wide range of functionalities, the SRads systems can be designed from radio systems that provide the same radio service e.g., communication only, or radio systems that provide different services e.g., Radar and communication. An example of former SRads is SCm, while symbiotic radar (SRD) is an example of the latter. In SCm, different radio systems share the radio resources to provide communication services [47]. However, in SRD or symbiotic sensing and communication (SSaC) communication radio systems and Radar and communication radio systems share the radio resources [4], [92], [93]. In this survey, we only focus on SCm systems with dependent coexistence and provide brief discussions on SRD systems for the sake of completeness.

C. SRad Enabling Symbiotic Relationships

Similar to biological symbiosis, SRads can have different symbiotic relationships irrespective of the type of symbiosis to meet the common or individual objectives from radio resource sharing. Definitions of possible symbiotic relationships are given below:

- **Mutualism:** In a mutualistic relationship, radio systems in symbiosis share the radio resources and benefit each other to improve their performances and evolve together.
- **Commensalism:** When two radio systems are in a commensal relationship, one system gets benefits by sharing the radio resources, but the other gets no benefit or harm.
- **Parasitism:** In a parasitic relationship, one system gets benefits by sharing radio resources but it harms the other system in the association.
- **Neutralism:** This symbiotic relationship defines the association where both systems share the resources independently but no one gets benefits or harm from the association.
- **Amensalism:** In an amensal relationship one system when sharing the radio resources with other systems, harms the performance of the other system; however, it gets no benefits or harm from this association.
- **Competition:** This type of symbiotic relationship defines the association in which both systems compete with each other in sharing the radio resources and affects each other’s performance negatively.

IV. SYMBIOTIC COMMUNICATION

This section discusses the architecture of the SRad systems for SCm with dependent coexistence between PCS and ACS. Different symbiotic relationships are explored while highlighting the recent research developments related to SCm. Then, we present the techniques to overcome the performance of SCm.

A. Overview

The difference between conventional ABCmS and SCm is the different ways of radio resource sharing between the SRads in coexistence through symbiotic relationships. These relationships are usually provide mutual benefits to both systems. Examples of symbiotic relationships are shown in Fig. 5.

B. Symbiotic Relationships

The SRad system for SCm with different symbiotic relationship scenarios is shown in Fig. 5(a), where ABCmS performs the passive communication using the ambient signals transmitted by ACS and both systems have mutualistic relationships. The system consists of three components: a transmitter and a receiver of ACS, and BD. The transmitter transmits the radio signal to transfer its information to the receiver, which is also re modulated and backscattered by the BD for its data transmission. In this system, the receiver receives two signals: direct link high power signal from the transmitter and low power reflected signal from BD. The receiver needs to detect the data of its own and BD, while both systems are in mutualistic relationships, the BD sends the data at a very low symbol rate compared to the transmitter’s symbol rate, and it creates the multipath diversity at the receiver. Besides, the receiver first decodes its data and then applies successive interference cancellation to decode the data of BD. The other symbiotic relationship scenarios for SCm are also shown in Fig. 5. A commensal system is shown in Fig. 5(b), where the BD gets the benefits by utilizing the ambient signals of ACS for its communication and transmit at a low symbol rate to not affect the communication of ACS. A full-duplex transmitter based parasitic SRad system is shown in Fig. 5(c), in which the BD transmits concurrently during the ACS transmission to improve its communication but the performance of ACS is degraded due to interference. An amensal SRad scenario is shown in Fig. 5(d), where an illegitimate BD creates the interference to harm the performance of the ACS but it does not get any benefit or harm from the association. Lastly, a competition-based symbiotic relationship is shown in Fig. 5(e), where both system compete each other for improving their performance and BD send at equal symbol rate as AT.

