Symbiotic Radio

Subjects: Telecommunications
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The sixth generation (6G) wireless technology aims to achieve global connectivity with environmentally sustainable networks to improve the overall quality of life. The driving force behind these networks is the rapid evolution of the Internet of Things (IoT), which has led to a proliferation of wireless applications across various domains through the massive deployment of IoT devices. Symbiotic radio (SRad) technology is a promising solution that enables cooperative resource-sharing among radio systems through symbiotic relationships.

Keywords: coexistence ; symbiotic communication ; symbiotic radio

1. Introduction

6G technology has the potential to revolutionize communication networks by connecting the world through sustainable means, with the goal of improving quality of life [1]. The rapid advancement of IoT is driving this change, as it is projected that by 2030 the number of connected devices will reach 125 billion [2], exacerbating the issue of spectrum scarcity. In addition, the majority of IoT devices are energy-constrained and designed to have a long lifespan. One of the major power-consuming components of these devices is the communication radio, which requires energy-intensive components such as amplifiers and oscillators. To address the challenges of spectrum scarcity and power consumption in IoT devices, a new class of IoT known as passive IoT has been proposed in 3GPP technical studies [3]. The goal of this new class of IoT is to design and implement ultra-low power passive communication technologies to enhance spectrum efficiency and support the deployment of large numbers of IoT devices and sensors, using the existing wireless infrastructure.

BackCom is an emerging candidate for ultra-low power wireless communication, in which backscatter technology is used to modulate and reflect incident signals transmitted by RF source for information transfer [4]. This approach eliminates the need for energy-intensive and costly electronic components for RF signal generation at the device, thus congruent with the objective of passive IoT to reduce power consumption and enhance the longevity of IoT devices. The signal required for BackCom can be sourced from a dedicated signal generator or an ambient RF source such as the base station of cellular, TV, or radio broadcast systems. While the use of a dedicated signal generator has been widely adopted in RFID technology due to its low power and low-cost advantages at the device level, the deployment costs of such systems can be a major limitation to scalability. This is because as the network grows, more dedicated signal sources are required, leading to increased costs [5].

The utilization of ambient RF signals for BackCom has been the subject of extensive investigation as a means of surmounting the limitations of RFID and establishing an alternative technology that is known as ABCm [6]. Interestingly, it eliminates the need for dedicated RF source deployment by enabling BackCom to use the signals from wireless systems in the surrounding environment. This approach not only reduces the cost and complexity of deployment but also allows for greater scalability and flexibility in terms of the available signal sources, which can be sourced from existing infrastructure, rather than requiring dedicated RF sources [7]. For instance, in [8], researchers have demonstrated information transfer between two BD by re-modulating and backscattering the incident signals emitted by a nearby TV station. While ABCm has the potential to enhance overall radio resource utilization and spectral efficiency, its performance is often hindered by interference from strong direct-path signals at the receiver [9]. To address this issue, various approaches have been proposed, such as shifting the incident signal to a different frequency band [10][11][12][13], exploiting the cyclical features of the source signal [14][15][16][17], and utilizing multiple antenna receivers for interference suppression [18][19][20]. However, it should be noted that these methods tend to come with a trade-off, such as increased spectrum utilization or receiver complexity, which can limit the practical applications of ABCm. To overcome these challenges, one potential solution is to enable cooperative coexistence between passive devices and existing wireless systems, through radio resource sharing. This approach can help to mitigate the impact of increased spectrum utilization and receiver complexity, while also enabling more efficient use of available resources and increasing the scalability of the system.

In traditional coexistence methods, devices from different systems independently share radio resources by transmitting their own RF signals. However, in the case of ABCm-assisted passive IoT, devices depend on the signals emitted by other devices and RF sources in the environment. This type of resource sharing is similar to symbiotic relationships in biology, where different species form associations to share resources such as food, shelter, and protection. These associations, known as symbiosis, can be either obligatory or facultative, depending on the degree of mutual dependence between the organisms [21]. In facultative symbiosis, two organisms can survive independently but also choose to share resources. In contrast, in obligatory symbiosis, one organism is dependent on the other and cannot survive independently. In both cases, the resource sharing between the organisms can range from mutualism, where both organisms benefit, to competition, where each organism primarily benefits itself [22]. The concept of symbiosis can also be applied to the coexistence of passive devices and existing wireless systems. In this scenario, a SRad paradigm has been introduced, where the wireless systems are designed to support the passive devices with their radio resources for communication while still performing their primary functions. This allows for a mutually beneficial relationship, where both the passive devices and the existing wireless systems can thrive [23].

