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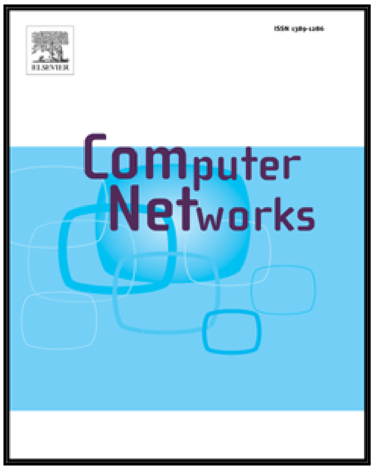

Battery-less Internet of Things –A Survey

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Battery-less Internet of Things âĂŤA Survey

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ABSTRACT

Traditional wireless communication technologies such as Bluetooth and Wi-Fi are used extensively over the last two decades. They offer various advantages like higher data connection rates, good coverage, mobility, expandability, ease of use, etc. However, these traditional wireless communication solutions are expensive and also drain the battery life of devices connected to it. Internet-of-Things (IoT), demands devices that consume very little power and are less bulky. A solution to this is newly emerging passive technology called Ambient Backscatter Communication System. It is a cutting edge primitive that allows wireless communication between the devices by leveraging ambient radio frequency (RF) signals of TV and cellular transmissions. Its competency in consuming very low power during communication brings us closer to the world of IoT and its applications. In this paper, we present a detailed survey of backscatter communication systems. In particular, the fundamentals, architecture and the challenges involved are discussed. Using the multilevel classification framework, we review the major experimental and theoretical work carried out in literature.

1. Introduction

INTERNET of Things (IoT) refers to the interconnection of multiple devices connected through the Internet. The devices are not only limited to desktop computers, laptops, tablets, wearable devices, and smartphones but also involve household appliances and industrial automation solutions. The applications of IoT can be broadly categorized into the following types: transportation and logistic domain, healthcare domain, smart environment domain, and personal and social domain [1]. Presently, the total number of connected devices available globally exceeds 17 billion and the number of IoT devices (this excludes computers, laptops, smartphones and fixed-line phones) exceeds 7 billion. The total number of IoT devices is expected to take a huge leap of up to 22 billion by 2025 [2]. The devices involved in various IoT applications are usually powered by batteries, have limited computing power and are equipped with multiple sensors. These sensors when placed inside the appliances or in dangerous environments (e.g., radioactive area, pressurized pipes) makes battery recharging or replacement a challenging task [3]. The machine to machine (M2M) communication, communication between multiple devices connected in IoT is usually performed using various wireless standards such as Zigbee (IEEE 802.15.4), Wi-Fi (IEEE 802.11), Bluetooth (IEEE 802.15.1), Bluetooth Low Energy (BLE), Wi-Max (IEEE 802.16) and Low Rate Pulse-Ultra Wide Band-Physical (LRP-UWB-PHY). These standards consume power in hundreds of mW. Fig. 1 shows the power consumption by different popular wireless communication standards and Fig. 2 represents the data rate achieved by them.

To overcome this power consumption problem, one of the solutions is to use low power backscatter communication (BackCom). BackCom refers to a communication technique that works on the principle of modulated signals that are reflected back from an RF receiver. The concept of BackCom was first introduced by Stockman in the year 1948 [6]. Therein the methodology of using reflected power for the communication was presented. In this paper, BackCom is used for identifying the presence of the target in the vicinity of the radar. In a backscatter communication system, the communication is done by simply reflecting the received RF signals instead of generating the RF signals by itself [7]. BackCom can be broadly classified into the following three categories: A) Monostatic BackCom System (MBCS), B) Bistatic BackCom System (BBCS), C) Ambient BackCom System (ABCS). These BackCom systems are explained in section 2. The example of the MBCS is radio frequency identification (RFID). The key difference between BBCS and

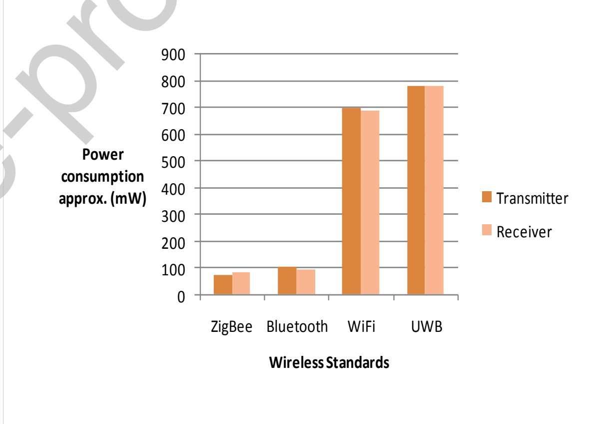

Figure 1: Power consumption by different wireless communication standards [4].

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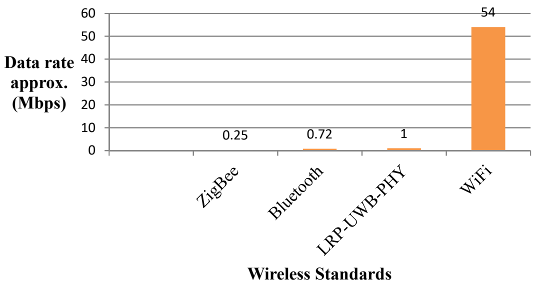

Figure 2: Data rate of different wireless communication standards [4]. The LRP-UWB-PHY standard has a data rate of 1 Mbps [5]

MBCS is that in MBCS the carrier emitter and information receiver are located at the same node while in BBCS these two entities are positioned at separate nodes. These three different BackCom systems are explained further in detail in section 2. The RFID is based on modulated back-scattering of radio waves. A typical backscattered RFID system comprises RF transponder (tag), RF base station module (reader) and a computer controller [8]. A tag consists of a microchip and a coil (antenna). The antenna gets the power and RF signals from the RFID reader. These signals are internally processed by the microchip and are sent back to the reader. The tags are commercially available in two types: active and passive. An active tag is powered by a dedicated battery, whereas a passive tag rely on the reader for its power requirement. Along with being a power hungry, the RFID system also suffers from three major limitations: A) The backscatter transmitter is activated by external power supply (e.g., reader) which is costly and bulky. B) A backscatter transmitter initiates the communication only when inquired by the reader. C) The signal reflected by the backscatter transmitter could be interfered by adjacent active readers [9]. To overcome these limitations and also for utilizing the potential in IoT to its fullest, we need to deploy sensors and actuators which work for lengthy duration that too by consuming very minimum power.

This can be achieved with ABCS, the work of which is based on RF signals present in the surrounding area. Particularly, here the backscatter transmitter communicates with the backscatter receiver by harvesting the energy from RF signals and then modulating and reflecting the surrounding RF signals. Thus ambient backscatter technique bypasses the need of using dedicated infrastructure e.g., reader for generating the RF signals. Also, it does not consume any additional energy except the one which is present in the air. Another advantage of the ambient backscatter communication system is that RF components are minimized to a great extent as carrier emitter and backscatter receiver are separated. In spite of so many advantages, the ambient backscatter communication system goes through a lot of challenges that come under communication and networking perspective.

The existing literature focuses on various challenges and technological advancements in this new and exciting field of ambient backscatter communication. For a detailed discussion on various techniques in backscatter communication, readers are encouraged to refer to the work by [10], [11]. Authors in [10] have discussed the basics and provided complete details of various techniques in BackCom. Xu *et al.* [11] discussed the practical aspects of BackCom. Also, the real world applications that are based on BackCom are highlighted.

Our contribution is focused on three principal axes. The first one is evolution of backscatter communication systems. Secondly,this survey specifically gives the various methodologies a detailed categorization that is not found in other surveys. The paperâĂŹs final contribution is to identify upcoming trends and technological developments in the field providing crucial insights into battery-less IoT.

In general, this paper aim is to represent evolution of backscatter communication systems and how they are useful in making battery less technology a reality and this is attempted through extensive projection on the following steps:

- The development of backscatter communication methods and the difference between their architectures is discussed.
- An in-depth survey of various BackCom systems is presented by highlighting recent work in the literature.
- Emphasized the importance of new technologies in BackCom. Also addresses the forthcoming developments in terms of use of visible light, mm-Wave, relay network in BackCom systems.
- By providing brief comparative summary of various schemes in BackCom systems.

This paper is organized as follows. In Section 2, we introduced different types of modulated BackCom along with their conceptual representation, followed by basic principles of BackCom. In Section 3, we present a review of research methodologies in the BackCom. In section 4, we provide an overview of the emerging BackCom systems and discuss the open research issues in section 5. Finally, we conclude the paper in section 6.

2. Modulated Backscatter Communication Systems

2.1. BackCom Systems

Any backscatter communication system consists of three main components, i.e., backscatter transmitter, backscatter receiver and carrier emitter. A carrier emitter is an RF signal source. The backscatter transmitter is basically a tag that modulates and reflects back the incoming signal from carrier emitter towards the backscatter receiver. The receiver can further decodes this backscattered signal. Depending

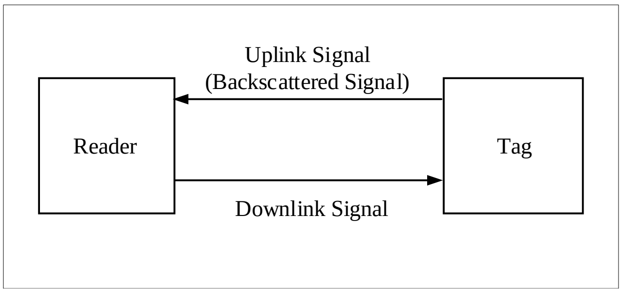

Figure 3: Monostatic Backscatter Communication System.

upon the type of carrier emitter and also on its position the backscatter communication systems are classified into three categories. Fig. 3, 4 and 5 illustrates the conceptual representation of these three categories.

