NONCOHERENT FREQUENCY SHIFT KEYING FOR AMBIENT BACKSCATTER OVER OFDM SIGNALS USING ANN: A SURVEY

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Abstract: Recent developments have resulted in the development of a cutting-edge technology known as ambient backscatter communications. This technology makes it possible for smart devices to communicate with one another through the utilization of radio frequency (RF) signals that are present in their environments, without the need for active RF transmission. This technique is particularly useful for resolving issues relating to communication and energy efficiency in low-power communications systems like sensor networks. It is anticipated that it will be used in a wide variety of Internet of Things (IoT) applications. As a result, the purpose of this study is to offer a modern and exhaustive literature overview on the fundamentals, applications, and problems of ambient backscatter communications, as well as research efforts and advancements. In specifically, we begin by introducing the foundations of backscatter communications and then proceed to conduct a quick overview of bistatic backscatter communications systems. After that, a discussion is had about the overall design, the benefits, and the solutions to solve the constraints and problems already present in ambient backscatter communications systems. New uses of ambient backscatter communications are also explored in this article. In conclusion, we discuss some outstanding questions and potential avenues for future research.

Index Terms—Ambient backscatter, internet of things, green communications, performance analysis, OFDM.

1. INTRODUCTION

The Modulated backscatter technique was initially presented by Stockman in 1948 [1] and rapidly became the primary technology for low-power wireless communication systems after its initial debut. In modulated backscatter communications systems, a backscatter transmitter does not generate RF signals on its own; rather, it modifies and reflects incoming RF signals in order to send data [2-4]. As a consequence of this, this method has been put to use in a wide variety of practical applications, including radio-frequency identification (RFID), tracking devices, remote switches, medical telemetry, and low-cost sensor networks [5, 6]. Conventional backscatter communications, on the other hand, are unable to be widely implemented for data-intensive wireless communications systems [11], as a result of a number of restrictions [7]–[10]. To begin, conventional backscatter communications demand that the backscatter transmitters be positioned in close proximity to the RF sources, which restricts both the device's applications and the region it can cover. Second, in conventional backscatter communications, the RF source and the backscatter receiver are both located in the same device, which is referred to as the reader. This can lead to self-interference between the receive and transmit antennas, which in turn lowers the performance of the communication. In addition, traditional backscatter communication systems function passively. This means that backscatter transmitters only send data when asked to do so by backscatter receivers. As a result, they are exclusively utilized in a select few different applications.

Recently, ambient backscatter [12] has been emerging as a promising technology for low-energy communication systems. This technology has the potential to successfully solve the limitations that were previously discussed in relation to traditional backscatter communications systems. Backscatter devices are able to communicate with one another through the use of surrounding signals that are broadcast from ambient RF sources such as TV towers, FM towers, cellular base stations, and Wi-Fi access points. This type of system is referred to as an ambient backscatter communications system (ABCS) (APs). In specifically, the backscatter transmitter in an ABCS can modulate and reflect ambient signals everywhere around it in order to send data to the backscatter receiver. Therefore, the communication within the ABCS does not require the expensive and scarce allocated frequency band. The receiver is able to decode the transmitted data and acquire usable information from the transmitter by using the signals it has received from the backscatter transmitter as well as the RF source or carrier emitter. In backscatter devices, the number of RF components can be minimized by separating the carrier emitter from the backscatter receiver. This allows the devices to operate actively, which means that backscatter transmitters can transmit data without initiation from receivers when they have harvested sufficient energy from the RF source. Because of this feature, the ABCSs have the potential to be utilized in a wide variety of practical applications [13].

Even though ambient backscatter communications have a lot of potential for low-energy communication systems in the future, especially Internet of Things (IoT) systems, they are still up against a lot of obstacles. Specifically, in contrast to conventional backscatter communications systems, the transmission efficiency of an ABCS is highly dependent on the ambient source. This includes factors such as the type of signal, such as a TV signal or a Wi-Fi signal; the location of the RF source; and the environment, such as an indoor or outdoor setting. As a result, ABCS needs to be tailored particularly to the exact ambient sources that will be used. In addition, because of the dynamics of ambient signals, one of the most critical protocol design issues is the scheduling of data transmissions for backscatter devices. This is done in order to make the most of the usability of ambient signals.

TABLE I: LIST OF ABBREVIATIONS

Abbreviation	Description	Abbreviation	Description
MBCSs	Monostatic backscatter communications systems	UHF	Ultra high frequency
SHF	Super high frequency	UWB	Ultra-wideband
NRZ	Non-return-to-zero	OSTBC	Orthogonal space-time block code
ASK	Amplitude shift keying	FSK	Frequency-shift keying
PSK	Phase shift keying	BPSK	Binary phase shift keying
QPSK	Quadrature phase shift keying	FDMA	Frequency division multiple access
QAM	Quadrature amplitude modulation	OOK	On-off-keying
BBCSs	Bistatic backscatter communications systems	IoT	Internet of Things
MCU	Micro-controller unit	CFO	Carrier frequency offset
BER	Bit-error-rate	SNR	Signal-to-noise ratio
TDM	Time-division multiplexing	CMOS	Complementary metal-oxide-semiconductor
CDMA	Code division multiple access	ABCSs	Ambient backscatter communications systems
AP	Access point	D2D	Device-to-device
ML	Maximum-likelihood	OFDM	Orthogonal frequency division

			multiplexing
WPCNs	Wireless powered communication networks	CRN	Cognitive radio network

In addition, the communication protocols of ABCSs must ensure that licensed users' transmissions are not disrupted by employing ambient signals derived from licensed sources. These signals can be obtained from a variety of sources. As a consequence of this, a significant amount of research effort has been documented to improve the ABCS in a variety of ways. This study is the first to provide a thorough overview of the state-of-the-art research and technological breakthroughs on the architectures, protocols, and applications of emerging ABCSs. The overview is presented in the form of a paper.