Several research studies have been done to exploit the aforementioned symbiotic relationships for the performance enhancement of SRad systems. Authors in [51] investigate the resource allocation problem for maximizing the data rate in cooperative ABCm based SRad system in different fading states.
Three symbiotic relationships including commensal, parasitic, and competitive, are proposed based on the transmission rate of ACS and BD. In a commensal relationship, ACS tries to maximize its data rate without considering the performance of BD. On the other hand, in a parasitic relationship, BD transmits with maximum reflection coefficient and at the same rate as ACS to achieve the maximum data rate while sacrificing the transmission rate of ACS. In the competition, both systems try to achieve the maximum transmission rate by competing for resources and harming each other. Lastly, the closed-form solution is derived for optimal power allocation for each symbiotic relationship under average power constraint. The extension of this work is proposed in [53], where the authors analyze the maximum achievable rates of each system in both symbiotic relationships. Furthermore, the optimal beamforming is applied at the ACS transmitter to optimize the rates of each system.

In [98], resource allocation problem is studied for SRad system under fading channels. Commensal and parasitic symbiotic relations between ABCmS and ACS are investigated to overcome the spectrum growth problem, in which BD transmits at different data rates compared to ACS transmitter. Further, the maximum transmission rate of BD and ergodic weighted sum rates of ACS transmitter are achieved by jointly optimizing the reflection coefficient and transmit power of BD and ACS transmitter, respectively. The authors in [99], investigated the resource allocation problem in cooperative and non-cooperative SRad systems and try to solve it with the finite blocklength channel codes under different transmission rates and symbol periods of BD. Two optimization schemes are also proposed to minimize the transmission power of ACS and maximize the energy efficiency of BD.

A decode and forward relay-based SRad for ABCm is investigated in [96], where the relay is capable of simultaneous information and power transfer. The relay assists the ACS and parasitic ABCmS in forwarding their information to their destinations using power domain non-orthogonal multiple access (NOMA). While observing the performance of both systems, it is concluded that this relaying mechanism achieves better throughput than the conventional at the cost of minor throughput degradation of ACS system.

In [95], a SRad system with mutualism is proposed for ABCm and CR. Instead of doing active transmission, CR backscatters the primary ACS signals for secondary communication, and joint decoding is performed at the secondary receiver to decode the secondary and primary signals. Further investigations are made using a full-duplex secondary transmitter and reconfigurable intelligent surfaces (RIS), to improve the performance of primary ACS and backscattered-CR systems. Other than that in [86], CR based ABCmS is proposed as a SRad system with an active load assisted BD as a parasite in the ACS. The authors considered this SRad system as a secondary user and designed the beamforming vector to maximize the rate of CR system along with the reflection gain of BD while minimizing the interference to the primary user.

In a SRad system, different radio systems can have multiple transmitters and receivers sharing the resources in a symbiotic manner. However, interference between the users and resource allocation are the critical issues that need to be addressed for the concurrent communication of multiple users with better performance. In [97] authors investigated the interference...
TABLE III

SUMMARY AND CATEGORIZATION OF SCM SYSTEMS

| Reference | Design objective | Symbiotic Relationships |
|-----------|------------------|-------------------------|
| [53]      | BD transmission rate maximization and AT power minimization. | ✓ |
| [51]      | BD and AT transmission rate maximization | ✓ |
| [94]      | Optimal BDs association | ✓ |
| [95]      | BD and AT transmission rate maximization | ✓ |
| [86]      | BD transmission rate maximization and interference reduction at AR | ✓ |
| [96]      | Performance analysis of decode and forward relay network | ✓ |
| [97]      | Interference free multiple BD access. | ✓ |
| [56]      | Multiple BD access | ✓ |
| [98]      | BD Resource allocation | ✓ |
| [99]      | BD Resource allocation | ✓ |
| [100]     | Stochastic transceiver design for multiple BD | ✓ |
| [101]     | Outage probability and ergodic rate analysis of BD | ✓ |
| [102]     | Secure beamforming and secrecy rate analysis of BD | ✓ |
| [103]     | Full-duplex BD and AT transmit power optimization | ✓ |
| [104]     | AT and BD transit power optimization | ✓ |
| [105]     | BD Resource allocation | ✓ |
| [106]     | BD transmission rate optimization | ✓ |
| [107]     | Channel estimation and transmission rate analysis | ✓ |
| [108]     | AT transmit power minimization | ✓ |
| [109]     | AT transmission power minimization | ✓ |
| [110]     | BDs rate enhancement | ✓ |
| [111]     | AT transmit power minimization | ✓ |
| [112]     | Performance enhancement of RIS assisted SRad system by exploiting UAV signals and trajectory | ✓ |