2. History before Symbiotic Radio

The evolution of IoT has been significantly impacted by the issue of spectrum scarcity or the lack of available radio spectrum. However, this problem has been present since the early days of radio transmissions, as exemplified by Guglielmo Marconi's transatlantic transmission over a century ago, which occupied the entire radio spectrum at the time. As the number of people and companies using radio transmissions increased, debilitating interference became a significant concern [24]. Addressing the issue of spectrum scarcity requires a multi-faceted approach, which can be looked at from two perspectives: rule-based spectrum allocation and access and technological solutions aimed at improving spectrum utilization. Based on these perspectives, researchers and engineers have developed various mechanisms to improve the existing radio spectrum utilization, which are presented in **Figure 1**.

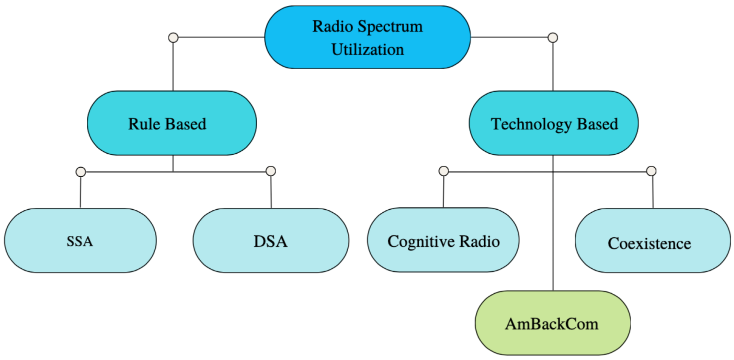

Figure 1. Conventional methods for radio spectrum utilization.

2.1. Rule Based Spectrum Sharing

In general, two approaches are considered for spectrum access, i.e., SSA and DSA. The SSA is categorized into licensed, rule-based, or unlicensed access. The exclusive licensing strategy has served cellular networks until the recent development of IoT and the proliferation of wireless devices, which needs the spectrum in abundance more than ever before [25]. In 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 FCC in the ISM bands, which allows every technology to access the spectrum with equal rights under some basic regulations [26]. On the other hand, DSA provides more flexible spectrum usage methods than SSA to improve spectrum efficiency. It preserves the rights of exclusive use for licensees and permits them to trade and sell spectrum. Besides, dynamic spectrum allocation can be performed to assign spectrum based on the traffic statistics of a particular service to enhance spectrum efficiency [27]. These regulations and allocations may 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 [28].

2.2. Technology Based Spectrum Sharing

From a technological perspective, different approaches have been considered to accommodate the upcoming surge of IoT devices and high spectrum demands, including allocation of new bands (i.e., mmWave and THz) [29], re-allocation of legacy licensed spectrum bands [30], the coexistence of wireless technologies [31][32][33], and CR [34][35][36][37]. The first two approaches require either innovations, technological enhancements, transfer of property rights, or clearing the existing users, which are exorbitant and time-consuming [30]. The coexistence of technologies is considered more convenient to overcome the spectrum scarcity issue, where different wireless systems can share and access the resources with minimal interference. Several spectrum-sharing approaches have been proposed in the literature for the coexistence of systems such as WiFi and TV in TVWS [38][39][40], integrated non-terrestrial and satellite [41], WiFi and LTE in the unlicensed 5-GHz band [42], narrow band IoT and LTE [43], and communication and Radar [44]. The coexistence of different wireless systems has been a successful approach for efficient spectrum utilization; however, resource sharing among different wireless systems brings major interference issues.

During the last two decades, CR has been extensively explored for enhancing the spectrum efficiency of under-utilized bands. CR technology enables efficient use of the limited radio spectrum by allowing secondary users to access unused spectrum bands licensed to primary users in a non-interfering manner [45]. Secondary users in CR technology use four primary spectrum sharing techniques: overlay, underlay, interweave, and opportunistic. Secondary users require to vacate the frequency band in overlay spectrum sharing when a primary user is detected. In contrast, secondary users transmit at a power level lower than the primary user's signal power threshold in underlay sharing. Interweave spectrum sharing involves secondary users identifying unoccupied frequency bands and transmitting only when the primary user is not using the spectrum. Finally, opportunistic spectrum sharing allows secondary users to access the spectrum when primary users are not using it but requires them to vacate the band as soon as a primary user is detected. The goal of spectrum sharing in CR is to enable more efficient use of the radio spectrum while protecting primary users from interference [38]. These techniques are essential for the effective deployment of CR technology, which promises to create a more flexible and efficient wireless network in the future. However, CR systems can create unavoidable interference to the primary systems if not operated under defined regulations. Due to the interference concerns of CR, their adoption in real-time applications is limited so far [22].