- To provide a fundamental background for general readers to understand basic concepts, operation methods and mechanisms, and applications of ABCSs;
- To summarize advanced design techniques related to architectures, hardware designs, network protocols, standards, and solutions of the ABCSs; and
- To discuss challenges, open issues, and potential future research directions. These are the key features and objectives of this paper.

2. AMBIENT BACKSCATTER COMMUNICATIONS: AN OVERVIEW

In the following part of the article, we will begin by giving an overview of wireless energy harvesting networks. Following that is a discussion of backscatter communications systems as well as an introduction to the foundations of modulated backscatter communications. After that, the most important aspects of designing antennas for ABCSs are brought to light. In conclusion, the usual modulation and channel coding techniques that are utilized in ABCSs are talked about.

A. *Energy Harvesting for Green Communications Networks*

The energy harvesting (EH) approach has recently garnered a lot of attention from both academia and business due to its promising features for environmentally friendly communications networks such as wireless sensor networks (WSNs) and the internet of things (IoT). The most important aspect of EH is that it makes it possible for wireless devices to get operational power from RF signals by harvesting that energy. As depicted in Figure 1, electromagnetic harvesting can be broken down into three primary types of schemes: wireless power transfer (WPT), wireless-powered communication network (WPCN), and simultaneous wireless information and power transfer (SWIPT).

- Wireless power transfer (WPT): in this configuration, the power transmitter does not send any information along with the energy that it sends to the user devices. The energy is put to use by charging the batteries of the various devices. WPT can be used in a variety of real-world contexts, including in the fields of consumer electronics, medical implants, electric vehicles, and wireless grid [14].
- Wireless-powered communication network (WPCN): This method enables the user devices to collect energy, which can subsequently be used to actively transfer data. This method was developed by Qualcomm. In this sense, wireless devices have the potential to be created for future applications such as Internet of Things (IoT) or, more generally, Internet of Everything [15].

- Simultaneous wireless information and power transmission (SWIPT): In SWIPT, the power transmitter can transport energy and information wirelessly to the user devices at the same time by utilizing a hybrid architecture. This allows for simultaneous wireless information and power transfer. The users can then choose to harvest energy or decode information sent from the power transmitter by simply switching between harvesting and decoding modules, which results in a high energy-information transmission efficiency [16]. This allows the users to achieve a high level of flexibility in their use of the system.

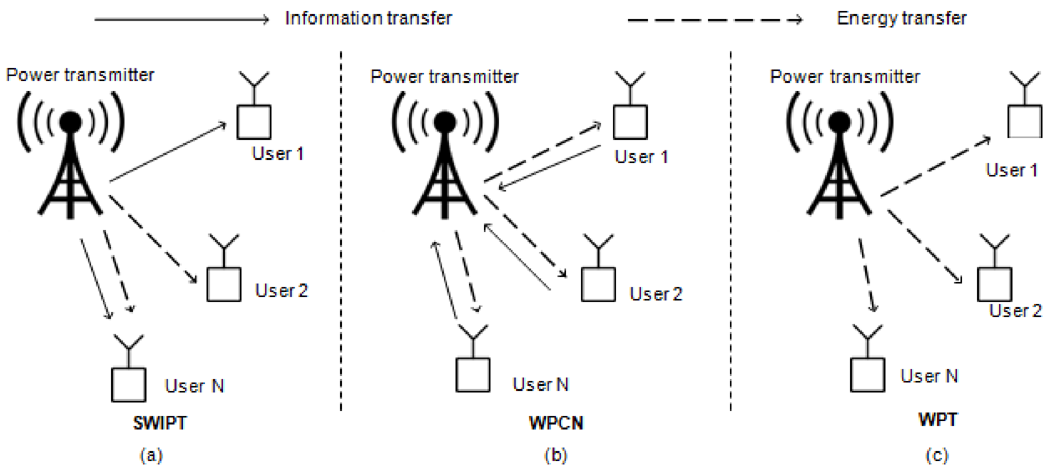

Figure 1: Scenarios for wireless energy harvesting schemes

These energy harvesting strategies, despite having many benefits, are not without their drawbacks when used to low-cost and low-power networks, such as wireless sensor networks (WSNs) and the internet of things (IoT). For instance, with WPCNs, the users may need a significant amount of time to collect sufficient RF energy to enable data transmission, which in turn restricts the performance of the system. The scheduling of resources and the communications between M2M devices are also key concerns for SWIPT [17-18]. More significantly, the addition of active RF transmission components results in a rise in both the cost of the devices and the complexity of their circuits. It's possible that anything like this wouldn't work well for low-cost and large-scale wireless communications networks. ABCS is presented as an additional option for solving the problem in order to considerably boost the network's performance. As can be seen in Table I, despite the fact that a great number of studies published in the past have concentrated on WPT, WPCN, and SWIPT, there is not a single one that looks at ABCSs.

B. Backscatter Communications Systems

As seen in Figure 2, monostatic backscatter communications systems (MBCSs), broadcast backscatter communications systems (BBCSs), and acoustic backscatter communications systems (ABCSs) are the three primary categories that can be utilised to categorise backscatter communications systems.