issues in a multi BD ABCm based SRad system, where multiple BDs transmit simultaneously to the ACS receiver. The authors designed the coding algorithms with orthogonal code chips to enable interference-free communication for multiple BDs. Another multiple BD SRad system is proposed in [56] with distributive multiple BD access scheme to overcome the frequent inter-system and inter-BD coordination, where precoding is performed at each BD by multiplying the data with random spreading code. Furthermore, an iterative-based algorithm is proposed to optimize the signal to interference plus noise ratio at BD and minimize the transmission power of ACS transmitter. A stochastic transceiver is designed in [100] to solve the challenges faced by multiple BD SRad systems in the downlink transmission, that are inter-BD interference and downlink interference. The authors also proposed a batch stochastic parallel decomposition algorithm as a solution to the stochastic multiple ratio fractional non-convex problems such as coverage analysis and acquiring the real-time tag’s symbol information with minimum feedback signaling. Moreover, resource allocation problem is investigated in full-duplex SRad network with NOMA based ACS system in [105]. The ACS transmitter has full-duplex functionalities and simultaneously sends the signals to ACS receiver while receiving signals from BDs. Also, a NOMA enhanced dynamic time division multiple access is proposed to enhance the spectral efficiency of the SRad system. In [94], optimal user association problem is studied in multi-user SRad system with network of ACS users and BDs i.e., IoT devices, to maximize the sum rate of all BDs. The main challenge in solving this problem is to estimate the channel of all ACS users and BDs in real-time. The authors proposed two deep learning algorithms namely centralized deep reinforcement learning (CDRL) learning and distributed deep reinforcement learning (DDRL) to infer the current channel state information (CSI) utilizing the historical CSI and concluded that both algorithms achieve optimal users association close to the one with perfect real-time CSI. Furthermore, the DDRL algorithm outperforms the CDRL algorithm in terms of scalability for varying numbers of BDs, while the centralized algorithm needs less information than the distributed algorithms to solve the user association problem.

In SRad system, backscattered signal is a very weak signal compared to direct link signal, which is similar to power domain NOMA, where two users are which allows the multiple users to share the same spectrum resource with distinction in power, code or space domains [101]. Until now, the NOMA systems are used to improve the spectral efficiency of ACS;
however, the spectrum efficiency can be enhanced further with the inclusion of the PCS to support the passive IoT systems. For examples, an ABCmS can support its communication by developing a symbiotic relationship with NOMA assisted ACS e.g., cellular NOMA system. Some studies have been conducted on SRad systems with ABCmS and NOMA based ACS [101], [102]. In [101], a SRad system consists of an ABCm and NOMA based ACS system is presented, where BD backscatters its data to the NOMA users and the near user retrieve its data through successive interference cancellation. However, the far user treats the BD signal as noise. The performance of the system is analyzed in terms of ergodic rates of BD and NOMA systems. A secure beamforming approach is proposed in [102] to enhance the secrecy of BD in a multiple input-single-output NOMA based SRad system. The contributions of the aforementioned research studies related SCM are summarized in Table III along with the classification in terms of symbiotic relationships that are used for the analysis.

C. Performance Enhancement

To improve the performance of the SRad systems, different methods and technologies have been proposed such as multi-input multiple-output (MIMO), full-duplex, RIS and active-load assisted BD. This presents the discussion on the implementation of these technologies in SRads and their benefits.

1) MIMO SRad System: Multi-antenna technology has been deployed widely to improve the performance of the ARS through spatial diversity and spatial multiplexing. Therefore, to exploit the benefits of MIMO technology for improving the performance of SRad systems different studies have been conducted [106], [107]. An end-to-end MIMO SRad system is proposed in [106], where each component of the system is equipped with multiple antennas as shown in Fig. 6(a). An optimal beamforming design problem is investigated to maximize the transmission rate of BD subject to the constraints of ACS transmission rates. To solve this problem a locally optimal solution is proposed based on an exact penalty to obtain the capacity upper bound. A SRad system based on symbiosis of ABCmS and cell-free massive MIMO systems is investigated in [107]. Firstly, a two-step uplink training algorithm is also proposed to estimate the CSI of the backscattered and direct links, wherein the first step is to estimate the direct link from the pilots received from ACS transmitter without the involvement of BD while in the second step both BD and ACS transmitters transmit for estimation of backscattered link. Secondly, low complex beamforming is exploited to derive the achievable transmission rates of both systems.

