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Review

Backscatter communication-based wireless sensing (BBWS): Performance enhancement and future applications

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ABSTRACT

Wireless Sensing (WS) provides a low-cost means of monitoring humans and objects for the next generation of IoT. However, the deployment of WS for various applications is limited by; the heterogeneous nature of underlying technology in IoT devices, limited battery, and computational power of sensing devices. Backscatter Communication (BackCom) enables wireless sensing and communication by reflecting wireless signals (such as radio frequency (RF), acoustic and visible light (VL)) from a source to a receiver using a backscatter tag at an ultra-low (microwatt) power level. Hence, backscatter communication-based wireless sensing (BBWS) could enable ubiquitously and battery-free applications (such as human and plant physiology, orientation sensing, and localization). Despite existing surveys and literature on BackCom, a study on leveraging BackCom for WS is still lacking. This paper takes the first approach in discussing applications of BackCom in WS and techniques for enhancing performance (such as power management, channel model, range and coverage, throughput, security, quality of backscatter signal, modulation, and coding) in BBWS applications. It also discusses future sensing applications where BBWS is applicable and research issues related to such applications.

1. Introduction

The next generation of the Internet of Things (IoT) promises ubiquitous connectivity through the massive deployment of connected devices. The IoT devices should work at low power budgets to provide sensing and communication functionalities. Achieving this goal will enable applications such as intelligent manufacturing (Qiu et al., 2020), smart city (Chen et al., 2018), and machine type communication (Mohammed et al., 2019). Wireless sensing (WS) has emerged as a key enabling technology for future IoT. It involves using wireless signals such as radio frequency identification (RFID) (Cui et al., 2019) and WIFI (Khalili et al., 2020) to sense processes related to humans or objects. WS provides low-cost means of sensing on a large scale. However, its implementation is limited by; the heterogeneous nature of technologies employed in various IoT devices, limited battery, and computational processing power of sensing devices. Before proceeding further, a list of abbreviations used in this paper and their meanings are given in Table 1.

To address the challenges of WS, backscatter communication (BackCom) employs the reflection of wireless signals by tags attached to sensing devices to achieve continuous and battery-free sensing and communication. Even though the BackCom still has some limitations (Dehbashi et al., 2021; Elsayed et al., 2021), it shows much promise. Hence, BackCom-based wireless sensing (BBWS) will have a crucial role to play in the next generation of wireless sensing applications (Ha et al., 2020; Duan et al., 2020; Talla et al., 2017b). The technique of using reflected signals for communication has been in use since 1948 (Stockman, 1948). However, recently, it has gained much attention mainly due to the advent of commercial off-the-shelf (COTS) devices (such as software-defined radio (SDR), smartphones, and intelligent vehicles) with significant computational processing capabilities. The processing capabilities of the COTS devices allow for the drastic reduction of complex signal processing and computational overhead from the sensing devices. Recently, research efforts have intensified towards discussing wireless sensing and communication applications, techniques for deployment, and enhancement of BackCom. The authors in Jameel et al. (2019) discussed utilizing BackCom for sensing and communication applications in healthcare. The authors discussed the various architectures (monostatic, bistatic, and ambient) of BackCom and the types of backscatter tags. They also discussed the various existing in-body and on-body applications of BackCom and classified them based on; radio frequency (RF) source, networking technologies used for BackCom, antenna frequency, and service level objectives. Lastly,

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Table 1
Abbreviations used and their meanings.

Abbreviation	Meaning	Abbreviation	Meaning
AP	Access Point	BackCom	Backscatter Communication
BAN	Body Area Network	BBWS	Backscatter communication Based Wireless Sensing
BER	Bit Error Rate	BLE	Bluetooth Low Energy
CDMA	Code Division Multiple Access	COTS	Commercial off-the-shelf
CRFID	Computational Radio Frequency Identification	CSI	Channel State Information
CSS	Chirp Spread Spectrum	CTI	Cross Technology Interference
DSM	Delayed Superimposed Modulation	DTW	Dynamic Time Warping
EH	Energy Harvesting	FFT	Fast Fourier Transform
FM	Frequency Modulation	FSK	Frequency Shift Keying
IoT	Internet of Things	IQ	In-phase and Quadrature
Kbps	Kilobits per second	LCD	Liquid Crystal Display
LoRA	Long Range Radio	LoS	Line of Sight
MAC	Medium Access Control	Mbps	Megabits per second
MCB	Multi-Carrier Backscatter	MCCU	Multi-Channel Cluster Union
MCS	Modulation and Coding Scheme	MDP	Markov Decision Process
MFS	Multiple Frequency Scheme	MIMO	multiple-input–multiple-output
NIC	Network Interface Card	OFDMA	Orthogonal Frequency Division Multiple Access
OFG	One Flip Graph	PAM	Pulse Amplitude Modulation
PQAM	Polarization-based Quadrature Amplitude modulation	PS	Power Splitting
QTT	Quantum Tunnel Tag	RF	Radio Frequency
RFID	Radio Frequency Identification	RIF	Retrodirective Ideality Factor
RNR	Region of Negative Resistance	RSSI	Received Signal Strength Indicator
SDR	Software Defined Radio	SIC	Successive Interference Cancellation
SNR	Signal-to-Noise Ratio	SPI	Serial Peripheral Interface
SVM	Support Vector Machine	T2T	Tag to Tag
ToF	Time of Flight	TS	Time Switching
UAV	Unmanned Aerial Vehicle	VL	Visible Light
VLC	Visible Light Communication	WPCN	Wireless Powered Communication Network
WS	Wireless Sensing		

Table 2
Perspectives of existing studies on BackCom.