2.1.1. Monostatic Backscatter Communication Systems

It consists of two major components: a tag and a reader. The carrier emitter (RF source) and a backscatter receiver are equipped within the same reader. In this system a tag is first activated by sending RF signals from a source. These signals are modulated by the tag and are reflected back to the receiver. This kind of communication system suffers from the problem of round trip path loss as the backscatter receiver and RF source are located onto the same device (reader) [12]. Another limitation of this communication system is the fact that it gets affected by doubly near-far problem, where the users that are near to the RF source can extract more energy and and yield higher throughput as compared to the users that are located at farther distance from the RF source [13]. MBCS is used for small distance communication.

2.1.2. Bistatic Backscatter Communication Systems

As mentioned earlier, in BBCS the RF source and backscatter receiver are separated from each other as shown in Fig. 4. This helps in overcoming the limitation of round trip path loss. Separating the RF source and backscatter receiver makes way for increasing the efficiency by placing the RF sources variety of optimal locations. A more flexible communication network can be set up using a bistatic configuration. Also, the communication range can be increased compared to a monostatic counterpart. It also helps in reducing the effect of doubly near-far problem as backscatter transmitters extract the energy from RF signals sent by nearby carrier emitters and backscatters the data. Proper deployment of RF sources is a matter of costly affairs but because of simplicity in design, the BBCS is more cost-effective than MBCS [14].

2.1.3. Ambient Backscatter Communication Systems:

This configuration is almost similar to BBCS. However, instead of using a dedicated carrier emitter, an existing carrier emitter available in the surrounding like a TV tower, Wi-

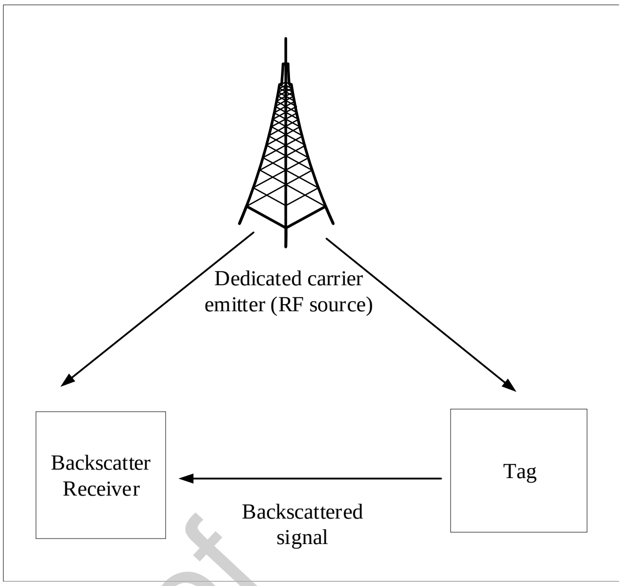

Figure 4: Bistatic Backscatter Communication System.

Fi access point, cellular base stations, frequency modulation (FM) tower, etc are used as shown in Fig. 5 [15]. Here these ambient RF signals are first received by the tag. Tag then harvest the power from these ambient RF signals to modulate their information. And further tags transmit their bits towards the receiver. This configuration posses certain advantages compared to the previous two. Firstly, the cost as well as power consumption is reduced as there is no need to install and maintain the dedicated RF source. Also, the spectrum utilization is more efficient as it does not require new frequency spectrum allocation. However, as compared to BBCS, the ABCS is less stable and inconsistent. This is because the ambient RF signals have natural variations and hence they are dynamic in nature. Also, the tag may cause interference to the legacy receivers present in the close vicinity from the tag.

2.2. Fundamentals

The main difference between the conventional wireless communication system and a modulated backscatter communication system is that the modulated backscatter communication system does not generate their RF signals. Instead, it receives the RF signals from ambient sources and reflects the signals towards the backscatter receiver by tuning its antenna impedance. The backscatter transmitter piggybacks its symbols which are to be transmitted on to the backscattered waveform by adjusting the load impedance. The antenna reflection coefficient is given by [16]:

$$\Gamma_i = \frac{Z_i - Z_a^*}{Z_i + Z_a}. \tag{1}$$

where Z_a represents antenna impedance, $*$ represents complex conjugate operator and $i = 1, 2$ indicates switching

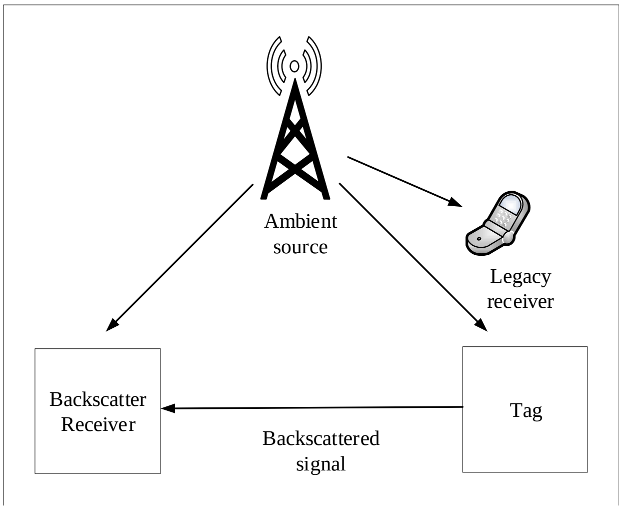

Figure 5: Ambient Backscatter Communication System.

state. The antenna reflection coefficient toggles between absorbing state and reflecting state by switching between the loads as shown in Fig. 6. Absorbing state means there is impedance matching and RF signals are absorbed. This state is represented by bit âĂŸ0âĂŹ. As against this, reflecting state means there is impedance mismatching and RF signals are reflected. This state is represented by bit âĂŸ1âĂŹ. Thus in the reflecting state, there is the superposition of the original RF signal and backscattered signal at the receiver. During absorbing state only the original signal will be present at the receiver. The signal received at the backscatter receiver can be decoded in two ways: (i) using Analog to Digital converter (ADC) and (ii) using Averaging mechanism. Decoding the backscattered signals at the receiver is a challenging task because ambient signals are already in encoded form and piggybacking the backscattered signals over it is a difficult task. Also decoding them using ADC requires a large amount of power and hence in [7] authors designed an ultra-low-power receiver using only analog components. To communicate on a frequency other than carrier frequency, shifting operation is performed together with modulation operation by multiplying the carrier signal with the square wave produced by a backscatter tag. Let the frequency of this square wave is denoted by required offset $\triangle f$, between the carrier frequency f_c and the desired frequency [17]. The square wave is given as,

$$S_{tag}(\triangle ft) = \frac{4}{\pi} \sum_{n=1,3,5...}^{\infty} \frac{1}{n} \sin(2\pi n \triangle ft). \quad (2)$$

By multiplying the carrier signal $S_c = \sin(2\pi f_c t)$ with the square wave given by equation (2), the resultant signal r(t)

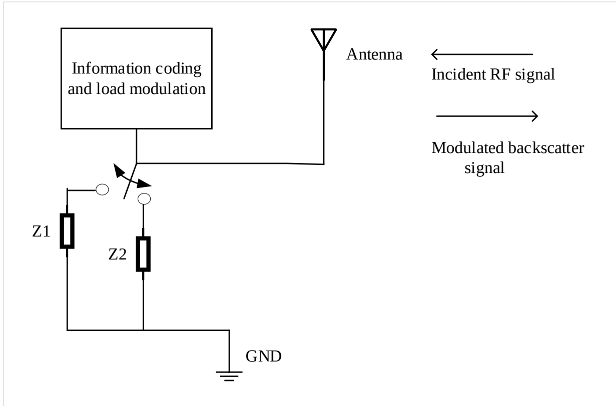

Figure 6: Ambient Backscatter Communication System Transmitter [14].

leads to equation (3) as,

$$\begin{aligned} r(t) = S_c \times S_{tag}(\triangle ft) &= \sin(2\pi f_c t) \times S_{tag}(\triangle ft) \\ &= \frac{2}{\pi} \sum_{n=1,3,5...}^{\infty} \frac{1}{n} [\cos(2\pi(f_c - n \triangle f)t)] \\ &\quad \times [\cos(2\pi(f_c + n \triangle f)t)] \end{aligned} \quad (3)$$

The backscattered signal is therefore moved to the desired frequency $f_c + \triangle f$ and its copy to the frequency $f_c - \triangle f$.

3. State-of-the-Art Methodologies in Literature

In this section, we discussed various methodologies present in literature to make battery-less wireless communication a reality. Research in the BackCom system given in literature can be classified as shown in the tree diagram given in Fig. 7.

3.1. Signal Processing in BackCom:

In this subsection, we highlight encoding and data extraction policy in BackCom by considering various channel coding and decoding, interference and detection schemes.