2) RIS Assisted SRad System: RIS or large-intelligent surface (LIS) is a two-dimensional metasurface that consists of a large number of low-power scattering components. It is capable of reflecting the incident signals into desired directions through passive beamforming [113]. Recently, due to its low power consumption and passive beamforming feature, it is considered as a promising solution to minimize the transmit power of ACS while enhancing the achievable rate of BD in a SRad system [108], [112], [114]. A simple RIS assisted SRad is shown in Fig. 6(b), where multiple BDs are integrated to the RIS and passive beamforming is approach is used to improve the communication link of ACS link as well as to transfer the information of BD to the receiver.

In [108], RIS is deployed in a downlink SRad system to enhance the performance of ACS and multiple BDs, where the BDs face the severe blockage from the obstacles. Besides, the transmission power of the ACS is minimized by jointly designing the active beamforming at ACS transmitter and RIS considering the signal-to-noise ratio and transmission rates of both systems as optimization constraints. A cooperative beamforming approach is proposed in [109] for a simple ABCm based SRad system. Whereas, RIS transmits the data of IoT device (i.e., connected to it through a wire) to ACS receiver by modulating the incident signals while reconfiguring those signals to enhance the performance of ACS receiver. RIS can also transmit the data of multiple BDs connected to it via wired links to ABCm receiver while assisting the wireless transmission of ACS. To enhance the transmission rate of the ABCmS without affecting the ACS rate, a joint optimization approach for active and passive beamforming is studied in [110]. Other works on RIS assisted SRad system with multi-user ACS and a single IoT device are investigated in [111], [114]. The IoT device is connected to RIS through wire, when RIS reflects the ACS transmission signals to its users, it simultaneously modulates the data of IoT device and sends to IoT. Furthermore, this study focuses on the ACS transmission power minimization problem under the rate constraints of ACS users and IoT device, which is solved by jointly optimizing active and passive beamforming at base-station and RIS, respectively. Authors in [112], investigated the RIS assisted SRad system under the coverage of UAV. The RIS modulate the signals transmitted by UAV to transmit its data to the base station of terrestrial ACS and in the meanwhile, it reconfigures the transmission link between UAV and base station to improve the performance of UAV. Further, the UAV mobility is also exploited in this study to improve the transmission links between UAV-base station and UAV-RIS. Particularly, to improve the error rate performance of RIS through joint optimization of the UAV trajectory and RIS scheduling along with its phase shift matrix.

3) Full-duplex SRad System: Full-duplex technology is critical for spectral efficiency and reducing the latency of the system. However, it requires sophisticated and complex hardware for successive interference cancellation, which is not suitable for low power and low complex PCS i.e., IoT. In An ABCmS, BD also receives some control information to maintain proper communication, which creates latency in the system. A SRad system with full-duplex BD is shown in Fig. 6(c), where a BD is capable of simultaneously transmitting and receiving data from the incident signal. To enable full-duplex ABCm based SRad system, a low complex full-duplex BD design is proposed in [103]. An extension of this work is proposed [103], where the authors optimized the transmit power of the ACS along with the optimization of power splitting factor at BD. The performance of the full-duplex SRad system is measured in terms of transmission rates of
4) Active-load Assisted BD SRad System: One of the main reasons for the short range of PCS is double-fading attenuation. The backscatter signal received at BR is a low power signal compared to the interference signal [86]. One way to solve this problem is to use RIS at BD and increase the signal power through passive beamforming [110]. However, this is not possible in all cases, especially when the BD is a small IoT device or sensor. In this case, an active-load can be used at BD to amplify and backscatter the incident signal through negative resistance [115]. Furthermore, it can reduce the dynamic range between the backscatter and direct link signal powers to increase the probability of correct signal detection at BD with an additional cost of power to amplify the signal. This additional power consumption is still less than the power consumed by AT with RF chains [116]. A SRad system with active-load assisted BD is shown in Fig. 6(d), where different symbiotic relationships can be possible between BD and AT. For instance, if the BD transmit with equal symbol rate as AT with power amplification to increase its transmission rate, the performance of ACS can be significantly affected. One the other, BD can also assist the ACS by providing a strong additional multipath, or it can relay the data of ACS while backscattering its data in case of direct signal blockage at AR [117].