Reference	Year	Perspective
Jameel et al. (2019)	2019	Detailed study of BackCom applications (current and future) from healthcare perspective.
Liu et al. (2019)	2019	Detailed study of BackCom for future IoT applications by discussing existing and future techniques and architectures of BackCom based IoT.
Xu et al. (2018)	2018	Detailed study of BackCom from signal processing perspective and survey of recent literature focusing mostly on bistatic architecture. Future real-world applications and open research issues
Van Huynh et al. (2018)	2018	Detailed study of BackCom communication with focus on Ambient BackCom. A survey of how existing techniques enhanced the performance of ambient BackCom. Real-world applications and open research issues
Memon et al. (2019)	2019	Detailed study of BackCom as a solution to limited battery life problem and its potential in future (5G) battery-free (heterogeneous wireless) communication applications

future research work in healthcare BackCom, such as testing on live humans, security, and broader coverage, were discussed. Further, authors in Liu et al. (2019) discussed BackCom in next-generation IoT. The authors discussed the architectures and principles of the BackCom tag operation. Further, they classified existing BackCom-based IoT into; architectures (multiple access BackCom, ambient BackCom with power beacons, and inter-technology BackCom) and techniques (full-duplex BackCom, multiple-input–multiple-output (MIMO) BackCom, and time-hopping BackCom). Lastly, they discussed future research issues in biomedical, smart home and city, and logistics applications. Similarly, authors in Xu et al. (2018) discussed the signal processing techniques of BackCom in IoT. They provided an overview of BackCom, and the processing of backscatter signal by manipulating the reflection coefficient of tag was given in detail. They evaluated existing works based on; range, cost, energy efficiency, and bit rate. Lastly, they discussed open research issues (MIMO, full-duplex, and multiple access) related to future applications (universal localization, universal surveillance, and invasive monitoring). Authors in Van Huynh et al. (2018) discussed BackCom in detail with an emphasis on ambient BackCom. They discussed the architectures, operating principles, and various techniques for designing efficient BackCom systems. Then, they gave the advantages and disadvantages of various architectures of BackCom. Existing works on the various architectures were evaluated based on; communication range, communication rate, and energy consumption reduction. Lastly, open research issues (interference, heterogeneity of ambient signal, full-duplex, and security) and future applications (tag-to-tag communication, visible light (VL) BackCom, and relay networks with BackCom) were discussed. Lastly, authors in Memon et al. (2019) discussed the problem of limited energy in communication systems, evolution, architectures, and protocols in BackCom. They classified and discussed existing works based on the aspect (range, reliability, signal processing, and power transfer) of BackCom they address. Then, open research issues (interference management, eavesdropping, and limited range) and future applications (new protocols, BackCom with artificial intelligence, and BackCom channel coding) were discussed. Table 2 shows the perspectives of existing survey papers on BackCom.

Despite the breadth of existing studies on BackCom, a study discussing how BackCom can be used to achieve wireless sensing is still lacking. Hence, this paper sets out to achieve that aim by making the following contributions;

1. Describe BackCom, its operating principle, and its various categories based on; architecture, type of carrier signal, number of underlying technologies, number of excitation sources, and number of backscatter hops.
2. Describe BBWS, its applications, and techniques (power management, channel model, range and coverage, throughput, security, quality of backscatter signal, modulation, and coding) to enhance its performance.

3. Discuss future BBWS applications and open issues related to the future applications.

The rest of the paper is structured as follows; Section 2 provides description of BackCom, its categories and evolution. Section 3 discusses BBWS and its applications. Section 4 discusses techniques for enhancing performance of BBWS. Section 5 identifies future applications of BBWS and research issues related to those applications. Lastly, Section 6 concludes the paper.

2. Backscatter Communication (milestones, operation and categories)

This section explains the evolution of BackCom, the operating principle of BackCom, and its categories based on; architecture, type of carrier signal, number of excitation sources, number of backscatter hops, type of modulation, and number of underlying technologies.

BackCom involves using carrier signals (such as WiFi (Zhang et al., 2016a), RFID (Kimionis et al., 2012), acoustic (Jang and Adib, 2019), frequency modulation (FM) radio (Wang et al., 2017) or cellular (Liu et al., 2013)) from a source (exciter) to modulate data at a tag and reflect (backscatter) the data-laden modulated signal to a receiver. The receiver could be the same source that generated the carrier signal or another device. In a nutshell, BackCom operates just like a heliograph. The heliograph uses a mirror to reflect a light source from the sun towards a remote target (receiver). BackCom's ability to transmit information without active generation of a carrier signal enables microwatt-level of operation. Hence, allowing for the sustainable battery-free operation of IoT devices.