1) Channel coding: Similar to the conventional wireless communication, the channel coding techniques acts like the heart of modulated backscatter communication system. The main intention of channel coding is to safeguard the message from errors (due to collision, interference and changes in the certain signal characteristics) and improve the efficiency of BackCom [18]. Like traditional wireless communication, the signal is encoded in BackCom before the transmission begins, so that the missing data can be retrieved via noisy networks. The channel coding schemes available for traditional wireless communication are computationally expensive as well as consumes high amount of power.So EPC Gen-2 standard suggests two encoding schemes for BackCom: (i) Miller code

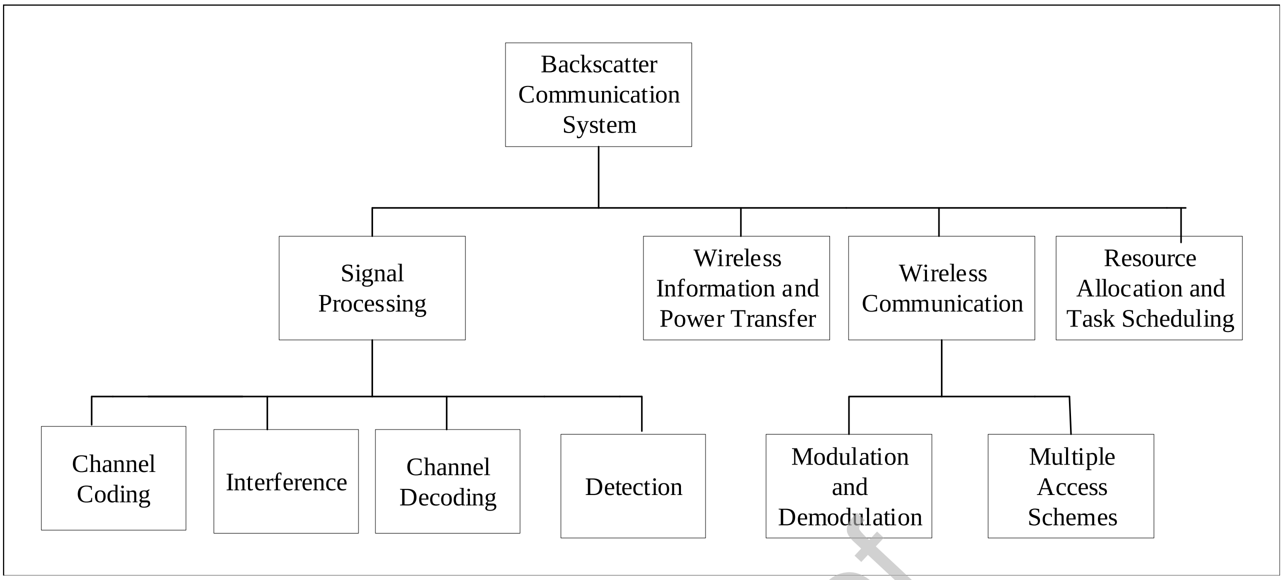

Figure 7: Broad areas of research in BackCom

and (ii) FM0 code. These two coding techniques offer advantages such as simplicity, noise reduction and improved signal reliability [19] [20] [21]. Other coding techniques like NRZ and Manchester are also widely used in RFID systems.

The NRZ and Manchester coding techniques have certain disadvantages such as more bits are required than the original signal in Manchester codes and NRZ code transmission consists of a long length of âĂŸ1âĂŹ or âĂŸ0âĂŹ bits. The channel coding scheme for BackCom should have low complexity, less power consumption and have minimal cost. Durgin and Degnan [22] demonstrate the application of high rate channel codes to RFID link and increase the throughput by minimum 50 % without increasing power consumption, cost and complexity. To this end, authors proposed a balanced block codes that increase the throughput by maintaining the simplicity. In [23] authors show that using proper combination of channel coding and modulation schemes, the energy harvesting is done in more efficient manner.

The coding method based on Run-length limited (RLL) codes is proposed in [24] to avoid the Doppler spread interference in backscatter channel. The proposed framework can work with any shape waveform available at reader. This RLL code based technique is able to take away the signal from clutter interference and also provides tradeoff between data rate and interference rejection. It can be seen from the results that with RLL codes, reducing the data rate, the interference rejection ratio can be improved. The cyclic code based coding technique namely short block length cyclic error correcting code for coherent detection is proposed by Hilliard *et al.* [25] to increase the range of communication for BBCS. The experimental observation shows that the proposed encoding technique increases the tag-reader communication range up to 150 meters with a power consumption of 20 mW. Authors in [26] demonstrate the use of low complexity small block-length channel codes for non-coherent reception in BBCS. In this work, the composite hypothesis testing decoding rule is designed which helps to achieve high diversity order through interleaving.

Several research works in literature consider that tag can operate in three states i.e., not-reflecting, reflecting in same phase and reflecting in opposite phase [27]. Thus tag reflects eight states with three binary symbols. To extract the information from ternary coded signals, a maximum *a posteriori* (MAP) detector is also designed. Experimental results show that the MAP detector is also able to detect the signals encoded in traditional manner (i.e., two state representation of tags). Parks *et al.* [28] implemented a low power consuming Âţcoding scheme which makes long range communication and parallel transmission of data feasible without increase in power consumption. The decoding of the signal is made purely using simple analog components. Authors built hardware prototype for multi antenna, μcoding schemes and achieve increase in range and data rate of the communication. Particularly the data rate and range is increased by 100X and 40X respectively.

Tao *et al.* [29] proposed the method based on Manchester coding and differential Manchester coding. In passive RFID the Manchester coding is widely used in which âĂIJ0âĂİ and âĂIJ1âĂİ is mapped to âĂIJ01âĂİ or âĂIJ10âĂİ. In [29] âĂIJ0âĂİ is is mapped to âĂIJ10âĂİ and 1 to âĂIJ01âĂİ. The differential Manchester code follows a simple change rule. When there is a change between present bit and previous bit, then the bit is denoted by âĂIJ1âĂİ otherwise by âĂIJ0âĂİ. Conceptual representation of Manchester code and differential Manchester code is shown in Fig. 8. Unlike traditional wireless communication system, the requirements of BackCom systems such as high data rates, robustness etc cannot be fulfilled by conventional channel cod-

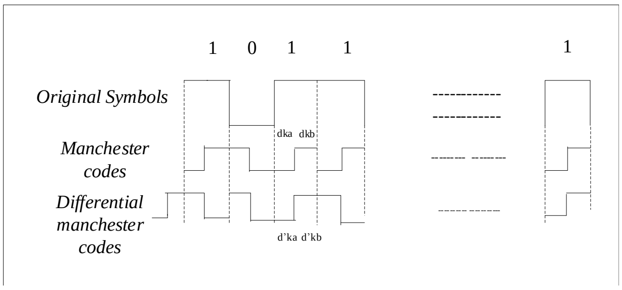

Figure 8: Conceptual representation of Manchester and Differential Manchester coding where dka and dkb represents first and second half of the Manchester code for kth binary symbol and dâĂŹka and dâĂŹkb represents first and second half of differential Manchester code for kth binary symbol.

ing schemes and hence novel coding scheme named orthogonal space-time block code (OSTBC) is proposed in [30]. Therein, OSTBC is used for dyadic backscatter channel with more than one antenna at both tag and reader. Experimental results suggest that multiple antennas at receiver makes the impact on coding gain and signal-to-noise ratio (SNR) threshold which ultimately decides the diversity order.

Table 1 represents the summary of channel coding techniques in a BackCom system.

The conclusion and key observation on the considered channel coding techniques are summarized as follows:

- For high data rate in limited bandwidth scenario 6/8 channel block code are preferable.
- Cyclic error correcting codes with short length are preferred to improve throughput when carrier wave (CW) is far from reader.
- The standard coding scheme used in RFID is FMO and Miller codes and they have maximum rate of one half.
- Communication range can be increased by using concurrent transmissions instead of serial transmissions. Nonetheless, doing so more space is consumed because of multiple antenna requirements.

2) Interference in BackCom: In particular, the ABCS makes use of ambient signals present in the surrounding. As a result, there may be interference and collision of these ambient signals with nearby legacy receivers. Chen *et al.* [31] analyzed the bit error rate (BER) performance by considering the interference of ambient signals to legacy receivers. Simulation results show that BER performance depends upon, distances and angles between the tag, the radio frequency (RF) source, and the legacy receiver. The authors calculate the minimum and maximum range of interference and found it to be 0.1 meters (when channel state information is known) and 12 meters (when channel state information is partially known) respectively. In [32] the authors proposed the anti-collision algorithm for FM0 code and Miller subcarrier sequence to find the location of bit collision. Numerical results

Table 1
summary of channel coding techniques

References	Schemes	Advantages	Remarks
Durgin *et al.* (2017) [22]	Balanced block codes	Increases the throughput by 50%	Power consumption, cost and complexity remains low.
Boyer *et al.* (2014) [23]	Coupled coding and modulation	Efficient energy harvesting and improved data rate.	New channel model 'dyadic backscatter channel' is proposed.
On *et al.* (2017) [24]	Run-length limited	Avoids the doppler spread interference.	reducing the data rate the interference rejection ratio can be improved.
Hilliard *et al.* (2015) [25]	short block length error correcting code	Increases the communication range for bistatic(150 m with 20mW power consumption	20 mW power consumption is still high.
Alevizos *et al.* (2015) [26]	Block length	High diversity order.	composite hypothesis testing decoding rule.
Parks *et al.* (2015) [28]	μcoding	parallel transmission over a long distance.	Hardware prototype is built that has data rate 100 X and range 40X.
Tao *et al.* (2018) [29]	Manchester coding and differential manchester coding	No need to estimate decision threshold and avoids the delay.	Its more practical as it considers information bits to be not equiprobable.
Boyer *et al.* (2014) [30]	Orthogonal space âĂŞtime block code (OSTBC).	High data rate and robust.	Used for 'dyadic backscatter channel'.

show that the throughput of the algorithm is 0.5 for both the FM0 code and Miller code and 0.35 for the traditional binary tree algorithm.