To support low-power devices, ABCm has become popular due to its ability to improve overall spectral efficiency without additional energy or infrastructure costs, in which the communication device utilizes the resources of existing wireless systems in a passive manner [8]. Unlike earlier co-existing systems, dedicated infrastructure and resource allocation are not required for ABCm systems [7]. One of the main advantages of this technology lies in its passive way of spectrum sharing without causing significant interference, which can enhance the spectral efficiency of the existing wireless system. Furthermore, it can work with the current spectrum-sharing approaches. However, the backscattering system faces strong interference because of the absence of coordination with the existing wireless systems. As a result, the performance of ABCm is limited by interference [9]. Although coexistence mechanisms have been mentioned sporadically in the literature [26][38][39][40][41][42][43][44][46][47][48][49], researchers need a general framework that can define other possible means of coexistence and coordination between active and passive radio systems.

The SRad framework facilitates coexistence and coordination among wireless systems to enable efficient resource sharing, combining the benefits of both CR and ABCm [48]. SRad enables the cooperative sharing of spectrum resources among devices from different systems while mitigating interference issues through coordinated access. Compared to CR, the secondary system in SRad employs backscattering communication, resulting in minimal interference to the primary system. Additionally, SRad allows for infrastructure sharing, where multiple systems can share a common transmitter or receiver, thus achieving reliable backscattering communication and overcoming direct link interference issues encountered in ABCm. Overall, SRad offers a flexible and efficient approach to resource sharing and coexistence, making it a promising technology for future wireless communication systems.

3. Basics of Symbiotic Radio Paradigm

3.1. Classification of Radio Systems

The radio systems can be categorized into active and passive types based on the RF signal generation requirement at the device. Active radio systems generate an RF signal at the device for information transfer and extract the information from the transmitted signal at the receiver. In a passive radio system, there is no need for active RF signal generation at the device. Instead, external signals are reflected/backscattered for information transfer. The receiver processes the reflected/backscattered signals for information extraction.

A simple active radio system consists of two parts; a transmitter equipped with a dedicated signal source and a receiver. The transmitter sends the information by transmitting a radio signal in the air, where the receiver detects the signal and extracts the information. The radio signal can be an information-modulated signal or a continuous wave signal depending on whether the system is for communication or Radar. **Figure 2**a shows an active communication system with a transmitter sending a signal to the receiver for information transfer. On the other hand, **Figure 2**b shows an active Radar system, which contains a transceiver that radiates the radio wave in the air to detect the presence of the target and its related information. The common examples of active communication systems are TV, cellular, Bluetooth, and WiFi while active Radar systems are mapping, earth monitoring, and navigation.

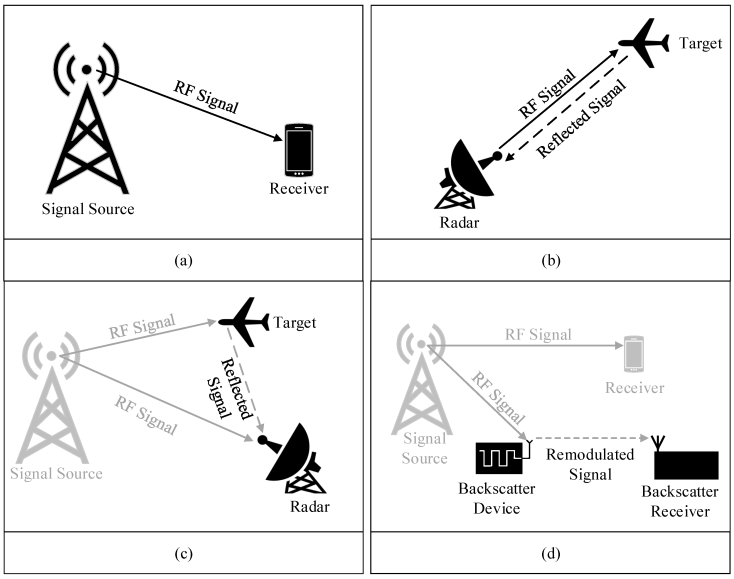

Figure 2. Classification of radio systems: (**a**) active communication system, (**b**) active Radar/ Sensing system, (**c**) passive Radar system, (**d**) passive communication system.

The use of passive radios based on the backscattering principle can be dated back to the development of passive Radar technology used in World War II. A passive radio reflector was mounted on the allied aircraft to backscatter the signal transmitted by the home Radar with better illumination than enemy aircraft [50]. Afterward, Harry Stockman proposed the idea of reflected power communication in 1948, which contributed to the development of RFID technologies [51]. However, a completely passive RFID system that is operated and controlled by the illuminated signals was demonstrated by Alfred Koelle in 1975 [52]. Since then, RFID technology has been widely used in various fields such as medical, business, logistics, and so on [53]. Passive radio systems are used for communication in simple low-power devices and sensors and for Radar in military applications. A passive Radar system is shown in **Figure 2**c, where the receiver utilizes the radio waves radiated by ambient radio systems for target detection instead of generating a signal [54]. On the other hand, in a passive communication such as BackCom, a BD or tag re-modulates the ambient RF signals to send the information to a receiver as shown in **Figure 2**d. The ambient RF signal source can be any wireless system including a tiny Bluetooth device, a large satellite base station placed in space, and every system in between [55][56][57][58].