Systems for Monostatic Backscatter Communications: As can be seen in Figure 2, an MBCS, also known as an RFID system, is comprised of two primary elements: a backscatter transmitter, also known as an RFID tag, and a reader (a). A radio frequency (RF) source and a backscatter receiver are both contained within the same apparatus that makes up the reader. The tag can be activated by RF signals that are generated by the RF source. After that, in order to send its data to the backscatter receiver, the backscatter transmitter modulates and reflects the RF signals that are being delivered from the RF source. Since both the RF source and the backscatter reception are located on the same device, namely the tag reader, the modulated signals may experience a round-trip route loss [19]. This is because the RF source and the backscatter receiver are located on the same device. In addition, MBCSs may experience difficulties due to the doubly near-far dilemma. In particular, because of signal loss from the RF source to the backscatter transmitter, and vice versa, if a backscatter transmitter is located far from the reader, it can experience a higher probability of energy outage and a lower modulated backscatter signal strength [20]. This is because of the signal loss that occurs in both directions. The MBCSs are typically implemented for RFID applications that have a short range.

Systems for Bistatic Backscatter Communications: In a BBCS, as opposed to an MBCS, the radio frequency (RF) source, also known as the carrier emitter, and the backscatter receiver are physically separated, as depicted in Figure 2. (b). Because of this, BBCSs are able to avoid the round-trip route loss that MBCSs experience. In addition to this, the performance of the BBCS can be significantly improved by positioning carrier emitters in strategically advantageous areas. To be more specific, a single centralized backscatter receiver can be deployed anywhere in the field, and many carrier emitters can be strategically positioned around backscatter transmitters. As a direct result of this, the entire field coverage can be increased. Additionally, the doubly near-far problem can be solved by having backscatter transmitters derive unmodulated RF signals from adjacent carrier emitters in order to collect backscatter data and energy [20]. This will allow the problem to be solved. Due to the straightforward nature of the component designs, BBCSs have lower production costs than MBCSs do for both their carrier emitters and their backscatter receivers [21]. This is despite the fact that carrier emitters are cumbersome and their deployment is expensive.

Systems for Ambient Backscatter Communications: In an ABCS, carrier emitters and backscatter receivers are physically separated in the same way as they are in a BBCS. ABCSs are not the same as BBCSs since, unlike BBCSs, the carrier emitters in ABCSs are available ambient RF sources such as TV towers, cellular base stations, and Wi-Fi APs. This is in contrast to BBCSs, which use dedicated RF sources. As a direct consequence of this, ABCSs hold a number of benefits over BBCSs. First, because ABCSs may make use of RF sources that are already accessible, there is no requirement to deploy and maintain separate RF sources. As a result, both the cost and power consumption of ABCSs can be reduced. Second, by making use of already existing radio frequency (RF) signals, there is no requirement to designate additional frequency spectrum for ABCSs, which means that the usage of spectrum resources can be enhanced. On the other hand, because ABCSs rely on modulated ambient signals for backscatter communications rather than BBCSs, the former have a few disadvantages in comparison to the latter. First, modulated ambient RF signals are unpredictable and dynamic, and they act as direct interference to backscatter receivers. This significantly limits the performance of an ABCS, in contrast to unmodulated ones of a BBCS, which can be easily removed prior to the detection of backscattered signals. Second, because ambient RF sources of ABCSs are not controllable, such as transmission power and locations, the design and deployment of an ABCS to achieve optimal performance is typically more complicated than that of a BBCS. This is because a BBCS is able to better isolate its own transmissions from the interference caused by ambient RF sources.

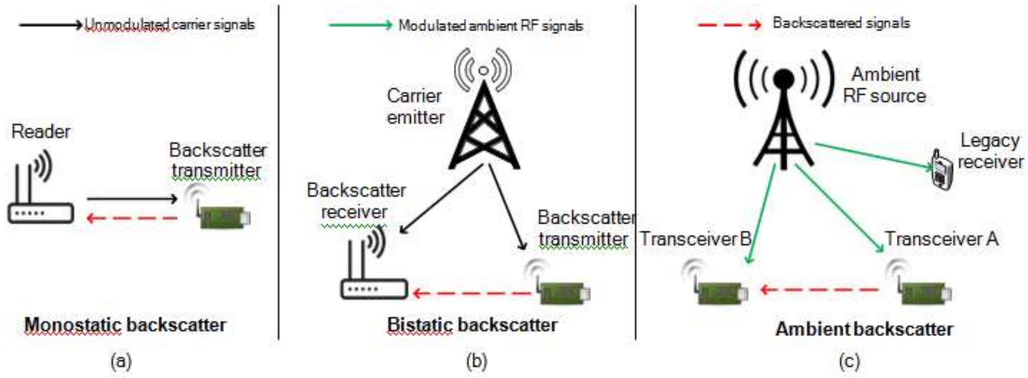

Figure 2: Scenarios for backscatter communications

C. Channel Coding and Decoding

Coding in the baseband, also known as channel coding, is a technique that involves matching the features of a message and its signal representation to the qualities of the transmission channel. The primary objective of the coding process is to assure trustworthy transmissions by shielding the message from being corrupted as a result of interference, collision, or the deliberate alteration of particular signal properties [22]. Decoding the encoded baseband signals is done at the backscatter receiver, which allows for the recovery of the initial message and the identification of any transmission faults.

Conventional coding methods such as non-return-to-zero (NRZ), Manchester, Miller, and FM0 are all viable options for use in backscatter communication systems [22-23].