V. SRad Enabling SRD/SSaC

In this section we first discuss the SRD/SSaC and symbiotic relationships. Afterwards, we discuss three use case scenarios of SRD in which PRS have dependent coexistence with ARDS and PRDS.

A. Overview

A SRad system can be a SRD/SSaC system if it performs both Radar and communication functionalities. A common example of the SSaC system is a PRS that utilizes the ambient signals emitted active communication or radar systems (also known as illuminators of opportunity) for a target detection. The PRSs also termed as commensal Radar systems because they do not affect the performance of the ambient signal source unlike PCS as they do not transmit any information. Therefore, these systems are called joint radar and communication, integrated sensing and communication, joint communication and radar, joint sensing and communication, and symbiotic sensing and communication [4]. Interested user are directed to the following surveys and tutorials [4], [19], [20].
B. Symbiotic Relationships

SRDs/SSaC can also have different symbiotic relationships for sharing the radio resources which are expressed as follows:

- Mutualistic SRD: A mutualistic relationship between a Radar and a communication system occurs when both systems are associated in all aspects e.g., hardware design, spectrum, networks, etc., and promote each other for mutual benefits. They fully collaborate and coordinate with each other to achieve the highest performance gains.

- Commensal SRD: Commensal symbiotic relationships can be found in SRD systems with both ARDS and PRS. As mentioned earlier in PRS, the Radar system utilizes the ambient signals of ARS for detection or sensing of the targets. In contrast to PRS, ARDS can develop a cooperative SRD system with ACS, where they exchange the information that helps in improving their performance without harming the other system.

- Parasitic SRD: The uncoordinated association between the ARDS and ACS leads to the parasitic symbiotic relationship, where one system shares the spectrum of the other without any coordination and degrades the performance of the other system by creating interference. For instance, ACS utilizes the spectrum of ARDS without coordination, when it transmits the communication signal, this signal interferes with the ARDS and reduces its performance.

- Neutral SRD: In this type of SRD systems, both ARDS and ACS use the same spectrum resources but in an opportunistic manner, which is possible if both systems share the information of their locations and the spectrum resources utilization. In this way, neither of the systems gets affected by the association but this SRD is not spectral efficient.

- Competitive SRD: When ARDS and ACS share the same radio resource under a competitive symbiotic relationship, each one tries to enhance its performance without taking into account the other system. For instance, when ACS shares the spectrum with ARDS, the Radar system transmits with high power to enhance its performance and degrades the communication of ACS.

PCS can also utilize the ambient RF signals generated by the Radar systems to perform their communication without affecting its functionality. We discuss three use case scenarios for symbiosis between PCS and ARDS to enable both Radar and passive communication. In the first case, a SRad system based on the commensal relationship between PCS and ARDS is considered as shown in Fig. 7(a), where BD utilizes the signal transmitted by the Radar transmitter for communication. In this SRad system, the major limitation is the short and intermittent pulses of the Radar systems that require strict synchronization at BD. In [118], a frequency modulated continuous wave Radar waveform is used to support both localization and BD communication. A framework is also designed for joint processing of BD communication and Radar signals and a line coding-based filter is used for clutter removal to detect the target of interest within clutter return. This work is extended for distributed sensing and communication in [119]. In the second use case, vehicle-to-vehicle/vehicle-to-infrastructure scenarios are considered, illustrated in Fig. 7(b), where a car transmits the frequency modulated continuous wave for SSaC functions. There is also a BD connect to an IoT device in the environment that wants to send its information to the car. When the signal strikes the BD antenna, it remodulates the signal with its information. A clutter return is received at the receiver of the vehicle, from which the sensing and communication information is extracted using the clutter filter [119]. Last but not least, a SRad system with a BD and a PRDS is presented in Fig. 7(c), where the PRDS use the signal of the ACS for performing the sensing/Radar functions and receiving the information of the BD. PRDS receiver get both the direct link and the BD signals, initially, it measures the direct signal and then correlates it with the backscattered signal to obtain the required information for both the communication and Radar. These use cases are discussed simplify the explanation of SRD/SSaC systems. Readers interested in PRDS are directed to study the tutorial given in [61].
VI. APPLICATIONS