Major milestones in BackCom's evolution start from the Great Seal bug (Brooker and Gomez, 2013) a spying device disguisedly placed in the US ambassador's office in the soviet union. The device was employed to eavesdrop on conversations taking place in the office. Next, a design and feasibility test was conducted using reflected power for communication. Therein, a carrier signal is generated by the receiver while the active radio transmitter is replaced by a modulated reflector (Stockman, 1948). Subsequently, RFID was developed, commercialized, and standardized. Initial deployment scenarios include; toll gate fee collection, securing access to locations and equipment, e-passport, automotive, and management of logistics (Chawla and Ha, 2007). Further, an architecture (Bistatic) aimed at enhancing the range of BackCom while retaining the excitation source was designed (Kimionis et al., 2012). Then, ambient BackCom was designed in Liu et al. (2013) where TV and cellular signals were used as sources of excitation. Similarly, ambient WiFi signal was used as a carrier in Kellogg et al. (2014a), and ambient visible light (VL) based BackCom was designed in Li et al. (2015). Then, full-duplex BackCom was designed in Liu et al. (2014) to have a feedback channel for addressing the effect of interference. To harness the benefits of short-range, low-power, and high data rates, authors in Kimionis et al. (2017) developed the first end-to-end mmWave BackCom network. Then, multi-hop techniques for enhancing the range and coverage of BackCom (Zhao et al., 2018b) while MIMO-based BackCom was introduced in Zhao et al. (2018a) to enhance throughput. Further, attempts to secure BackCom systems started with work in Luo et al. (2018b). The first implementation of acoustic BackCom was done in Jang and Adib (2019) to enable underwater networking. Most recently, ultra-wideband underwater BackCom (Ghaffarivardavagh et al., 2020) was enabled using metamaterial-aided acoustic communication. Further, integration of a hybrid (radio and visible light) BackCom was implemented in Galisteo et al. (2020) to address the uplink and downlink challenges of RF and VL BackCom, respectively. Recently, authors in Katanbaf et al. (2021) developed the first full-duplex LoRA BackCom for operation over long distances at low power. These milestones and future works to be carried out will further underscore the ability of BackCom systems to perform sensing and communication simultaneously while maintaining a micro-watt level of power consumption.

2.1. Architecture of BackCom system

The conventional BackCom system's architecture consists of a source (exciter), backscatter tag(s), receiver, and BackCom channels. The source provides a high-energy carrier signal. The carrier signal has two main functions; provide energy for the backscatter tag's onboard computation and serve as the carrier signal for modulating data at the tag for backscattering. The higher the strength of the carrier signal, the more energy is available for both operations. Simple energy harvesting techniques will suffice if the carrier signal is from a dedicated source (such as an RFID reader). However, the non-stability of non-dedicated sources (ambient signals) calls for more complex energy harvesting techniques. Further, the carrier signal can be information-laden before incidence at the backscatter tag. Hence, the tag must provide innovative ways of modulating the tag's information without affecting the information already present in the carrier signal. The source and backscatter tag channels are similar to conventional communication channels. However, the backscatter channel (between backscatter tag and receiver) is drastically different with many factors such as; antenna gain, modulation factor, and blockages, affecting its performance (Griffin and Durgin, 2009). An incident carrier signal is reflected by creating a mismatch between the impedance of the tag's antenna and that of the tag's load. This is shown in (1).

$$\tau_i = \frac{Z_i - Z_0}{Z_i + Z_0} \tag{1}$$

where; τ_i is the reflection coefficient at the tag, Z_i is the tag load impedance and Z_0 is the characteristic impedance of the tag's antenna. The values (i = 0, 1, 2,…, n) of the load takes finite number of states in digital BackCom. While it takes a countably infinite number in analog BackCom. Therefore, incident carrier signal (S_i) at the tag is used to modulate data using the instantaneous reflection coefficient (τ_i) to produce a reflected signal (S_r) as shown in (2).

$$S_r = \tau_i \cdot S_i \tag{2}$$

In digital BackCom modulation, a controller is used to select a state based on the data to be modulated. On the other hand, analog modulation uses passive components to directly map data for modulation unto continuous variations in amplitude, frequency, or phase of the carrier signal. Digital modulation allows for a wider range of data to be modulated into a carrier signal at the expense of additional power consumption. While analog modulation allows for lower power BackCom applications. The tag's antenna requires careful design considerations (Van Huynh et al., 2018). Though BackCom can work effectively with battery-free (passive) tags, adding a power source (or low-budget battery) to the tag and making it active would enhance its performance. At the receiver, signal processing techniques are applied to extract the modulated data (Xu et al., 2018; Van Huynh et al., 2018).