- In the NRZ code, strong signals are used to represent the bit "1," and low signals are used to represent the bit "0."
- In the Manchester code, the bit value "1" is denoted by a negative transition that takes place in the midst of the bit period. This transition goes from a high level to a low level. At the beginning of the clock, the bit '0' is denoted by a positive transition, which means that the level went from being low to being high.
- In the Miller code, the bit '1' is denoted by a change from high to low levels or low to high levels in the half-bit period, whereas the bit '0' is denoted by a continuation of the bit '1' level into the following bit period [22].
- At the beginning of each symbol in the FM0 code, the phases of all of the baseband signals are flipped over completely. The value of bit 0 changes during the middle of the clock's cycle. On the other hand, throughout the symbol period [24- 25], bit "1" does not undergo any transitions.

Both NRZ and Manchester are examples of straightforward channel coding methods that have found widespread application in backscatter communications systems, particularly RFID systems [22-23]. However, the NRZ code has a limitation in situations when the data that is being transferred contains a long string of bits that are either 1 or 0, whereas the Manchester code requires more bits to be transmitted than those that were included in the original signals. Therefore, existing backscatter communications systems, such as UHF Class 1 Gen 2 RFID, BBCSs, and ABCSs, typically adopt the Miller and FM0 channel coding techniques due to the numerous benefits that they offer [12], [25-27]. Some of these benefits include improved signal reliability, reduced noise, and ease of use.

However, considering how quickly backscatter communications systems are developing in terms of application, technology, and scale, it is possible that traditional channel coding methods will not be able to fulfil the requirements that are currently being established. These requirements include high data rates, a long communication range, and robustness. As a result, a number of innovative coding strategies have been developed. In the paper [53], the authors provide an orthogonal space-time block coding (OSTBC) with the goal of increasing the data rate of RFID systems while maintaining their dependability. The objective behind the OSTBC, also known as multiple-input multiple-output technology, is to send data via a number of different antennas that are orthogonal to one another. This particular channel coding method is responsible for the transmission of several symbols at the same time, which are then broken up into block codes and dispersed throughout space and time. As a result of this, the OSTBC is able to attain a maximum diversity order with linear decoding complexity, which results in an improvement in the system's overall performance. The authors of reference [54] point out that the FM0 coding that is used in the ISO 18000-6C standard for UHF RFID tags is straightforward, but there is a possibility that it does not achieve maximum throughput. After that, the authors suggest using a balanced block code in order to boost the throughput while keeping the complexity of the system to a minimum. In order to accomplish this goal, the balanced block code does the calculation necessary to determine the frequency spectrum for each of the resultant balanced codewords2. After that, the codewords that exhibit the most profound spectral nulls when subjected to direct current are chosen and allotted to a Grey-coded ordered set of the input bits. The current codeword and the neighbouring codeword are switched if the Hamming distance between the codeword and its non-adjacent neighbour is lower than that between the codeword and its adjacent neighbour. As a direct consequence of this, the currently selected codeword is positioned next to the neighbour that is not adjacent to it. By following these steps, you will reach a local optimal solution that reduces the number of bit mistakes. According to the findings of the experiments, the utilisation of balanced block coding resulted in a fifty percent increase in throughput in comparison to the utilisation of conventional channel coding methods such as FM0.

In BBCSs, an efficient encoding technique known as short block-length cyclic channel code was developed [25] to deal with the interleaving of backscatter channels. This was done so that the BBCSs could better handle the situation. In specifically, this method encodes data by coupling the code with polynomials, and it does so on the basis of the idea underlying the cyclic code [26]. Therefore, a straightforward shift register may be utilized to produce this short block-length cyclic channel code in a manner that is both effective and efficient. The findings of the experiments indicate that the encoding method that has been suggested is capable of supporting communication ranges of up to 150 metres. The authors of [27] present code, a low-power encoding approach, with the intention of expanding the communication range of ABCSs and ensuring that concurrent transmissions take place. A periodic signal is used to represent the information in code rather than a pseudorandom chip sequence. This allows the information to be more easily understood. If the receiver is aware of the frequency at which the sinusoidal signals are occurring, then it will be able to detect the sent signals at the backscatter receiver without needing to perform any phase synchronization. The authors also point out that the backscatter transmitter is unable to convey sine waves due to the fact that it is only capable of existing in two states, namely the absorbing state and the reflecting state. As a result, a sequence consisting of bits "0" and "1" that alternates periodically is used. Because there is no requirement for synchronization, the complexity of the backscatter receiver, in addition to the energy consumption, is decreased by using code. The authors show, through their research, that 'code provides long communication ranges, which is equivalent to forty times longer than that of standard backscatter communications systems, and also handle many concurrent transmissions'.