Future IoT communications will be amongst billions of devices connected on a single platform which reduces latency but also mark up the chances of interference. Therefore, Liu *et al.* [33] proposed a full-duplex BackCom to mitigate the effect of interference. The proposed scheme allows the energy transfer for each symbol as well as enables wireless energy harvesting from interference. Authors in [34] discussed the in-band full-duplex (IBFD) scheme which increases the throughput of the wireless communication system but at the cost of self-interference. In self-interference, the IBFD node's transmissions interfere with the desired recipient. Interference also depends upon where the devices are located. One of the concerns of interference is âĂIJdoubly near-farâĂİ problem [35]. In this, the devices which are located close to the RF source, harvest more energy than

Table 2
summary of Interference

References	Schemes	Advantages	Remarks
Chen *et al.* (2017) [31]	Presented the theoretical model for impact of interference on BER.	Simple.	BER depends on distance and angle between tag, source and receiver.
Kim *et al.* (2018) [32]	Proposed algorithm for FM0 code and Miller subcarrier sequence.	Higher throughput than traditional binary tree algorithm.	Throughput is 0.5 for both FM0 and Miller code.
Liu *et al.* (2017) [33]	Full duplex BackCom model.	Reduce latency and enables efficient spectrum utilization.	allows the energy transfer for each symbol as well as enables wireless energy harvesting from interference.
Sabharwal *et al.* (2014) [34]	In-band full-duplex (IBFD) scheme	Increases the throughput.	The IBFD node own transmissions interferes with desired reception and causes Self interference.
Bekkali *et al.* (2014) [36]	Impact of interference on performance of UHF RFID system is studied.	Two types of interference, R2R and R2T.	R2R interference causes increase BW usage. R2T Causes tag jamming.

those devices that are located at a far distance from the RF source. So the devices located at a far distance need high power to reach up to the required value of SNR than their counterparts.

Bekkali *et al.* [36] studied the interference effect in RFID systems. Interference in RFID can be of two types: (i) reader to reader (R2R) interference and (ii) reader to tag (R2T) interference. R2R interference results in improper signal detection and also leads to an increased bandwidth usage as well as it causes security risks. R2T interference also causes the problem of tag jamming. Cutler *et al.* [37] investigated passive RFID systems for three types of electromagnetic interference (EMI) namely impulsive continuous wave, Gaussian and Rayleigh EMI. The RFID system is affected most by Rayleigh EMI and least by impulsive EMI. Table 2 summarizes the most critical interference effects in BackCom system.

The conclusion and key observation on review of interference is given below.

- Use of ambient RF signals causes interference with legacy receivers.
- Interference cancellation requires complex analog circuits and algorithms and hence may not be suitable for IoT applications. Thus suppression of interference should be taken into consideration.
- Use of IBFD increases the throughput but it also results in self interference.
- Interference also results in the Near-Far problem.

Table 3
Summary of Channel Decoding

References	Schemes	Advantages	Remarks
Alevizos *et al.* (2015) [26]	composite hypothesis testing	Achieves higher diversity.	Computational complexity is less compared to ML.
Ou *et al.* (2016) [38]	parallel decoding	synchr-onization among tags and accurate channel estimation is not required.	BiGroup is implemented with USRP N210 software radio .
Jin *et al.* (2017) [39]	Flip Tracer-parallel decoding	Performs well in dynamic backscatter environment.	Data rate of 2 Mbps.

3) Channel Decoding: The signals backscattered from tag towards the reader are low power signals and hence decoding (extracting the information) such signals is a crucial task. Parallel decoding of the concurrent tag transmissions requires strict synchronization among the tags and accurate channel estimation. Ou *et al.* [38] presented the parallel decoding scheme for commodity-off-the-shelf (COTS) RFID tags that can decode packet collision from COTS tags without the above-mentioned constraints. Therein, the COTS tags do not require co-ordination to join the ongoing communications. Many parallel decoding techniques in the literature assume that backscattered signals from tag are highly stable and hence do not perform well in dynamic backscatter systems [39]. Hence, authors in that paper presented a parallel decoding scheme named Flip Tracer for highly dynamic backscatter systems. This technique can achieve a throughput of 2 Mbps. In [26], the authors presented a decoding rule named *composite hypothesis testing* for the proposed non-coherent scheme. Table 3 summarizes the channel decoding techniques in BackCom systems.
The conclusion and key observation on reviewing of channel decoding is presented as follows:

- The decoding standard should be fast, less power consuming.
- It should not require perfect channel state information (CSI).

4)Detection in BackCom: Typically, the transmitted signal in BackCom is not statistically stationary or a deterministic signal. This is because it gets affected by noise while commutating from transmitter towards the receiver. Thereby, for detecting such signals a proper signal detection scheme is

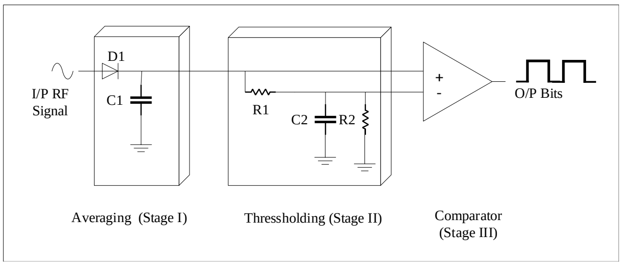

Figure 9: Circuit diagram for signal detection in BackCom .

required which correctly detects the signal with quite low power consumption. In [7] the authors proposed a multiple-stage detector circuit which consists of averaging, thresholding and comparator stages as shown in Fig. 9. The signal detection part has three stages: the first stage produces an average envelope of the signal, the second stage computes the threshold and the last stage compares the averaged signal with a threshold value.

The signal detection schemes mentioned in literature can be broadly classified into two types: (i) Coherent detection, and (ii) Non-coherent detection. Coherent detection needs carrier phase information at the receiver and they use matched filters to detect and decide which data was sent. In phase-shift keying (PSK) modulation, the phase is varied to modulate the signal and hence for PSK modulation the coherent detection is preferred.

In [25] authors experimented with the coherent detection scheme for the BBCS. Use of coherent detection techniques in bistatic BackCom is challenging task because it involves signal reception over three channels (i.e., between RF source and reader, between RF source and tag and between tag and reader) unlike single channel in traditional point to point communication. Also, the coherent detection becomes more difficult because of certain parameters like antenna structural mode, antenna reflection coefficients, scattering efficiency.

Many works in literature use non-coherent method for signal detection. Unlike coherent detection, non-coherent detection does not need phase information and hence when phase information is not available easily one can use non-coherent method of signal detection. In non-coherent detection, the methods of square law detector is used to recover the data. Unlike PSK, amplitude-shift keying (ASK) and the frequency-shift keying (FSK) modulation prefers non-coherent detection. Qian *et al.* [40] proposed the model for non-coherent detection of backscattered symbols with unknown CSI. They also derived the maximum likelihood detector and energy detector using the joint probability distribution function (PDF) of the received signal. The blind method is proposed in this paper with which the parameters required by all detectors can be obtained. The conventional energy detectors (ED) get affected because of the presence of co-channel *direct link interference* (DLI) from existing legacy receivers.

The process of non-coherent detection of backscattered signals as used in [41] is explained below. In this paper, authors investigated the binary frequency shift keying (BFSK) over ambient OFDM signals using non-coherent detection. The system model consists of legal OFDM transmitter and receivers, tag and reader. The signals transmitted by legacy transmitter can be received by legacy receivers as well as by readers. The complete signal received at reader is composition of direct signal and backscatter signal, and is given by,

$$y(t) = [\alpha x(t)b(t)] * g(t) + s(t) * f(t) + w(t) \tag{4}$$

Tag reflects the signals towards Reader and hence at any instant there are two signals at Reader. A detector is designed at Reader, to detect the backscattered signal.The two test statistics based on upper and lower guard subcarriers used at detector are given as

$$E_u = \frac{2}{\sigma_w^2} \sum_{m \in U} |Y[m]|^2, \tag{5}$$

$$E_l = \frac{2}{\sigma_w^2} \sum_{m \in L} |Y[m]|^2. \tag{6}$$

Based on these test statistics, the detection rule is defined as

$$\begin{aligned} \hat{B} &= 0, E_u > E_l, \\ \hat{B} &= 1, E_l \geq E_u. \end{aligned} \tag{7}$$

In this way using above test statistics we can estimate the received bits.

Guo *et al.* [42] proposed error-floor-free detectors using multiple receive antennas at the reader. In this work, the two energy detectors, one based on beamforming and the other on likelihood- ratio are proposed. These two detectors assume that perfect CSI is available at the reader. However, when CSI is not available then a clustering framework based method is proposed for symbol detection. In [12], the authors presented the method of signal detection at the reader in which they use differential encoder at the tag that does not require training symbols. They also formulate a theoretical system model that does not require CSI and based on this model two detection thresholds were proposed. Lu. *et al.* [43] proposed the theoretical model for uplink signal detection in a system that consists of one tag and one reader. Here the authors designed two detectors out of which the second one has equal error probability in detecting “0” and “1”.

The need for estimating the decision threshold for symbol detection was studied in [29]. In that work, the authors designed semi-coherent Manchester (SeCoMC) and non coherent Manchester (NoCoMC) detectors with lower communication delays. They derived BER expressions for both the detectors and found that the SeCoMC detector outperforms the NoCoMC detector. Also, these detectors work well even if the information bits are arbitrarily distributed. Devineni and Dhillon [44] investigated the signal detection at the reader using binary hypothesis testing. Hence, they used three detection techniques: a) *mean threshold* (MT), b) *maximum likelihood threshold* (MLT), and c) *approximate MLT*. Here the signal detection is done in two parts, firstly when CSI is available and secondly when it is not.