2.2. Categories of BackCom systems

BackCom systems can be categorized in many ways. Based on architecture, it can be classified into dedicated and non-dedicated source architecture as shown in Figs. 1–3. In the dedicated source architecture, an exciter is always available for BackCom. The exciter sends a carrier signal whenever it wants to communicate with the tag. Hence, there is always a stable and high energy carrier signal for energy harvesting and reflection at the tag. This category is further divided into monostatic (Durgin, 2015; Wang et al., 2019b; Akbar et al., 2016) (centralized exciter and receiver) and bistatic architecture (Kimionis et al., 2012, 2013) (distributed exciter and receiver). In the non-dedicated source architecture, a carrier signal originally meant for other communication purposes (FM radio (Daskalakis et al., 2017), TV or WiFi (Liu et al., 2013)) is exploited to achieve BackCom. These communication signals are not always available for the backscatter tags. Where available, they

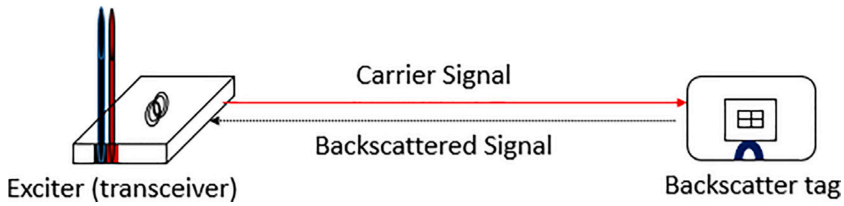

Fig. 1. Monostatic.

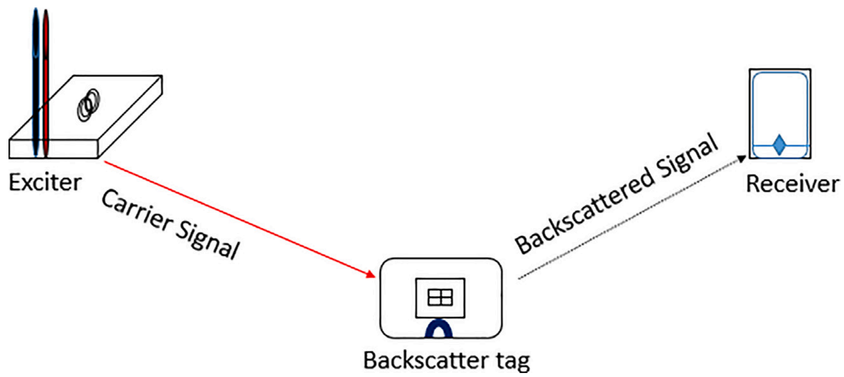

Fig. 2. Bistatic.

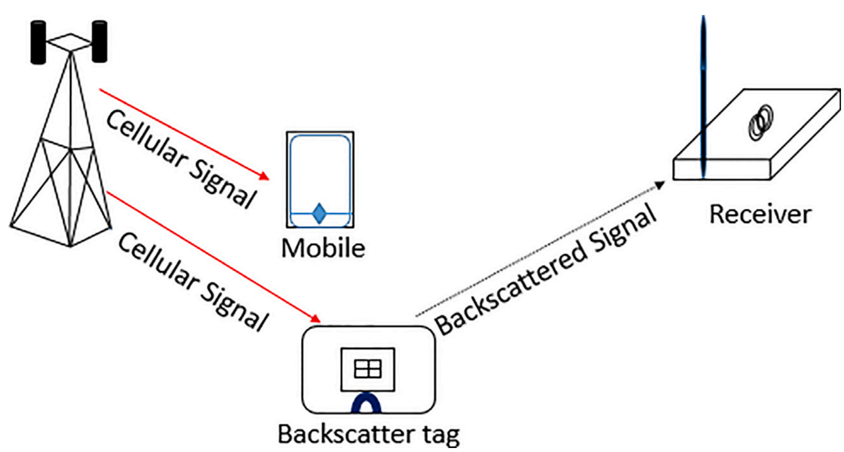

Fig. 3. Ambient.

might be weak due to fading. Hence, utilizing such signals requires the careful design of tags.

Based on the type of carrier signal, BackCom systems can be categorized into; modulated and non-modulated carrier BackCom as shown in Fig. 4. In non-modulated carrier BackCom (Ranganathan et al., 2018), a high energy tone signal is generated as a carrier. While in modulated carrier BackCom (Wang et al., 2017), the carrier signal contains information meant to be received and decoded by the backscatter tag or a legacy receiver. BackCom systems can also be classified based on underlying technology into; inter-technology and intra-technology BackCom (see Fig. 5). In intra-technology BackCom, the technology utilized by the source is the same technology utilized by the BackCom receiver (Zhang et al., 2016a; Jang and Adib, 2019; Rosenthal and Reynolds, 2019). The backscatter tag does not make any significant channel modification to its incident carrier during modulation and reflection. A particular case under this category is systems that shift the backscatter signal to another channel that can still be received on the same technology band (Zhang et al., 2016b) while avoiding interference. On the other hand, inter-technology BackCom allows backscatter tags to make channel modifications to its incident signal from the source. Hence, the modulated backscatter signal can be received using a device with a different underlying technology from that of the source (Iyer et al., 2016; Jung et al., 2020). Further, BackCom systems can be classified based on the number of sources into single and multiple excitation source BackCom. In a single source excitation BackCom (Ranganathan et al., 2018), the backscatter tag's operation depends only on one source. In contrast, multiple excitation source BackCom (Galisteo et al., 2020; Zhao et al., 2020a) allows for more than one source, thereby making more energy-containing signals available for the backscatter tags in the system. Lastly, the BackCom system could be classified into single-hop and multi-hop based on the number of hops between source and receiver. In single-hop systems (Iyer et al., 2016), there is only one tag between the source and receiver. While multi-hop systems (Zhao et al., 2018b, 2020a) have multiple tags and data is backscattered between tags towards a receiver. A summary of different types of BackCom systems and their advantages and disadvantages are given in Table 3.