D. Modulation and Demodulation

The process of modifying one or more characteristics of carrier signals, such as their frequency, amplitude, and phase, is referred to as modulation. By examining the properties of the signals that have been received at a backscatter receiver and detecting the variations in reception phase, amplitude, or frequency (also known as demodulation), it is possible to recreate the data that was transmitted originally. Table III provides a concise overview of the fundamentals, benefits, and drawbacks, as well as references, of some of the more common modulation schemes used in backscatter communications systems. In general, there are three fundamental modulation schemes that correspond to the changes in the amplitude, frequency, and phase of the carrier signals. These schemes are referred to as amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK). Amplitude shift keying (ASK) is the most common of these three basic modulation schemes (PSK). These modulation methods are frequently used in backscatter communications systems [22], [27-32]; they can be found in citations such as these. In BBCSs, the FSK is the most advantageous option. In particular, due to the fact that many backscatter transmitters in BBCSs are capable of simultaneously communicating with the backscatter receiver, there is a requirement for a multiple access method. Therefore, many works select frequency-shift keying (FSK) and frequency-division multiple access (FDMA) for BBCSs due to the fact that the properties of FSK are a great fit with FDMA [18], [30-34]. In addition, FSK is resistant to both noise and fluctuations in the amplitude of the signal [86]. On the other hand, PSK is mostly used in systems that deal with ambient backscatter [35]. In particular, because it sends data in a relatively small number of radio frequency cycles, PSK is capable of supporting large data rates during transmissions. The authors of [36] examine the difference in performance between PSK and ASK at various angles less than three. According to the findings from the numerical analysis, the quadrature PSK (QPSK) modulation with = /18 achieves the best capacity, whereas the 4-ASK modulation with = /3 provides the least amount of information transmission capacity. A multi-phase backscatter approach is presented for ASK and PSK in [34] as a means of mitigating the phase cancellation issue that can arise. When there is a relative phase mismatch between the carrier signal and the backscattered signal that is received at the backscatter receiver, the phase cancellation problem might occur [34]. The authors observe that the performance of PSK is superior to that of ASK, based on both the simulation and the experimental data. The reason for this is due to the fact that it is possible, in theory, to totally eliminate the phase cancellation by setting the difference between the phases of the two pairs of impedances to a value that falls between 0 and. Utilizing the PSK modulation method is a quick and simple way to accomplish this goal. Backscatter communications systems also make use of a variety of additional modulation methods. According to [29], a passive RF-powered backscatter transmitter that operates at 5.8 GHz and makes use of the n-quadrature amplitude modulation (QAM) technique, namely 32-QAM, is able to produce a data rate of 2.5 Mbps at a distance of 10 centimetres. However, the n-QAM modulation is vulnerable to noise, which ultimately results in a loss of normalized power [79]. The authors of reference [23] quantify the normalized power loss by examining the use of higher dimensional modulation schemes, such as 4-QAM or 8-QAM. This allows them to determine the normalized power loss. The numerical results demonstrate that switching from 2-QAM to 4-QAM leads in a considerable increase in the normalized power loss. In light of this, the authors offer a unique QAM modulation technique, which combines QAM with uneven error prevention in order to reduce the amount of normalized power that is lost. Bits at different levels can be protected by unequal forms of error protection. In particular, bits that are more likely to be corrupted will be afforded a higher level of security, and vice versa. The authors demonstrate that by utilizing the proposed QAM modulation technique, there is a significant reduction in the normalized power loss that can be seen through the numerical findings. To reduce the amount of interference experienced at the backscatter receiver, the authors of [67] propose using minimum-shift keying (MSK), which is a subtype of frequency-shift keying (FSK). The modulation of signals coming from the backscatter transmitter will take place at a variety of sub-carrier frequencies according to the MSK design principle. The authors demonstrate that the MSK modulation technique can considerably limit the collision at the backscatter receiver by the results of their experiments, which show that this is possible. When it comes to the backscatter receiver, it is necessary to be able to recognize modulated signals coming from the backscatter transmitter. In the body of research that has been done, numerous detection strategies have been proposed. Noncoherent detection is the method that is utilized the most frequently among these due to the fact that it is both straightforward and efficient [4, 27], [39-40]. Because noncoherent detection does not require an estimate of the carrier phase, the complexity of the backscatter receiver circuit can be reduced as a result. The ASK and FSK modulation schemes are both compatible with this detecting mechanism's capabilities. The noncoherent detection method, on the other hand, only provides a low bitrate [40]. As a result of this, some works utilize coherent detection in order to achieve a higher bitrate [22, 40]. In contrast to the noncoherent detection method, the coherent detection method calls for information regarding the carrier phase. As a consequence, the coherent detection method calls for a more sophisticated backscatter receiver circuit. Since PSK modulation uses varying its phases to modify signals, coherent detection is typically the method of choice for detecting it. It is also important to note that in ambient backscatter communications systems, since the ambient RF signals are unsure or even unknown, many of the existing works assume that the ambient RF signals follow zero-mean circularly symmetric complex Gaussian distributions. This is important to keep in mind because the ambient RF signals may follow other distributions as well. After that, maximum-likelihood (ML) detectors [92] might be utilised at the backscatter receiver [35, 38] to detect the modulated signals.

TABLE II SUMMARY OF MODULATION SCHEMES

Modulation	Principle	Advantages	Disadvantages	References		
				RFID	BBCSs	ABCSs
ASK	Represent the binary data in the form of variations in the amplitude levels, i.e., high and low voltage, of RF carrier signals	Provide continuous power to backscatter transmitters and enables relatively simple backscatter receiver design [47]	Very sensitive to noise and interference [59]	[60], [61]	[62]	[63], [64]
FSK	The frequency F_C of the carrier signals is switched between two frequencies f_1 and f_2 according to the digital signal changes, i.e., bits '1' and bits '0', respectively	Resilient to the noise and signal strength variations	The spectrum of FSK modulation doubles that of the ASK modulation.	[60]	[4], [19], [20], [30], [55], [65], [66]–[73]	[74], [75]
PSK	The phase of carrier signals varies to represent bits '1' and '0'. Based on the	Allow backscatter transmitters to backscatter data in a smaller	The recovery process is	[61], [76]		[74], [77], [78]–[81]

	number of phases, there are several forms of PSK such as binary PSK (BPSK), quadrature PSK (QPSK), and 16-PSK.	number of radio frequency cycles resulting in a higher data transmission rate	more complicated than other schemes.			
QAM	Convey two analog message signals, i.e., two digital bit streams, by changing the amplitudes of two carrier waves, i.e., two-dimensional signaling Support several forms of QAM such as 2-QAM, 4-QAM, 8-QAM, and 32-QAM	Increase the efficiency of transmissions	Susceptible to noise, require power-hungry linear amplifiers [82]	[83]	[84], [85]	[81]

3. AMBIENT BACKSCATTER COMMUNICATIONS SYSTEMS

In the following part, we will begin by discussing the overall architecture of ABCSs. The currently available strategies for enhancing the performance of the ABCSs are next dissected and analyzed. In conclusion, we will discuss some new uses for ABCSs. The breakdown of ABCSs can be found in Table VI.