3.2. Radio Symbiosis

A natural ecosystem consists of two components, namely biotic and abiotic. Biotic components include all 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. Multiple biotic components live together in a biological ecosystem and have different associations while sharing physical resources 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 [59]. He defines symbiosis as “interspecific associations, or symbioses, a phenomenon in which two different species of organisms depend on each other for food, shelter, or protection”. The organism that takes part in the symbiosis is called a symbiont. Symbiotic relationships define how two or more symbionts interact for resource sharing. The symbiosis can be facultative and obligatory as per the dependence of the symbionts on each other. If one or two symbionts depend entirely on each other and cannot survive without symbiosis, this type is called obligatory symbiosis. On the other hand, if both symbionts can survive independently and engage in symbiosis, this type of symbiosis is termed facultative or optional symbiosis. Symbionts can have different symbiotic relationships to achieve common or individual objectives. The possible symbiotic relationships include but are not limited to mutualism, commensalism, parasitism, and competition [60].

The radio ecosystem is somehow not different than the biological ecosystem. The radio resources and systems are similar to the abiotic and biotic components. The radio systems utilize the radio resources such as time, frequency, and space, to perform their functionalities, e.g., communication, and Radar. The radio ecosystem evolves rapidly with the proliferation of wireless applications. Yet, the radio resources, particularly the frequency spectrum, are limited and insufficient to accommodate the needs of radio systems. Different radio systems can engage in symbiosis to meet the radio resource requirements for intelligent radio resource sharing. Radio symbiosis is analogous to biological symbiosis, where two or more radio systems have inter-specific associations and interactions for sharing resources. The radio system that is developed from symbiosis is known as an SRad system. In addition, radio symbiosis can be obligatory or facultative according to the dependencies of radio systems. In facultative symbiosis, both systems are active and share the resources, even though they do not depend on each other e.g., LTE and WiFi. On the other hand, in obligatory symbiosis, one radio system is passive and the other is active and both share the same resources, where the passive radio system depends on the resources of the active radio system e.g., passive IoT and WiFi [6][58]. The radio symbiosis enables the coordination among the radio systems for intelligent resource utilization and to achieve common or individual objectives from symbiosis in an SRad system [48]. There are several types of symbiotic relationships that can be developed between the different radio systems and users for sharing resources [22][48]. **Figure 3** illustrates a flow diagram of SRad system from radio symbiosis to symbiotic relationships in the radio ecosystem. The possible symbiotic relationships include:

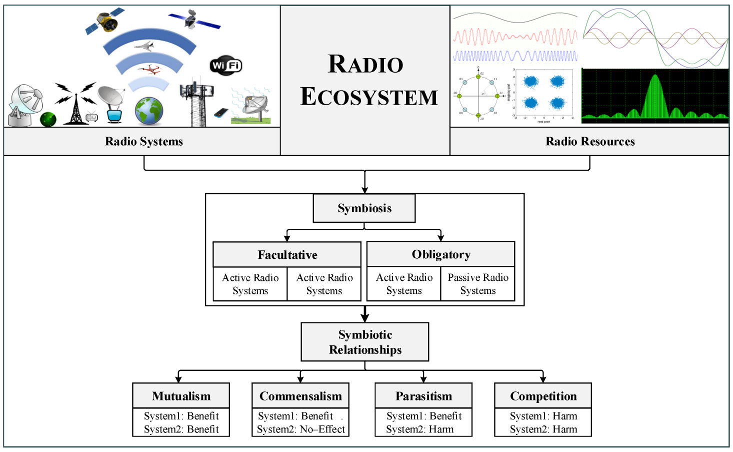

Figure 3. Symbiosis in the radio ecosystem.

- Mutualism relationship: In this type of relationship, both systems work together to improve the overall performance of the network, resulting in a positive impact on both systems.

- Commensal relationship: In this type of relationship, one system maximizes its data rate without considering the performance of the other.

- Parasitic relationship: In this type of relationship, one system transmits at the same rate as the other to achieve maximum data rate, but at the expense of the transmission rate of the other system.

- Competition relationship: In this type of relationship, both systems try to gain the maximum transmission rate by competing for resources, which can lead to a reduction in performance for both systems.

Interestingly, in each symbiotic relationship, one radio system receives the benefit from symbiosis but the other system either gets benefit or harm. Nonetheless, the overall resource utilization efficiency is increased. As the radio systems provide a wide range of functionalities, the SRad 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 SRad is SCm, while symbiotic RADAR is an example of the latter. In SCm, different radio systems share the radio resources to perform communication tasks [22]. However, radio systems share the radio resources to perform Radar/sensing and communication functions in symbiotic RADAR [61][62][63].

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