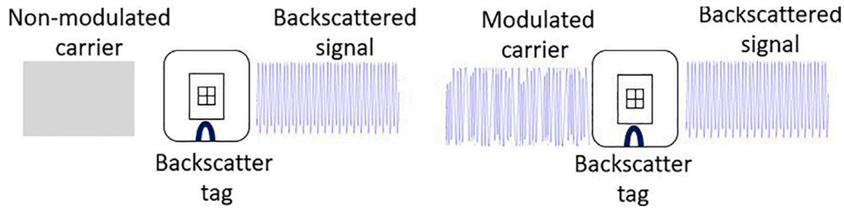

Fig. 4. Modulated and Non-modulated carrier BackCom.

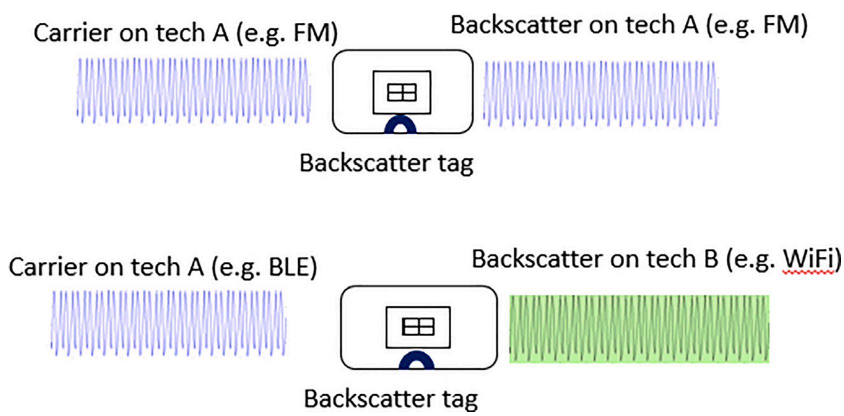

Fig. 5. Inter and Intra-technology BackCom.

Table 3
Categories of BackCom, their advantages and disadvantages.

BackCom system	Categorization metric	Category name	Advantage(s)	Disadvantage(s)
Durgin (2015) Wang et al. (2019b) Akbar et al. (2016)	Presence of excitation source	Dedicated source (Monostatic)	Ease of deployment	High cost of reader, Short range
Kimionis et al. (2012) Kimionis et al. (2013)	Presence of excitation source	Dedicated source (Bistatic)	Enhanced coverage, Suitable for low bitrate sensing	Interference of carrier and backscatter signal at receiver
Liu et al. (2013) Daskalakis et al. (2017) Bharadia et al. (2015) Xu et al. (2017)	Presence of excitation source	Non-dedicated source (Ambient)	Low cost due to non-generation of carrier signal	Non-stability of carrier signal
Ranganathan et al. (2018)	Type of carrier signal	Non-modulated carrier	Ease of modulation and demodulation	Generating non-modulated carrier adds cost
Wang et al. (2017)	Type of carrier signal	Modulated carrier	Ambient signals are usually modulated	Complex modulation and demodulation is required
Zhang et al. (2016a) Jang and Adib (2019) Rosenthal and Reynolds (2019)	Underlying technology	Intra-technology	Simpler tag design	Limitation on number of receivers
Iyer et al. (2016) Jung et al. (2020)	Underlying technology	Inter-technology	Pervasiveness	More complex tag design
Ranganathan et al. (2018)	Number of excitation sources	Single	Ease of matching circuit design	Less range and coverage
Galisteo et al. (2020) Zhao et al. (2020a)	Number of excitation sources	Multiple	More energy for tag excitation	More complex antenna required at the tag
Iyer et al. (2016)	Number of hops	Single	Ease of coordinating backscatter signal	More complex antenna required at the tag
Zhao et al. (2018b) Zhao et al. (2020a)	Number of hops	Multiple	Larger coverage and range	Tag-to-tag interference, Susceptible to noise after few hops

3. Backscatter communication-based wireless sensing (description and applications)

This section describes WS and its various applications. It also highlights the strengths of BBWS. Lastly, applications of BBWS are discussed.