The interdependent coexistence through multiple symbiotic relationships make the SRad systems a strong candidate to support the massive connectivity of IoT devices in 6G [120]. In this section, we discuss the applications of SRad systems and divide them into two categories: (i) human-centric; (ii) machine-centric. The human-centric applications are the ones that impact the living standards of humans, e.g., E-health, whereas the machine-centric are related to the communication between sensors and devices helping in a process to enhance the efficiency, e.g., manufacturing.

A. Human Centric

These applications are designed to support the healthy life and well-being of humans. Although SRad can support all the applications related to IoT, yet there are a few applications that have achieved significant developments and play a critical role in human life.

a) E-Health: Health monitoring through different devices and sensors is one of the critical applications of IoT in 6G [121]. New implantable sensors and devices are used to observe the temperature, oxygen level, blood pressure, etc. Due to the low power and limitation of computational capability, these devices cannot use conventional wireless communication technologies because their power consumption is very high. On the other hand, SRad consumes less power compared to the aforementioned technologies and enables the energy harvesting from ambient signals of ACS systems. Furthermore, information transfer between these medical devices and ARS is very easy as they share the same radio resources and infrastructure.

b) Wearable Devices: The second human-centric application of IoT is the wearable devices, which collect information from the human body and transfer it over the internet. These devices are also low-power devices and require low-power wireless connectivity for information transfer. Besides, providing a continuous connection to these devices under mobility is another critical challenge. SRad can provide these devices low power communication and continuous connectivity through a symbiosis between the PCS and long range ARS.

c) Ambient Assisted Living: The elderly population is increasing rapidly, and most of them prefer to stay at home. Due to old age, people suffer from loneliness, and diseases such as dementia, which creates difficulty for them to locate their daily use things, e.g., medication kits. To assist the elderly person in their daily activities, a SRad based IoT network can be developed in the home to support positioning, localization, and environment information. The household devices equipped with BD can send their information to WiFi access point during its communication to the elderly person’s cell phone in the uplink/downlink. The SRad can work in different symbiotic relationships with the WiFi or cell phone to improve each other performance.

B. Machine Centric

Proliferation of IoT devices and sensors in the industrial sector, agriculture, energy, and several other sectors is increasing continuously. These devices need to communicate and transfer their information among each other or to an information center. This is an open research problem to meet the radio resource needs through the existing wireless systems. SRad systems can be an enabler for such application areas to support massive connectivity within the limited spectrum through symbiosis with ambient ACS.

a) Manufacturing: In the manufacturing process, IoT devices, i.e., sensors, are deployed for machine-to-machine and machine-to-human communication, enhancing the information flow, centralized control, and intelligent monitoring. Accommodating these devices with wireless connectivity can be achieved by developing a SRad network. Through this, the large number of devices can use the signals of the ambient ACS through symbiotic relationships as well as play a part in improving its performance through multipath diversity.

b) Agriculture: Collecting the information about the environment and utilizing it to support agriculture can be realized through IoT based ecosystem, where the devices are placed far distant apart and require low power and long-range communication. SRad systems in commensal relationship to the TV and FM base station can provide these services to the devices with low power consumption compared to existing wireless technologies, e.g., LoRa.

c) Vehicle-to-Everything: Autonomous driving is one of the critical application areas of 6G, in which the vehicle needs to communicate to the other vehicles as well as to infrastructure for safe driving and prevent accidents. Several sensors are installed in the vehicle to obtain the critical information from the environment through Radar/sensing. If cellular V2X or dedicated short-range communication (DSRC) are supporting vehicular communication, signals coming from these systems can be utilized to enable passive communication between vehicles and infrastructure through SRad. Autonomous vehicles can share their mobility information with other vehicles, or the road safety sign boards can backscatter the critical information to the vehicles. Thus, SRad provides the spectrum efficiency with massive connectivity for vehicle-to-everything communication.