A semi-coherent detection based approach is presented in [45] in which CSI is not known and detection parameters are estimated using few training symbols instead of estimating the channels. Kim and Lee [46] proposed a flicker detector scheme that detects the symbols using the residual channel of Wi-Fi packets. Zhang *et al.* [47] uses machine learning wherein using modulation constrained (MC) and expectation maximization (EM) algorithm proposed two detection method: (i) constellation learning with labeled signals (CL-LS) and (ii) constellation learning with labeled and unlabeled signals (CL-LUS). Both these detection methods do not require knowledge of CSI. Table 4 reviews the detection techniques in BackCom.
The conclusion and key observation on reviewing the detection techniques is assessed as:

- Detection schemes in literature can be classified into two types: a) Coherent detection b) Non-coherent detection.
- Coherent detection requires carrier phase information at the receiver and uses Matched filter for detection.
- Coherent detection is preferred for PSK.
- Non-coherent detection does not require carrier phase information at the receiver and uses square law detector for detection.
- Non-coherent detection is preferred for ASK and FSK.
- For optimal detection, an Maximum likelihood (ML) detector is chosen and can be considered as a performance benchmark to establish other optimal detectors.

3.2. Wireless Communication in BackCom:

In this subsection we explicitly report the different types of modulation and demodulation schemes as well as various multiple access techniques used in literature are thoroughly reviewed.

1) Modulation and Demodulation: The commonly used modulation schemes for BackCom are ASK, FSK, and PSK. Among them, ASK and FSK are widely used in the BBCS. As PSK typically sends data in a few radio frequency channels, it supports high data rates and hence it is vastly used in ambient backscatter communication systems. The simplest type of modulation is On-Off keying (OOK) and is based on ASK. Kimionis *et al.* [48] proposed the use of both OOK and FSK modulation for the BBCS. FSK offers certain advantages over OOK such as increased range, increased receiver sensitivity, and use of simple multiple access.

The data rate offered by conventional modulation schemes such as ASK or PSK is rather low and hence to enhance it, a high order modulation scheme with M states(i.e.,M-PSK) is proposed by Qian *et al.* [49]. Particularly, they designed hardware using 4-PSK modulation and achieved a data rate

Table 4
Summary of detection techniques

References	Schemes	Advantages	Remarks
Liu *et al.* (2013) [7]	Multistage detector circuit consisting of Averaging, Thresholding and Comparator.	Analog to Digital converter is not used.	Hardware prototype is designed.
Hilliard et al. (2015) [25]	Coherent detection for Bistatic BackCom.	Extension in the range by 10 meters and also reduction in the Bit Error Rate.	more difficulty due to antenna structural mode, antenna reflection coefficients, scattering efficiency.
Qian *et al.* (2016) [40]	Non coherent detection without CSI.	Overcomes the disadvantages of Coherent detection.	ML and energy detectors are obtained using joint PDF.
Tao *et al.* (2018) [29]	semi-coherent Manchester and non-coherent Manchester detectors .	Works good even if information bits are arbitrarily distributed.	SeCoMC outperforms NoCoMC.
Qian *et al.* (2017) [45]	Semicoherent detection.	Detection using training symblols, So no estimation of channel.	CSI is not required.
Zhang e al. (2018) [47]	constellation learning with labeled signals (CL-LS), constellation learning with labeled and unlabeled signals (CL-LUS).	No need of CSI.	Using modulation constrained and expectation maximization algorithm proposed two methods.

of 20kbps for a distance of 2.5 feet. To increase the data rate, authors in [50] proposed a certain technique which uses higher-order M- quadrature amplitude modulation (QAM) that requires (relatively) reduced power demands. They used the Wilkinson power divider for phase shift and two transistors that act as switches to generate M-QAM. Authors in [51] used the 32-QAM scheme to design a backscatter transmitter that operates at 5.8GHz with a 2.5 Mbps data rate, which covers a range of ten centimeters. The M-QAM modulation has a major problem that it is susceptible to noise and hence results in a normalized power loss. Wang *et al.* [52] analyzed the performance of ambient FM signals for backscatter communication. Here the backscattered data is decoded by FM receivers usually present in cars and smartphones thus we can have communication with cars and smartphones. The authors designed a modulation technique whereby the RF signals are added to audio signals output by FM receivers. The authors designed a hardware prototype that has a range of 5-60 feet with a data rate of 3.2 kbps. Overall power consumption is in the order of 11.07μW. Similarly, Daskalakis *et al.* [53] built a prototype using a real FM source located 34.5 km away and used 4-pulse amplitude modulation (PAM) to modulate the ambient FM signals. The proposed method consumes 27μW and achieves a data rate of 345 bps. On the other hand, Tao *et al.* [54] uses multiple frequency shift keying (MFSK) modulation in ambient backscatter systems for symbol detection. Here, different detectors such as ML and energy detectors have also been studied and in case of energy detectors, MFSK modulation outperforms OOK modulation. The symbol error rate (SER) performance is evaluated for the MFSK energy detector. Experimental results show that to minimize the outage probability, tag should be placed closer to the reader.

Vougioukas and Bletsas [55] presented an ambient backscatter communication scheme that uses both analog and digital modulation schemes. Regarding the digital modulation, pseudo frequency shift keying (P-FSK) and frequency-shifted binary phase-shift keying (S-BPSK) are used. Unlike S-BPSK, the P-FSK needs illumination through constant envelope modulated signals. The short packet error correction coding is used for S-BPSK. In terms of analog modulation, they have used FM modulation principles. These modulation schemes consume more power compared to OOK but they are less affected by the interference of ambient signals. The proposed method has a communication range of 26 meters between tag and receiver in an outdoor environment and also the power consumption is 24 μW.

In [56], Correia and Carvalho designed 16 QAM backscatter modulator having very little power consumption of 59 μW. The per bit energy consumption of this modulator is very low i.e. 61.5 fJ/bits. It also has a high data rate of 960 Mbps. Correia *et al.* [57] presented a various combination of backscatter modulation along with power transfer. In most of the work, the tag of RF backscatter communication uses âĂIJOn-OffâĂİ switching to modulate the data. This causes an increase in spectrum occupancy due to rectangular pulses. To overcome this drawback, the authors in [58] presented a method that can vary the reflection coefficient of tag continuously without an increase in RF front end complexity.

One of the widely used modulation schemes especially in Wi-Fi and digital video broadcast (DVB) is orthogonal frequency division multiplexing (OFDM). Yang *et al.*[59] presented an ambient BackCom using OFDM modulated carriers in the air. They designed such a system from the spread spectrum point of view. Darsena *et al.* [60] showed analytically that the RF interference because of backscattering can be converted into multipath diversity in the case of legacy receivers using OFDM modulation, which ultimately increases system performance. Experimental results show that when the legacy transmitter and backscattered signal are lying on the same device then for short distances, the data rate can be increased by transmitting one symbol per OFDM symbol of the legacy system. In [61] authors use the Gaussian Frequency Shift Keying modulation technique Bluetooth Low Energy (BLE) compatible BackCom system. BLE makes use of the 1Mbps GFSK modulation scheme. There is a total of 40 BLE channels and in each channel, âĂIJ1âĂİ bit corresponds to a positive frequency deviation of greater than 185 kHz above the channelâĂŹs center frequency and âĂIJ0âĂİ bit corresponds to a negative frequency deviation of greater than 185 kHz below the channelâĂŹs center frequency. Qian *et al.* [62] used differential modulation and demodulation at tag and reader respectively for signal detection in case of an ambient backscatter communication system. Table 5 represents the review of modulation and demodulation techniques in BackCom.

The conclusion and key observation on the review of modulation and demodulation techniques is given below.

- The commonly used modulation schemes for BackCom are ASK, FSK and PSK.
- ASK and FSK are widely used in BBCS.
- PSK sends data in a limited number of radio frequency channels, it supports high data rates and hence it is mostly used in ABCS.
- For high data rates, the higher order modulation schemes such as M-PSK are used.
- OFDM is widely used in ABCS.
- BackCom is also capable of achieving the data rate of the order of Mbps [50].

The plot of data rate against modulation schemes mentioned in Table 5 is given in Fig. 10. Highest data rate is obtained for M-QAM. However, distance between transmitter and receiver , transmitter power affects the data rate to a large extent.

2) Multiple access schemes for BackCom system: Similar to conventional wireless communication system, the objective in BackCom system is to serve the maximum number of users at any given time instance as well as to increase the capacity of the system; hence various multiple access schemes based on time division, frequency division and code division are used in BackCom system. A key design factor when selecting different types of multiple access techniques is user cooperation. Ju and Zhang [63] used the time division multiple access (TDMA) scheme for the uplink so as to send the user data towards the hybrid access point (H-AP). Particularly, here the system model consists of two users (one located near and the other far from H-AP) and one hybrid access point. In that work, the user near to H-AP uses part of its allocated time to first help in relaying the information of the far user to the H-AP and then uses the remaining time and energy to transmit its information.

Table 5
Summary of Modulation and Demodulation techniques

References	Schemes	Advantages	Remarks
Kimionis *et al.* (2014) [48]	OOK and FSK for bistatic BackCom.	Increased comunication range (130 meters) with 20mW power consumption.	FSK offers certain advantages over OOK such as increased range and receiver sensitivity, and use of simple multiple access.
Qian *et al.* (2018) [49]	M-PSK (4-PSK)	Higher data rate for 98.7% of the times.	20 kbps data rate for 2.5 feet.
Correia *et al.* (2017) [50]	M-QAM	Achieves high bit rate with low power and less number of active devices.	Wilkinson power divider for phase shift and two transistors that acts like switches to generate M-QAM.
Wang *et al.* (2017) [52]	Ambient Frequency modulation (FM) signals for BackCom.	Less powe r consumption of 11.07 μW.	Hardware prototype that has a range of 5-60 feet with a data rate o f 3.2 kbps.
Daskalakis *et al.* (2018) [53]	4-PAM to modulate FM signals.	Less power consumption of 27 μW.	Uses real FM source located at 34.5 km . Achieves data rate of 345b/s.
Vougioukas *et al.* (2019) [55]	Uses both analog and digital modulation.	Communi- cation range of 26 m and power consumption of 24 μW.	For digital modulation: S-BPSK and P-FSK. Analog : FM
Yang *et al.* (2018) [59]	OFDM in the context of spread spectrum .	Better transmission rate, BER performance and operating range.	Timing synchronization algorithm are proposed.