WS for achieving ubiquitous sensing in the next generation of IoT systems involves using wireless signals to sense and transmit information. WS can be done with sensor nodes (Huang et al., 2017) or without sensor nodes (Lee et al., 2010). In the former, sensing information is modulated onto an onboard generated carrier signal and then transmitted. In the latter, the sensing information is transmitted by altering some properties of wireless signals when they interact with the entity to be sensed. Wireless signals meant for various communication technologies (such as; WiFi, visible light communication (VLC), Bluetooth low energy (BLE), RFID, FM radio) have been used in wireless sensing applications; fall detection (Wang et al., 2016), gesture recognition (He et al., 2015), sign language recognition (Zhang et al., 2020b), positioning (Wang et al., 2019b; Wu et al., 2012), orientation tracking (Jiang et al., 2019), building sensing (Zhang et al., 2019a; Stanaćević et al., 2021) and human pose sensing (Jiang et al., 2020).

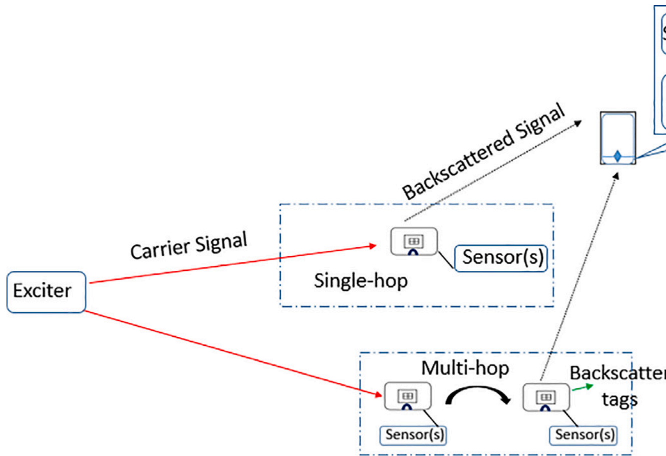

Fig. 6. Architecture of BBWS.

Table 4
Comparison between WS and BBWS.

WS	BBWS
Performance of sensing task is based on quality of wireless signals from the source	Performance of sensing task can be improved by enhancing backscatter signals at the tag
Sensing application is limited to the technology of source signal	Sensing application can be extended to other technologies by signal modifications at the tag
Higher cost of operation due to excitation signal generation	Lower cost of operation due to leveraging reflection of signals
Limited ubiquity i.e. cannot provide internet connections to sensing devices	Enable ubiquity through internet connections to sensing devices
Limited sensing of remote and challenging environments	Can enable sensing of remote and challenging environments such as; underwater and and deep in-body

These systems have shown promising results in various application scenarios. However, they fail to address certain WS challenges, including the elimination of dependence on battery, limited computational power in WS with nodes, and single technology-based sensing in WS without nodes. These challenges are addressed by incorporating BackCom into sensing systems, as shown in Fig. 6.

Battery-free operation of nodes in BBWS allows for continuous sensing of hostile environments (Fan et al., 2020), BackCom can move complex computation from tags to receivers (Vannucci et al., 2008) and multiple-technology domain sensing (Jung et al., 2020) allows for ubiquitous sensing. Also, in BBWS, a backscatter tag can be effectively transformed in a multi-parameter sensor (Wang et al., 2018). Merits of BBWS over WS are shown in Table 4. BBWS includes; human activity sensing, plant activity sensing localization and tracking, environment sensing, and other applications.

Human activity sensing applications with BackCom include; a body area network (BAN) for monitoring physical parameters on the human body (Zhang et al., 2016b). The backscatter tags enable reception on COTS devices without interference. A similar application for continuously monitoring human vitals in a hospital is designed in Ranganathan et al. (2018). A band that collects the vitals' signal to transmit to an SDR provided promising results. A first approach for enabling continuous and wearable device-free and battery-free gesture recognition on computing devices was designed in Kellogg et al. (2014b). Experiments with ambient RFID and TV signals individually showed high accuracy in identifying gestures. Further, the uncontrollable ambient signals from many (heterogeneous) devices were exploited together to perform gesture recognition EAR (Chi et al., 2018) with high accuracy even when traffic from devices is low. The authors in BARNET (Ryoo et al., 2018) designed a scalable human activity (such as walking, falling, and brushing) sensing system. The tag–tag backscatter channel state information (CSI) was exploited to identify the various activities within an environment where backscatter tags are deployed. To address occlusion suffered by camera-based motion tracking in indoor environments, authors in Joshi et al. (2015) designed WiDeo. WiDeo uses RF backscatter to trace human movements across a wall by mining the reflected signals. It showed the ability to trace movement in static and dynamic indoor environments. Lastly, BackCom was used to implement sentence-level language recognition (Meng et al., 2019) to enhance communication with deaf people and recognize speech affected by dysphonia (Wang et al., 2019a).