VII. OPEN PROBLEMS AND FUTURE DIRECTIONS

Although different research studies on SRad systems provide different insights and techniques for the development of these systems, yet there are many open research problems to solve before SRad become mature. Here are some of the critical challenges highlighted to direct the further research on SRad systems for SCm.

A. Transmitter Design

In a SRad system, the transmitter design of one system can affect the other system depending on the symbiotic relationship. Therefore, we first look at the challenges related to transmitter design and also discuss the possible solutions.

a) Joint Waveform Design: Unlike the ACS, where the carrier is a continuous wave signal, PCS uses the data modulated RF signal of ACS and remodulate it to send its information. In different symbiotic relationships, both systems
can have comparatively different data rates. For instance, in a competition to achieve better throughput both systems can transmit at the same symbol rate, which can affect the performance of both systems negatively. Therefore, joint waveform design can be a potential solution to support SCm with better performance and high spectral efficiency.

b) Joint Modulation Design: If the PCS uses the same modulation scheme as ACS with the same symbol rate, it makes the detection complicated at the receiver. To prevent this situation a joint modulation design can be considered that can allow using higher-order modulations coherently while improving the performance of both systems.

c) Smart Multi-antenna Design: Although multi-antenna technology and their implementation protocols as well algorithms have been explored extensively for ACS performance enhancement; however, these are not directly applicable to PCS due to their high power consumption and complexity. Therefore, novel smart antenna designs for PCS with low complex algorithms for communication and data aggregation are required to achieve performance improvements.

d) Hardware design of PCS transmitter: Synchronization of ACS and PCS transmitters’ symbols is a critical problem. The circuit used in ACSs for timing and phase recovery is power-consuming. There is a need for low power circuit and low complexity synchronization algorithms for synchronization at RF level in PCS transmitter. Active load and MIMO are the available options, but their power efficiency is less. The full-duplex capability can allow the PCS transmitter to harvest energy and enhance the power of the signal using the harvested energy. It can provide other benefits as well such as simultaneous signal detection and reflection.

B. Receiver Design

a) Signal Detection: The direct path signal is several times stronger than the backscattered signal, which is not visible within the dynamic range of the ADC controller; thus, results in a higher packet error rate. Different methods can be used to reduce the error rate: i) Before decoding the PCS signal first eliminate the direct path signal; ii) Use beamforming and directing the null of the antenna towards the strong signal can allow the reception of the PCS signal. Then, traditional ADC can sample the weak PCS signal and a non-coherent receiver can be used to detect it. Further performance improvement can be achieved using coding e.g., Hadamard codes, which allows the signal detection in very noisy and unreliable channels.

b) Signal Processing under Practical Limitations: Robust signal processing techniques are required in real-time implementation of PCS because the PCS signal is very weak, and the availability of CSI is not certain at all times. In addition, CSI becomes old and needs to be reattained after some time. Besides, NOMA-assisted SRad systems require the successive interference cancellations for a large number of PCS devices, which become computationally complex.

c) Sporadic Transmission: In practical scenarios, PCSs use the ambient signal sporadically for transmission of data and ambient signal tracking at PCS devices is critical for its successful transmission. One solution is the synchronization between the PCS device and ACS transmitter to have the pre-knowledge of ambient signal transmission time. This requires the design and implementation of low power and low complex algorithms at PCS device.

d) Downlink signaling/feedback and uplink channel: The low power and simple processing constraints limit the capabilities of the PCS device as a receiver. However, the downlink control channel is necessary to design a physical layer protocol for PCS. Besides, the uplink channel design is also important for feedback and data transfer. A non-coherent receiver design is comparatively simple than the coherent one but with low performance. On the other hand, an energy detector requires a much larger symbol length of PCS signal than ACS signal to average out the underlying modulated signal.