A. Overview of Ambient Backscatter Communications Systems

1) Definition and Architecture: The initial ABCS was presented in [12], and since then, it has rapidly developed into an efficient communication solution that can be implemented in a wide variety of wireless applications and systems. ABCSs, on the other hand, enable backscatter transmitters to communicate by utilizing signals from ambient RF sources, such as TV towers, cellular and FM base stations, and Wi-Fi access points (APs). This is in contrast to BBCSs, which require the use of dedicated RF sources. ABCSs have garnered a lot of attention from both academic institutions and businesses due to their role as a facilitator of device-to-device (D2D) interactions [127], [128].

As can be seen in Figure 3, a general ABCS design is made up of three primary parts: I RF sources, (ii) ambient backscatter transmitters, and (iii) ambient backscatter receivers. RF sources are responsible for the generation of radio frequency energy. The transmitter and receiver for the ambient backscatter can be co-located, in which case they are referred to as a transceiver. Static and dynamic ambient RF sources are the two categories that can be used to classify the whole environment's electromagnetic radiation [129]. The transmit power of several RF sources is compared in Table VII, along with the distance between the source and the transmitter.

- Static ambient RF sources: The sources that constantly broadcast RF signals are referred to as static ambient RF sources. Examples of such sources include TV towers and FM base stations. The transmit powers of these RF sources are typically rather high; for example, TV towers can have up to one megawatt of power [129]. There is a wide range of possible distances between a transmitter and an RF source, ranging from several hundred metres to several kilometres [12], [75].

- Dynamic ambient RF sources: Dynamic ambient RF sources are sources that run periodically or sporadically with typically lower transmit power, such as Wi-Fi access points. These sources tend to cause more interference in the surrounding environment. The distance from the transmitter to the RF source is often extremely short, for example, 1-5 metres [79].

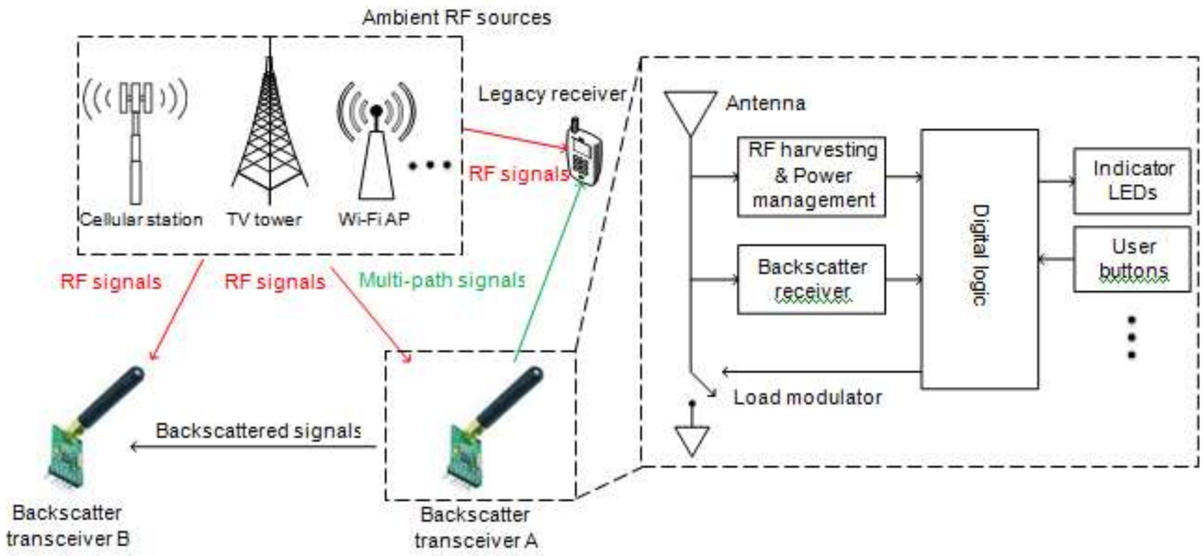

Figure 3: Ambient backscatter communications architecture

2) Ambient Backscatter Design: As illustrated in Figure 3, the authors of [12] design an ambient backscatter transmitter that is also capable of performing the function of a transceiver. A harvester, a backscatter transmitter, and a backscatter receiver are the three primary elements that make up a transceiver. I A backscatter transmitter (ii) A backscatter receiver (iii) Each individual component has its own connection to the overarching antenna. In order to accomplish data transmission, the harvester draws power from the surrounding RF environment and supplies that power to the backscatter transceiver A. After that, the backscatter transceiver A will be able to communicate data to the backscatter transceiver B by modifying and reflecting the background RF signals. Backscatter transceiver A accomplishes this goal by employing a switch that is comprised of a transistor that is coupled to the antenna. A stream of bits including ones and zeros serves as the input to the backscatter transceiver A. Because the transistor is turned off when the input bit is set to zero, the backscatter transceiver A is in the non-reflecting condition in this circumstance. If this is not the case, then the transistor will be active whenever the input bit is set to one, and the backscatter transceiver A will be in the reflecting state as a result. As a result, bits can be sent from backscatter transceiver A to backscatter transceiver B. It should come as no surprise that the backscatter transceiver B can likewise transfer data to the backscatter transceiver A in the same manner.