Plant activity sensing applications include; designing a bistatic BackCom-based sensor node for monitoring the physiology of plants (Konstantopoulos et al., 2013; Daskalakis et al., 2018b). This enabled low-cost optimum means of managing the stress of plants over a large area. To enhance the work in Konstantopoulos et al. (2013), authors in Konstantopoulos et al. (2015) harvested energy from the plants being monitored. Ambient BackCom techniques underlying FM signals were used in Daskalakis et al. (2017) to monitor plants by sensing temperature difference between plant leaves and air. Since the sensor nodes receive many incident FM signals, authors in Vougioukas and Bletsas (2017) designed selection diversity techniques to achieve better tag performance based on selected ambient (FM radio) signals. While the preceding systems monitor plant physiology from stem and leaves, authors in Daskalakis et al. (2016), Wang et al. (2020a) designed BackCom techniques for monitoring soil moisture and hence the plant physiology.

Localization and tracking applications have received much attention. In-body localization of implantable devices using time of flight (ToF) was designed in Vasisht et al. (2018). Similarly, an RFID tag array was used in SpareTag (Yang et al., 2019) to enhance indoor localization using the Direction of Arrival (DoA) technique. For batch localization of backscatter tags, authors in Tong et al. (2019) exploited the subcarrier CSI of the tags. While preceding systems utilized RF signals to localize tags, authors in Naderiparizi (2017) used BackCom to enable capture and surveillance. Tracking of robotic tasks using BackCom was implemented in Luo et al. (2019), Zhang et al. (2019b) while unmanned aerial vehicle (UAV) tracking applications were implemented in Ma et al. (2017), Zhang et al. (2020). Lastly, applications that require tracking the orientation of objects and the human body by exploiting phase changes in the tag's backscatter signal were presented in Akbar et al. (2016), Jiang et al. (2019), Jin et al. (2018b).

Many other applications such as; monitoring the underwater environment (Jang and Adib, 2019), sensing the environment in space (Qi et al., 2018), sensing physical (light) parameters in building with TunnelScatter (Varshney et al., 2019) and sensing overall activities in a building (Zhang et al., 2019a) with battery-free self-sustained tags were developed. Further, visible light-based sensing systems for gesture recognition (Varshney et al., 2017b) and infrastructure-to-vehicle (I2V) communication (Wang et al., 2020b) were designed.

4. Techniques for enhancing the performance of BBWS

This section discusses techniques that have been used to improve the performance of BBWS. These techniques are discussed based on the aspects of BBWS they improve. The various aspects of BBWS considered are; power management, channel model, range and coverage, throughput, security, quality of backscatter signal, and modulation and coding.

4.1. Power management in BBWS

The continuous operation of BBWS systems requires efficient energy harvesting (EH) and management of the limited power at the tag. This is necessary due to the tag's limited storage and minimal room for adding backup batteries.

In Kimionis et al. (2013), the bistatic architecture of backscatter systems was leveraged to enhance the performance of BBWS in a power-limited scenario. Since the reader and receiver are distributed, the possibility of a carrier signal generator (energy source) being close to a sensor significantly increases. Hence, the sensors can readily harvest energy and enable continuous sensing. Further, In-N-Out (Fan et al., 2020) used harvested energy from distributed antenna beams for continuous deep (10 cm) tissue sensing. Therefore, an iterative algorithm was designed to steer the energy beam towards the sensor based on the sensor's CSI. The challenge of obtaining the sensor's CSI is addressed by using backscatter signals at the implant to relay information to a master radio. In-N-out achieved a 0.37 mW average charging power and power gains when the implant device is static and in motion. Similarly, authors in SkinnyPower (Shukla et al., 2019) designed intra-body means of transferring power to on-body and battery-free sensing devices from battery-enabled ones. For a robust return path, a capacitive coupling model was used. SkinnyPower achieved 14.5% power transfer rate and the ability to support up to 1 mW of power.

In contrast to improving the hardware architecture, QuarkNet (Zhang and Ganesan, 2014) proposed an energy-aware scalable network stack. QuarkNet optimizes the performance of backscatter nodes by scaling (down to bit level) the size of the packet to be transmitted. The extent of scaling depends on the available energy at the tag. QuarkNet achieved a significant increase in range and throughput.

-Lessons Learnt

- We can observe that the existing literature has investigated various techniques that enhance the availability of energy for BackCom nodes. However, the techniques are limited to node EH and the architecture re-design at node and network levels.
- For enhanced sustainability of BBWS, a promising EH solution for the future is contextual energy harvesting, where nodes harvest energy from sensing activity such as vibration and temperature sensing. Also, 3D-printing techniques could be leveraged to enhance the power management in BBWS (see Tables 5–11).

4.2. Channel model of BBWS

The channel of a BackCom system requires careful modeling due to its extra complexity over conventional communication channels. With BBWS opening up some application scenarios that were not previously addressed with conventional channel models, additional modeling parameters need to be considered. A discussion on some of the channel models is presented.