C. Network Design and Management

a) ACS Source Selection and User Association: More ACS transmitters with multiple channels can improve the energy harvesting efficiency and provide more spectrum holes for concurrent active data transmissions. This complicates the whole system in terms of trade-offs among energy harvesting, backscattering, active transmission, and channel selection. Furthermore, in the presence of a lot of ambient signals coming from different ACS, but the selection of an appropriate source is critical for the development of sustainable PCS. The propagation and availability of RF signals vary in environments. For instance, the indoor environment has different channel characteristics than outdoor environments. Selecting the suitable ACS resource can have a strong impact on the performance of the PCS and the overall performance of SCm. Moreover, user association considering the performance of both PCS and ACS users as well as increasing the performance of the overall system. In the existing studies, it is assumed that the single PCS users is associated with the single ACS user and utilize the resources of that specific user for Scm, which is not practical because most of the time number of PCS user is less than or greater to the ACS users. In these scenarios, more than one PCS users can be associated to the single ACS user, or one PCS user can utilize the signal of multiple ACS users for Scm.

D. Channel Modelling and Estimation

In SRad systems for communication, modeling the channels of both ACS and PCS are essential to compensate for the combined effect of channels on both systems. Also, PCS has a different propagation channel than the ACS in the sense that its channel is cascaded and doubly faded. Moreover, channel estimation is also critical especially for PCS to detect the weak signal at the receiver in the presence of interference from the direct link signal of ACS. The conventional schemes for ACS are not directly applicable to the SRad systems due to their high complexity. To design a proper Scm, it is highly desired to estimate the channel accurately. Furthermore, RIS is being used in SRad to improve its performance; however, channel estimation in RIS is already an open problem, with the addition of PCSs devices to the RIS increase the severeness of the problem.
E. Security and Privacy

In SRad, both systems have different symbiotic relations in terms of resource utilization, disrupting the communication of one source can affect the other system directly. Besides an illegitimate ACS can also try to acquire the sensitive information of the PCS device and play an amensal role and harm the performance of the PCS users. Securing the data of PCS is vital due to its critical and sensitive data applications, particularly in healthcare. Conventional cryptography-based encryption and authentication schemes designed for ACS devices need high computationally complex algorithm implementation. Thus, the design of a low complexity scheme is necessary for such a device. Additionally, physical layer security techniques can be utilized to provide security and privacy in PCS. Authentication of ambient signal prior utilization is needed to secure the PCS signals. Furthermore, the broadcast nature of backscattered signals makes them vulnerable to security attacks.

F. Performance Analysis and Metrics

In SRad systems the radio space shares the resources in multiple dimensions e.g., spectrum, energy, infrastructure, new performance metrics need to be designed to measure the performance in multiple dimensions, unlike the conventional performance metrics. In the commensal system, PCS device has a very high data rate which can be considered as additional multipath to the ambient system. The ambient system can utilize this to improve its performance. The overall capacity of the system increases with the addition of the PCSs devices to the ACS in a mutualism symbiotic relationship. This is an interesting research area to investigate that how much throughput or capacity gains can be achieved with the addition of the PCS device to the ACS.

VIII. Conclusion

To meet the needs for future wireless systems within limited radio resources is challenging, especially with the proliferation of wireless applications. The continuous development of IoT devices and sensors is making the problem worse and existing radio resource sharing mechanisms are failing to fulfill the need of radio systems. Thus, new paradigms should be explored for spectrum sharing and coexistence. In this survey, we highlight the importance of using PRS i.e., PCS and PRDS along with the ARS, and discuss a bio-inspired mechanism called symbiosis for resource sharing and coexistence of in radio ecosystem to enable 5G and SRD. There are two types of symbiosis, i.e., obligatory and facultative depending on the radio system dependency and mapped it to coexistence. If one of more radio systems in symbiosis depend on each other completely, e.g., ARS and PRS then symbiosis is obligatory (i.e., dependent coexistence). On the other hand, if the radio systems can survive separately and have symbiosis as well then the resultant symbiosis is facultative (i.e., independent coexistence). Our focus is on dependent coexistence due to PRS. Then, different symbiotic relationships between dissimilar SRad systems are analyzed. It is observed that these relationships may have significantly varying realizations ranging from the cooperation of the symbionts to competition between them for the radio resources. The performance enhancement techniques for SRad systems are presented along with the different use case scenarios. Applications of SRad communication from human and machine-centric visions are also described for future wireless networks. We foresee SRad as a potential candidate for efficient spectrum sharing between PRS and ARS as well as for the coordination between the dissimilar ARS in the future.

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