An averaging mechanism is implemented at the ambient backscatter receiver in ABCSs in order to facilitate the extraction of data that has been transmitted from the ambient backscatter transmitter. When the bitrates of the backscatter signals and the ambient RF signals are sufficiently dissimilar, the backscatter receiver is able to differentiate between the two types of signals and extract the backscattered signals. This is the core concept of the ageing mechanism. Because of this, the backscatter transmitter sends out the backscattered signals at a frequency that is lower than that of the ambient RF signals. As a result, the likelihood that adjacent samples in the ambient RF signals are uncorrelated is higher than the likelihood that adjacent samples in the backscattered signals are uncorrelated. As a consequence of this, the backscatter receiver is able to eliminate the variations in the ambient RF signals while preserving the variations in the signals that were backscattered. Using the two average power levels of the signals that are ambient and backscattered, the backscatter receiver is able to decode the data that is included in the backscattered signals.

It is essential to emphasize the fact that the inputs of the mechanism for averaging are digital samples. Therefore, another obstacle that must be overcome while developing the backscatter receiver is finding a way to decode the data that was backscattered without making use of an analog-to-digital converter, which requires a considerable amount of power. Therefore, the authors in [12] build a demodulator that looks like the one in Fig. 3. (b). To begin, an envelope circuit is used at the receiver to smooth out the signals that have been received. After that, a compute-threshold circuit is used to determine a threshold that lies between the voltage levels of zero and one bits. After that, the output bits are generated by the comparator through a comparison of the average envelope signals with a previously determined threshold.

3) Advantages and Limitations: Because backscatter transmitters in ABCSs can be created with low-cost and low-power components, the system costs as well as the system's power consumption can be greatly reduced [12]. This is made possible by the fact that backscatter can be designed with low-cost and low-power components. For instance, the ambient backscatter transceivers described in [12] contain a number of analogue components. These components include a micro-controller called an MSP430 [41] and an RF switch called an ADG902 [42]. **While** the power consumption of the analogue components of a standard backscatter system, such as the Wireless Identification and Sensing Platform (WISP) [42], is 2.32 W TX and 18 W RX, the power consumption of the analogue components of this transceiver is as low as 0.25 W TX and 0.54 W RX. When ambient RF signals are used, there is essentially no expense associated with the deployment and maintenance of RF sources. Some examples of these sources include carrier emitters in BBCSs and readers in RFID systems. ABCSs make it possible to perform ubiquitous computing as well as direct D2D and multi-hop communications [43,44]. In addition, the only thing that backscatter transmitters in ABCSs do is modulate and reflect the signals that are already present; they do not actively transmit signals in the licensed spectrum. As a consequence of this, the interruption that they cause for users with valid licenses is virtually nonexistent. Therefore, the ABCSs can be deemed to be legal in accordance with the current regulations regarding the usage of spectrum [12], and they do not require specialized frequency spectrum in order to function, which results in a further reduction in the cost of the system.

ABCSs do, however, suffer from a number of shortcomings. ABCSs are susceptible to being affected by the strong direct interference from the ambient RF sources to the backscatter receivers, as the RF spectrum is shared by both of these types of devices. Furthermore, backscatter transmitters rely on environmental radio frequency (RF) signals for both the operation of their circuits and the transmission of data. Because of this, it is typically not possible to control the RF sources in terms of quality-of-service parameters such as transmit power, frequency scheduling, and scheduling of transmissions. A further disadvantage of ABCSs is that the backscatter transmitters are relatively straightforward devices, and the RF sources cannot be managed in any way. This could result in a number of safety concerns. In addition, the amount of energy that can be harvested from ambient RF signals is typically quite low [45], and the fact that these signals can be affected by fading and noise on the communication channels means that the bitrate and communication range between backscatter transmitters of ABCSs are severely restricted.

4. SERIOUS CONCERNS AND PROSPECTIVE GUIDANCE FOR RESEARCH

In this section, we will talk about a few open research challenges, which are issues that have not been completely investigated in the existing study and call for additional research attention.

1) Ambient Signal Heterogeneity

Nearly every form of ambient backscatter transmitter is tailored to the transmission of a particular type of signal, such as Wi-Fi or television broadcasts. On the other hand, in many instances, the signal coming from the particular source is not accessible. As a result, UWB backscattering strategies have been implemented [46]. FM radios, digital TVs, and cellular networks are some examples of the ambient sources that can be used thanks to the approaches that allow the backscatter transmitter to employ a wide variety of ambient sources operating in the range of 80 MHz to 900 MHz. On the other hand, various signals coming from various sources exhibit a variety of distinct properties and patterns. It is essential to improve the backscatter transmission strategies in order to maximize network throughput. One example of this would be combining FM bands and digital TV transmissions.

3) Disruption of Licensed Systems

The transmission of ambient signals from licensed sources is used by many ABCSs. As a result, licensed users may experience interference as a result of backscattering. The authors of [12] demonstrate through experiments that if the ambient backscatter rates are less than 10 kbps, the TV receiver does not observe any apparent errors over distances that are higher than 7.2 inches away. On the other hand, this might not be the case in general, particularly when it comes to high bitrate ABCSs. As a consequence of this, it is essential to exercise caution while modelling interference for ambient backscatter transmitters. To analyze and evaluate the interference to licensed systems, in particular, stochastic geometry models and spatial analysis might be utilized.