One of the major concerns in BackCom is concurrent transmissions. In [64] a multiple access technique was used in backscatter spike train (BST). BST enables concurrent transmission by using intra-bit multiplexing of OOK signals from different devices. The experimental observation shows that the throughput of BST is 5 times and 10 times higher than Buzz and TDMA based schemes respectively. Liu *et al.* [65] proposed a new channel model named multiplicative multiple-access channel (M-MAC). In the said model, the signal directed from carrier emitter is not treated as interference at the receiver, but the receiver extracts the information simultaneously from carrier emitter and tag.

Most of the work in literature consists of the ambient backscatter communication system with a single reader and

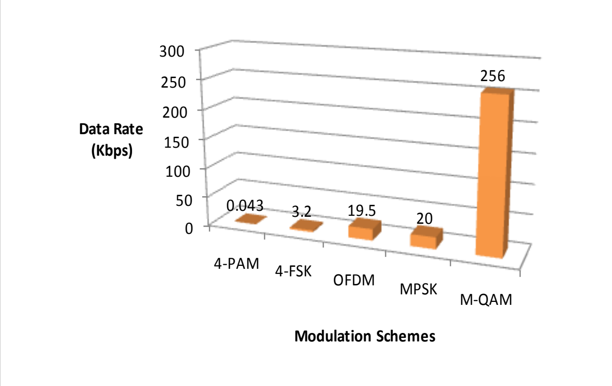

Figure 10: Data rate versus modulation schemes

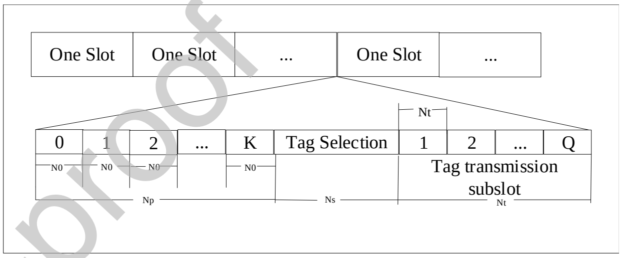

Figure 11: Communication process between backscatter receiver and K backscatter transmitters [66]

a single tag. Zhou *et al.*[66] investigated the BER performance of multiple tag ambient backscatter communication systems by making the following assumptions: 1. Unless and until the tags are awaked to backscatter, all the tags are in sleeping mode. 2. The channel present between tag and reader is invariant as all the tags are stationary. 3. There is proper line-of-sight (LoS) between tag and reader. To avoid interference from multiple tags, the slotted structure is considered in this work which is shown in Fig. 11. Here data transmission is done on a slot basis. Each slot is further divided into three sub-slots. (K+1)No symbols are present in the first sub-slot and in the K-th No symbols only k-th tag will backscatter the RF signal. The second sub-slot is for tag selection in which based on certain criteria the tag is selected by the reader. During the third sub-slot, the selected tag sends the data to the reader and the other tag remains silent.

Liu et al [67] investigated the multiple access ambient backscatter communication system where they do not adopt the cancellation technique but the backscatter receiver is authorized to detect signals from RF source as well as backscatter transmitter. Thus they proposed a backscattered multiplicative multiple access system (BM-MAC) which is different from traditional linear additive multiple access system in the sense that here the backscattered transmitter uses multiplicative operations. The monostatic backscatter systems (RFID systems) suffer from a tag collision problem that oc-

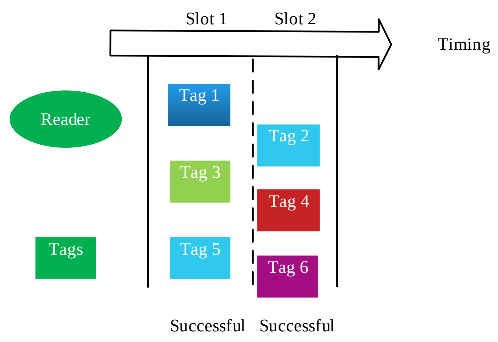

Figure 12: CDMA in backscattered communication.

curs as all the devices in the system share a common wireless channel. To overcome this limitation, the TDMA method is used. But due to inherent limitations of TDMA such as predefined time slots and multipath distortion, a fixed spectrum allocation (FSA) based CDMA algorithm is proposed for EPC global generation 2 to deal with the problem of tag collision [68]. Therefore, with the aid of orthogonal spreading the reader can identify multiple tags in its vicinity. Fig. 12 shows the use of the CDMA technique in BackCom.

One of the main disadvantages of traditional multiple access is low spectral efficiency. To overcome this limitation, nonorthogonal multiple access (NOMA) is discussed in the literature. The main feature of NOMA is that it can serve multiple users at the same time/frequency/code yet discretized with different power levels which results in increased spectral efficiency [69]. For NOMA systems to be successful, the user clustering and power allocation should be proper [70]. In this paper, the authors discussed differences in working principles of uplink and downlink NOMA for wireless communications systems. A total throughput maximization problem was also formulated for both uplink and downlink NOMA.

Yang *et al.* [71] presented the wireless powered communication network (WPCN) that works in backscattered mode. Here for data transmission both NOMA and TDMA schemes are considered. With NOMA the higher spectral efficiency is obtained and TDMA helps to achieve maximum system throughput. The symbiotic relationship between cellular and IoT network and backscatter system for NOMA is studied in [72]. They have analyzed the ergodic rate and outage probabilities for the backscatter NOMA system and the SR system. Guo *et al.* [73] proposed a power domain NOMA based monostatic backscatter communication system. In these, various backscatter nodes are multiplexed with different backscattered power levels or in different regions. The reflection coefficient of all multiplexed backscatter nodes is different to utilize NOMA efficiently. Based on the average number of bits that can be successfully decoded, the performance of the proposed system is analyzed. Kim *et al.* [74] proposed a sparse code based BackCom system that allows NOMA with M-ary modulation which helps to achieve modulation diversity. Table 6 represents the review of multiple access techniques in BackCom.

Table 6
Summary of Multiple access techniques

References	Schemes	Advantages	Remarks
Ju *et al.* (2014) [63]	TDMA is used for uplink.	Allows two users to harvest the energy simultaneously.	Model consists of two users and one H-AP. Future work: more than two users , use of relay.
Hu *et al.* (2015) [64]	Backscatter Spike Train (BST).	Enable concurrent transmissions from many devices.	1. BST works on OOK signals received from different tags. 2. 10 times higher throughput than TDMA.
Liu *et al.* (2018) [65]	multiplicative multiple-access channel (M -MAC).	Receiver extracts the information simultaneously from tag and RF source.	Multiple access system.
Wei *et al.* (2018) [68]	CDMA (Code Division Multiple Access)	Multiple users can communicate with each other without interference.	Overcomes limitations of TDMA like multipath distortion, predefined time slots.
Ng *et al.* (2013) [75]	OFDMA (Orthogonal Freq. Division Multiple Access)	Allow synchronous power and information transfer simultaneously.	Based on the division of received power.
Ali *et al.* (2016) [70]	NOMA (Non Orthogonal Multiple Access)	Increased spectral efficiency.	formulated total throughput maximization problem for uplink and downlink.
Lyu at al. (2017) [71]	NOMA and TDMA	NOMA results in higher spectral efficiency and TDMA in max system throughput.	Wireless powered communication network.

The conclusion and key observation on reviewing multiple access techniques is outlined below.

- Various multiple access techniques like TDMA, CDMA, OFDMA and NOMA are proposed for BackCom system.
- All schemes accommodate the maximum number of users at the same time.

- NOMA has better performance than all others. Therefore expected to be widely used in 5G communication systems.
- NOMA has the potential to meet future demands of connecting the large number of IoT devices.

3.3. Wireless Information and Power Transfer in BackCom:

The radio waves carry both energy and information simultaneously. For the conventional RF transmission, these two parameters were treated as a separate entity. To accelerate the performance of wireless communication systems the efficient information and power transfer are attracting the research community to power up the passive devices. To further improve the backscatter wireless communication systems, the efficient energy management approach is also investigated by the research community. The backscatter communication systems consume a few micro-Watts [76] [77]. Thereby, various works in the context of energy management in BackCom is discussed in this section.

Due to the advancements in the wireless power transfer (WPT), the latest wireless communication standards such as 5G, mm-waves and small cells have adopted WPT [78]. In [7] the backscatter device harvests the energy from ambient RF signals and utilizes it for backscattering. Hence, it does not require a dedicated power source and the entire communication is carried out using ambient RF signals taken from a TV tower. Non-dedicated power sources such as TV transmitters, AM/FM radio transmitters, Wi-Fi access points, cellular base stations, etc. can also be utilized for backscatter communication. Especially, the cellular base stations and TV transmitters are widely used for ambient backscatter communication in urban areas due to their all-time availability and transmitting power.