4) Network Protocols & Standards

Testbeds and network protocols that are used in ABCSs have, up until this point, been developed for specific reasons and have incorporated proprietary elements. For instance, FM0 encoding is utilized in [12] to lower the amount of energy consumption on backscatter devices, whilst in [46] a multi-bit encoding scheme is adopted to boost the data rate for ambient backscatter communications. Both of these examples can be found in the same article. Because of this, backscatter devices become less interoperable and may even become completely incompatible with one another. For this reason, the development of communication standards and network protocols, such as packet format, network stack, and MAC protocol, is a pressing necessity for future ABCSs.

5) Jamming and Security Concerns

Backscatter communications are susceptible to security flaws such as eavesdropping and jamming since the coding and modulation algorithms that are used are relatively straightforward. Because of the non-active nature of backscatter communications, maintaining backscatter confidentiality might be difficult. On the one hand, any attacker that makes use of active RF transmitters has the potential to be more forceful in their attempt to disrupt the modulated backscatter [47]. Backscatter communications can also be put at risk by assaults launched against the sources of the signals themselves, such as a denial-of-service attack. The lack of available resources in backscatter transceivers also makes it difficult, if not impossible, to apply conventional security solutions such as encryption and digital signatures. Existing research efforts to safeguard secrecy often concentrate their attention primarily on various physical-layer security techniques. For instance, references [48-49] use a technique known as artificial noise injection to protect backscatter communications in RFID systems. This technique is carried out with the assistance of the reader. This strategy, however, cannot be directly used in ABCSs because there are not enough readers who are dedicated to the format. It is absolutely necessary to devise methods that are not only straightforward but also efficient in order to provide secure ambient backscatter communications.

6) Ambient Backscatter based on Millimeter Waves

It has been determined that one of the key enabling technologies for fifth-generation cellular networks is the application of high-frequency millimetre waves, also known as mmWave, for the purpose of high-speed communication. mmWave signals require line-of-sight (LOS) communication channels, as well as compact high-gain antennas and antenna arrays [50]. This is because mmWave signals have different physical characteristics than UHF waves. Recent research published in [51] reveals that MBCSs operating in mmWave frequencies are capable of achieving a backscatter transmission rate of 4 Gigabits per second when using binary modulation. The ABCSs that make use of mmWave have the potential to be developed.

7) Ambient Backscatter based on Full-Duplex

Because devices that generate ambient backscatter may communicate with one another, the full-duplex technique can be applied to ABCSs in order to increase their overall performance. For instance, in [45], the authors present an ambient backscattering system in which the backscatter receiver can send feedback to the backscatter transmitter to warn the emitter of any errors that occurred after receiving the data. Time-hopping full-duplex backscatter communication is presented in reference [46] as a means to simultaneously reduce interference and make it possible to engage in asymmetric full-duplex communication. However, these methods have a number of significant drawbacks, the most significant of which being interference caused by reflections from the nodes equipped with backscatter antennas and inefficient use of the spectrum. Therefore, additional efforts are required to address these concerns in order to make progress.

8) Communications using ambient backscatter and wireless body area networks

Due to its extensive list of advantageous characteristics, ambient backscatter can be utilized to support a wide variety of useful applications for wireless body area networks (WBANs). Recent research published in [52] proposes the design of smart sneakers that can measure both the wearer's heart rate and the number of steps they take. To successfully monitor vital indications like heart rate and respiration rate, the authors of [35] successfully construct smart fabric applications that are based on backscatter communications. In addition, the authors of the study [53] design a sensor that requires a low amount of power and does not require a battery in order to monitor multiple biomedical signals. These signals include respiratory sounds, blood oxygen saturation, heart sounds, blood pressure, and body temperature. The authors accomplish this by implementing a backscatter module that transmits data by making use of ambient RF signals. Despite this, there are not many works that concentrate on this particular line of inquiry. Therefore, additional research on the practical uses of communication protocols, network design, and industry standards is required.

9) Backscatter Communications for Internet of Things

Backscatter communications pave the way for empowering Internet of Things devices thanks to their numerous notable qualities. However, the system's performance may be significantly hindered as a result of interference and double fading effects in large network architectures in which the backscatter devices and RF sources are located randomly in the same area, for example as points of independent Poisson point processes. This can have a negative impact on the system's ability to function optimally. There are a few different ways to approach dealing with this problem. For instance, in [54], the authors examine the coverage and capacity of the network using tools derived from stochastic geometry. Additionally, adaptive transmit multisine waveforms [55] can be utilized to maximize the SNR-energy region for general scenarios, such as those involving multiple antennas and multiple backscatter devices.

7. CONCLUSION

The use of ambient backscatter in today's large-scale self-sustaining wireless networks, such as wireless sensor networks and the Internet of Things, is an exciting development in wireless networking technology. We have provided a complete overview of ambient backscatter communication systems in this post that we hope you find useful. First, we went over the fundamentals of backscatter communications in a variety of various configurations. In addition to it, standard methods of channel coding and modulation were examined. Then, we offered literature studies of bistatic backscatter communications systems, discussing their fundamental principles, advantages, limits, and potential remedies to improve the system's overall performance. Next, we covered the fundamentals of ambient backscatter communications systems in addition to providing an overview of the system's overall architecture. We did a comprehensive analysis of the literature and looked at a number of different state-of-the-art concepts, solutions, and implementations. Additionally, new applications in a variety of fields related to backscatter communications have been covered in this article. In conclusion, we have discussed the practical issues that lie ahead, as well as the future avenues of study.

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