To harvest the energy from these many ambient RF energy sources Pinuela *et al.* [79] surveyed London wherein they built four harvesters (comprising antenna, impedance-matching network, rectifier, maximum power point tracking interface, and storage element). Based on the observation they found that in an urban and semi-urban environment, the single band harvesters can work with an efficiency of up to 40 % and they can work with power as low as -25dBm. Correia *et al.* [57] developed a prototype in which the wireless sensor network is provided continuous energy. The system consists of two matching networks, a backscatter modulator, and a dual-band rectifier. Compared to a single band rectifier, the dual-band rectifier achieves more gain on output DC voltage.

In [80], the energy minimization in the wireless energy transfer (WET) based passive communication model was investigated. The authors proposed a harvest while scatter (HWS) protocol whereby if a particular passive node scatters the signal then the remaining passive nodes harvest the energy from active nodes. The advantage of combining energy harvesting along with data transfer is that passive nodes get a longer time for energy harvesting and hence they can harvest more RF energy. Kuo *et al.*[81] in their work proposed an inductive wireless power transfer and backscatter link using a CMOS tag coil of 0.01mm^2 area. At 4.7 GHz, it generates the power of 0.1mw with the reader at a distance of 1.2 mm. They employed the OOK modulation scheme and achieved a data rate of 20 kbps.

Shah *et al.* [82] investigated the ambient backscatter communication system which consists of RF powered decode and forward (DF) relay node along with simultaneous wireless information and power transfer (SWIPT) technology. The proposed model uses the power splitting relaying protocol for energy harvesting. The SWIPT technique that deals with the simultaneous transmission of information and power wirelessly suffers from the problem of limited sensitivity, non-linearity, and saturation of far-field energy harvesting. Alevizos and Bletsas [83] investigated on reducing the above-mentioned problems associated with RF energy harvesting. Nevertheless, the SWIPT research should take into account the nonlinearity of the actual harvesting efficiency and the limited sensitivity of the harvester.

Yang *et al.* [84] proposed a WET scheme based on energy beamforming for a system that contains multiple antennas both at the reader and tag. In such a system the acquisition of forward channel (reader to tag) state information is a challenging task as the tags are energy and hardware constrained. In that paper expression of the harvested energy is analyzed using backscatter channel (tag to reader) state information (BS-CSI). Ju and Jhang [85] proposed a harvest-then- transmit (HTT) protocol for wireless energy transfer via a hybrid access point (H-AP). Therein, the energy is transmitted in downlink from H-AP to different users, while the users first harvest the energy and then send their individual information to the H-AP in the uplink. This approach suffers from the doubly near-far problem and hence to solve it an equal rate is given to all the users irrespective of their distances from H-AP.

In [86] authors used HTT protocol with non dedicated sources to obtain optimal harvesting ratio. The optimal harvesting ratio enhances the throughput for both direct and DF transmissions. The proper balance between rate of energy harvesting and information transfer by tags is required to achieve the desired long distance read range [87]. To this end, the authors used an power amplifier and a capacitor in the hardware architecture. The proposed approach outperforms the conventional passive tags scheme with increased read range. Correia *et al.* [88] presented the method in which rectifier is used to harvest the electrical energy for powering the wireless sensor networks. The proposed method works with dual load for two different frequencies. Table 7 reviews the wireless information and power transfer in BackCom.
The key observations of the aforementioned methods are subsequently provided:

- Amongst various wireless communication technologies, the backscatter communication systems consumes less power (in μW).
- Advance techniques like 5G, mm-wave and small cells

Table 7
Summary of wireless information and power transfer in BackCom system.

References	Schemes	Advantages	Remarks
Correia et al. (2016) [57]	A mixture of backscatter modulation and wireless power transfer using diodes.	Compared to single band rectifier, the dual band rectifier achieves more gain on output DC voltage.	The system consists of two matching networks, a backscatter modulator and a dual band rectifier.
Yao *et al.* (2018) [80]	Harvest âĂŞ while-scatter (HWS) protocol.	Passive nodes get more time for harvesting and hence harvest more energy.	Based on combination of energy harvesting and data transfer.
Shah *et al.* (2018) [82]	Simultaneous Wireless Information and Power Transfer (SWIPT) along with DF relay.	Enables simultaneous information and power transfer.	SWIPT suffers from limited sensitivity, non-linearity and saturation .
Ju *et al.* (2013) [85]	Harvest-then-transmit (HTT) protocol.	Increases system capacity, efficiency.	Energy is transmitted in downlink from H-AP.

introduce direct implementation of WPT.

- By combining energy harvesting with data transfer enables passive nodes to obtain longer time for energy harvesting and hence can harvest more RF energy.
- Basic HTT protocol suffers from the doubly near-far problem.

3.4. Resource Allocation and Task Scheduling in BackCom:

One of the essential requisites for the successful implementation of a backscatter communication system is the effective utilization of available resources and their scheduling. In this context, scheduling means in a particular time slot which user is active and which is not. Similarly, resource allocation refers to allotment of bandwidth and power based on the number of active users in a particular time slot. In this subsection, we discussed various resource allocation schemes.

In a conventional wireless powered communication network, the first time slot is used only for energy harvesting from the RF source. Thus it is underutilized as no information is transmitted during this time slot. To maximize the throughput, Lyu *et al.* [89] presented a backscatter assisted wireless powered communication network (BAWPCN) where during the first-time slot it corresponds to backscatter mode, while the HTT mode is adopted for the remaining time slot. In [90] [91] the throughput among all the backscatter devices (BDs) is maximized by jointly optimizing time allocation among these BDs. In these works, the resource allocation for a single as well as multiple backscatter devices were considered.

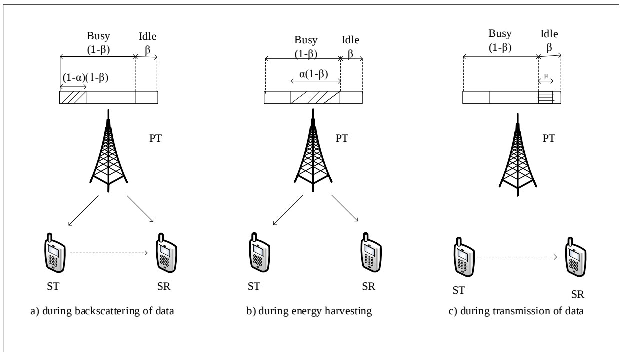

Figure 13: RF powered cognitive radio network [97].

Most of the existing research related to WET do not take into consideration the energy utilization efficiency, which is also an important parameter from the green communications standpoint. Wu *et al.* [92] formulated the multiuser energy efficiency (measured in bits per joule) maximization problem by considering the time allocation and power control for wireless energy transfer in downlink and wireless information transfer in uplink. Kalamkar *et al.* [93] proposed the model that integrates wireless powered communication networks (WPCN) with co-operative cognitive radio networks (CCRN). To increase the fairness in this combined network, the authors discussed three resource allocation schemes, i.e., equal time allocation, minimum throughput maximization, and proportional time allocation. IoT consists of a densely populated network of sensors that communicates with each other as well as with the RF signal transmitter in a backscatter communication system. If multiple sensors backscatter at the same time then it leads to interference.

To avoid interference, time scheduling among the sensors is studied by Huynh *et al.* [94]. The allocation of time to a sensor depends on various factors such as channel conditions, backscatter capability and energy demands. Based on the compressive spectrum sensing technique, the optimal time scheduling scheme is proposed in [95] to manage time schedules among the spectrum sensing module, energy harvesting module, and ambient backscatter communication module. To avoid the direct link interference caused due to primary transmitters, Guo *et al.* [96] proposed the concept of co-operative receiver in which the primary receiver and IoT receiver are integrated. In that paper, the problem of resource allocation is investigated for symbiotic radio systems by taking into account the effect of channel fading.

For effective utilization of channels the use of cognitive radio networks along with backscatter element has been proposed so far. In [97], the authors proposed an integrated model consisting of ambient BackCom network and RF powered cognitive radio network as shown in Fig. 13. It consists of a primary transmitter (PT), secondary transmitter (ST) / primary receiver (PR) and secondary receiver (SR).

In fact, the ST can harvest the energy from PT signals and use this energy for sending the data to the SR. This mode is thus an HTT mode. As per the authors, there is a trade-off between RF powered backscatter cognitive radio networks. Here when the primary channel is busy then ST can either harvest energy or can backscatter the data to the SR. Let (1-β) and β denote the channel busy period and channel idle period respectively. When the channel is busy, let (1-α) and α represent time ratio for backscattering and energy harvesting respectively. If α is small then ST harvest a small amount of energy and due to this it cannot utilize the channel idle period for direct data transmission and hence the total transmission rate is small. With the increase in α, the total transmission rate also increases. If the α is very high then the total transmission rate decreases because the channel idle period is limited and backscattering is not efficiently done during the channel busy period. In this paper by considering the trade-off between HTT and backscattering time the optimization problem is formulated. The numerical results show that the use of HTT mode along with backscatter communication largely improves the performance as compared to the use of backscatter communication or standalone HTT mode.

Kang *et al.* [98] presented a spectrum sharing model termed as Riding on the primary (RoP) for the cognitive radio (CR) system. This model is based on the concept that energy is harvested from the primary signal by the secondary transmitter. Further, the secondary transmitter modulates its information bits to the primary signal and reflects the modulated signal to the secondary receiver without violating the primary systemâĂŹs interference requirement. Wang *et al.*[99] proposed a method for data rate enhancement in the CR network. The method consists of multiple secondary transmitters that can work in both HTT and backscatter mode. To avoid interference among multiple STs, the authors used a pricing mechanism for the primary network in which time is allocated to ST.

Kishore *et al.*[100] proposed the framework in which the analysis of energy efficiency is made in presence of error sensing for ABC-HTT based CR network. By integrating ABC-HTT modes, the energy efficiency of the system increases compared to the use of only HTT or ABC mode. In [101], the authors proposed the model which is based on auction in RF powered backscattered CR network. The model here was designed by considering both fixed and variable demand cases. In the proposed model the ST plays the role of a buyer and the secondary gateway (SG) plays the role of the seller as well as auctioneer. Table 8 represents the review of resource allocation and task scheduling in BackCom. The conclusion and key observation on review of resource allocation and task scheduling is given below.

- There are two types of scheduling in BackCom. The energy scheduling and the data scheduling.
- The allocation of resources is carried out depending on different parameters such as time, throughput and energy.
- The CR based allocation of resources is considered for ABCS and this depends on the availability of channels.

4. Emerging Backscatter Systems

Because of the highly attractive features of backscatter communication, many new BackCom systems have been developed. In this section, the upcoming trends and technologies in BackCom are discussed.

4.1. *Relay Based Backscatter Communication System*

The use of relay networks helps in increasing the communication coverage of a typical wireless communication system. In order to increase the single-hop communication range of a backscatter network, one of the solutions is to use relay nodes. In simple terms, the relay receives the signal from one side of a network and re-transmits it to the other side. In [102] authors proposed the use of a three-time slot two-way decode and forward relay system. The BER expression in closed-form is derived and the simulation results show that the considered relay scheme outperforms the direct transmission systems.

Lu *et al.* [103] proposed a hybrid relay that integrates both ambient backscatter and wireless powered communication. The hybrid relay can perform both the operations of backscattering and wireless powered communication. The authors also proposed a mode selection protocol to coordinate between the two different types of transmissions. Moreover, the authors in [104] presented a two-hop relay model that maximizes the throughput by jointly optimizing relay strategies and WPT. Ma *et al.* [105] suggested the use of RFly which is a drone relay for battery-free networks. This relay system is full-duplex and it can store phase and timing information of the forwarded packets. It achieves a communication range of 50 m to 55 m.

The BackCom technology can also be used in unmanned aerial vehicle (UAV). Gang *et al.* in [106] proposed a energy efficient UAV backscatter communication scheme that consists of multiple backscatter devices (BDs) and carrier emitters (CEs) both on ground as well as UAV. Authors designed the communicate-while-fly scheme where BDs exchange the information with flying UAV. One of the limitation of UAVs is that they have limited on board energy. This issue is addressed by jointly optimizing the UAVâĂŹs trajectory, the BDsâĂŹ scheduling, and the CEsâĂŹ transmission power.

Table 8
Summary of resource allocation and task scheduling in BackCom system.

References	Schemes	Advantages	Remarks
Lyu *et al.* (2017) [89]	Backscatter Assisted Wireless Powered Communication Network (BAWPCN).	Overcomes the limitations of conventional WPCN.	First time slot corresponds to backscatter mode and rest to HTT mode.
Yang *et al.* (2018) [90], [91]	Resource allocation in ambient backscattered communication.	the throughput among all the backscatter devices (BDs) is maximized by jointly optimizing time allocation among these BDs.	resource allocation for single as well as multiple backscatter devices is considered.
Wu *et al.* (2016) [92]	Related to energy utilization efficiency.	maximize the multiuser energy efficiency.	Considers time allocation and power control for wireless energy transfer in downlink and wireless information transfer in uplink.
Kalamkar *et al.* (2016) [93]	WPCN integrated with co-operative cognitive radio network (CCRN)	Achieves the advantages of both techniques.	Three schemes equal time allocation, minimum throughput maximization and proportional time allocation are discussed.
Huynh *et al.* (2018) [94]	Time scheduling approach for multiple sensors.	It avoids the interference among multiple sensors deployed in dense IoT networks.	Time allocation depends on channel conditions, backscatter capability, energy demands
Gao *et al.* (2019) [101]	Auction based model in RF powered backscattered CR network.	It considers both fixed and variable demand cases.	ST acts as buyer and secondary gateway (SG) acts as seller as well as auctioneer.

4.2. *Visible Light Backscatter Communications*

In RF restricted areas like hospitals or airplanes (at higher altitude), the Visible Light Backscatter Communications System (VLBCS) can provide effective data transmission rate. Authors in [107] designed a âĂIJViTagâĂİ backscatter transmitter that transmits information using visible ambient light. To promote its inner activities, ViTag firsts harvests power from ambient light through solar cells and then further adopts a liquid crystal screen (LCD) shutter for modulating the light carrier reflected by a retro-reflector i.e. blocking or passing. Similar to the conventional RF communication, at the receiver side the modulated light signal is first amplified then is being demodulated and digitized and lastly it is decoded. The experimental observations indicated that for a distance of 2.4 meters, the ViTag achieves the downlink data rate of 10kbps and uplink data rate of 0.5 kbps. Most of the VLBCS use OOK modulation and hence results in less throughput. To overcome this problem Shao *et al.* [108] presented VLBCS that uses 8-PAM as the reference modulation scheme. Experimental results showed that a 600bps rate for 2 meters is achieved using 8- PAM instead of 200 bps with OOK modulation. By replacing the LCD shutter with a faster modulator, this rate can further be improved. In [109] authors used the trend based modulation and code-assisted demodulation techniques with the uplink data rate of 1 kbps.

4.3. *Long Range (Lo-Ra) Backscatter Communication*

Lo-Ra is one of the crucial technologies developed especially for machine to machine communications and IoT applications. Conventional backscatter communication suffers from the problem of short-range communication. With Lo-Ra technique, the communication range can be increased to a greater extent. Particularly Talla *et al.* [110] use the Lo-Ra communication method whereby it can backscatter the information for a distance of 475 m. Lo-Ra uses chirp spread spectrum (CSS) modulation in which âĂŸ0âĂŹ bit acts as a continuous chirp that increases linearly with an increase in the frequency and bit âĂŸ1âĂŹ is also a chirp that is shifted cyclically in time. Therein, the authors demonstrated the effectiveness of Lo-Ra technique by deploying the system in different scenarios like 1210 square meter office area, one acre (4046 square meters) vegetable farm, 446 square meters three-floor house. Peng *et al.* [111] proposed the Passive Long Range (PLoRa) backscatter design. In PLoRa, ambient LoRa transmissions are used as excitation signals, where these excitation signals are modulated into a chirp signal and are shifted to different LoRa channels. The PLoRa tag used in that work can backscatter up to 1.1 km by delivering 284 bytes of data every 24 minutes for indoor and or 17 minutes outdoor.

4.4. *mm- wave based Backscatter Communication*

The spectrum of Millimeter (mmWave) ranges from 30 GHz to 300 GHz. It can be used for high-speed wireless communications. mm-wave will bring 5G communication into reality by allocating more bandwidth that results in the delivery of faster, high-quality videos and multimedia contents and services. The recent work in [112] demonstrates that 4 Gigabit data rate is possible by incorporating mm-wave in monostatic backscatter communication systems. This new technology can also be used in ABCS.

5. Open Research Issues

ABCS has recently attracted the attention of industry and academic researchers, but still it is in evolving stage.We had already listed numerous research areas in section III. This section outlines the potential research area for future exploration.

5.1. *Physical Layer Security*

Practical application of BackCom involves communication of numerous sensors. These sensors may carry essential information (personal, medical data) and hence the communication must be secured. Thus, physical layer (PHY) security mechanisms need to be built that exploit wireless channel characteristics like noise to protect wireless transmission from eavesdropping. Saad *et al.* [113] presented the simulation model for MBCS that maximizes the secrecy rate in which reader broadcasts random signal (noise) along with conventional signal towards the eavesdropper. Similar study can be addressed for multi-reader/tag case.

5.2. *Energy Efficiency Maximization*

Energy constraint causes the nodes to backscatter just a few bits once, resulting in BackCom being unable to be implemented in applications needing more data (e.g. an image). Hence energy saving for BackCom is vital so that the nodes can provide more data with the finite resources. In [114] a multi antenna two hop information cum energy transmission scheme is designed using maximum ratio transmission (MRT) precoding method. The system achieves better energy efficiency with increasing power splitting factor and is highest for power splitting factor of 0.5. The energy efficiency is also a function of number of antennas and it initially increases then decreases with increase in number of antennas.

5.3. *Spectrum Sharing*

Spectrum sharing in BackCom is different from conventional spectrum sharing in two sense [115]. First, the conventional spectrum sharing is developed for downlink long-packet communication unlike uplink short-packet communication in BackCom. Second, the BackCom have limited signal processing capability compared to conventional one. The low computations and limited signal processing capabilities makes spectrum sharing a challenging task.

5.4. *Machine Learning Algorithms*

Wireless communication in IoT evolves around vital techniques like spectrum sharing, optimized routing, dynamic spectrum access. Thus BackCom must have expertise to adjust various communication parameters such as coding rate, symbol modulation, route selection, etc dynamically. The above issue can be tackled effectively using machine learning algorithms. In [116] the tag symbols are detected using supervised machine learning algorithms: support vector machine and random forest. BER performance is improved due to use of these algorithms than conventional detector.

6. Conclusion

Backscatter communication is a promising technology for todayâĂŹs large-scale self-sustainable wireless networks such as wireless sensor networks and the Internet of Things. Because ambient backscatter avoids the maintenance-heavy batteries and dedicated power infrastructure, it can be used in future IoT networks. In this paper, we introduced the three different types of backscatter communication system. Then we thoroughly analyzed and described the basic principle of BackCom. Further, a broad literature review of existing BackCom system and network architectures was summarized. Finally, a brief overview of emerging backscatter communication systems along with open research issues was also provided. It turns out that the newly arising technology of BackCom is expected to play a key role in future IoT by enabling truly ubiquitous network connectivity as well as pervasive sensing and computing.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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