BBWS involves modulating radio signals that sometimes already have modulated information (such as WiFi, cellular, and FM radio signal). Hence, its range and signaling will have certain limitations. An RF link budget that models the expected returns and range was developed in Varner and Durgin (2018). Further, the authors in Alhassoun and Durgin (2019) modeled retrodirective tags' backscatter channel in the presence of fading. The retrodirective channels showed single fading similar to one-way radio links. Also, the channels were highly sensitive to the structure of the diffused multipath waves. Though BBWS systems provided a low-cost means of monitoring plants (Daskalakis et al., 2018b; Wang et al., 2020a), existing propagation models do not provide the effects of grass moisture on near-ground RF propagation in a sizeable non-uniform grass area. Hence, authors in Cheu et al. (2016) carried out experiments that involved the measurement of signal strengths between two horn antennas in a near-ground setting with varying moisture on grasses at 3–4 GHz. In the experiment, a decrease in moisture content of the grasses showed decreasing signal strengths implying a dielectric waveguide effect as a result of wet grasses. A 6.5 dB increase in signal strength at an 8 m separation between the antennas showed a vital result in developing path loss models for such a scenario. It also shows the promise of using propagation characteristics to wirelessly sense moisture content in vegetation. Similarly, authors in Shi et al. (2020) modeled the channel of BBWS using a cellular network signal as an ambient carrier. In contrast to existing models, Shi et al. (2020) considered; the effect of interference between legacy transmissions and backscatter transmission, interference between backscatter nodes, and non-linear EH model in modeling and analyzing the backscatter system. A time-switching (TS)/power splitting (PS) operations scheme was designed where devices can harvest energy and modulate and reflect ambient signals. Numerical results of the TS/PS scheme showed a near-optimal outage capacity performance. While previous simulation and numerical studies showed the theoretical performance limits of AmBC, authors in Gu et al. (2021) conducted ambient RF density measurements for city-wide planning of BackCom-based IoT network deployment. The RF power level measurements were conducted along major roads, highways, and high traffic density areas of Montreal in the 400–2700 MHz frequency spectrum. Cellular bands showed higher suitability (in urban areas), while TV bands showed higher suitability (in suburban areas) for AmBC.

In multiple-tag BackCom networks, the performance of sensing applications is limited due to difficulty in estimating the parallel channels between the tags and the receiver. Authors in Jin et al. (2021) proposed a novel technique for channel estimation in multi-tag AmBC. Based on the insight that the movement of signals in the presence of collision is maintained despite variation in tag modulation, models for characterizing the relationship between signal variation and collision

Table 5
Summary of power management techniques.

Reference	Approach	Implementation	Performance
Kimionis et al. (2013)	Increase proximity of sensor to carrier	Design a distributed (Bistatic) architecture to enhance energy harvesting	More energy is available for continuous sensing
In-N-out Fan et al. (2020)	Enable enhanced EH for deep tissue sensing	Algorithm that can concentrate the energy of distributed antenna beams towards the sensor	High (0.37 mW) average charging power
SkinnyPower Shukla et al. (2019)	Transfer power to on-body battery-free sensor via skin	Model the capacitive coupling and robust return path	Sensor can support up to 1 mW and high (14.5%) power transfer rate
QuarkNet Zhang and Ganesan (2014)	Reduce energy consumption via scaling of operating power	Design a scalable (bit-level) network stack based on available energy at tag	Optimum BackCom node performance

Table 6
Summary of channel modeling techniques.

Reference	Approach	Implementation	Performance
Varner and Durgin (2018)	Investigate the expected returns and gains of backscatter channel	Model the backscatter channel considering the mechanism of RF propagation	A complete BackCom link budget was developed
Alhassoun and Durgin (2019)	Investigate the expected returns and gains of backscatter channel	Model the channel of retrodirective tags in the presence of fading	Retrodirective channels showed similar properties to one-way radio link
Cheu et al. (2016)	Investigate the effects of RF propagation in wet grasses	Take signal strength measurements between two horn antennas close to the ground	Moisture showed direct relation with signal strength implying waveguide effect
Shi et al. (2020)	Investigate effect of interference in BackCom channel underlaying cellular network	Model an operating scheme that switches between harvesting and transmitting times	Near optimal outage capacity was achieved
Gu et al. (2021)	Investigate city-wide ambient RF signal density	Measure RF power levels along roads and busy areas with human traffic	Cellular communication bands were most suitable for BackCom in cities
Jin et al. (2021)	Channel estimation in multi-tag AmBC	Model the relationship between moving tag signals and collision	Estimate channel of multi-tag (up to five) AmBC network.

were used for channel estimation. The proposed technique enabled high accuracy channel estimation of a 5-tag AmBC network.

-Lessons Learnt

- We can observe that the existing literature has investigated RF channel models in BackCom. The effect of some physical phenomena on the channel models was shown. However, BackCom also has applications in underwater and visible light scenarios.
- Hence, future research on channel models should consider underwater and visible light applications of BBWS. The underwater models will be quite complex since they have to consider water's various physical and chemical properties.

4.3. Range and coverage in BBWS

Considering range from the perspective of the distance between a backscatter tag (sensor) and a receiver (or reader), BBWS requires different ranges depending on the application. Factors such as; the signal strength of the ambient carrier, the strength of the backscattered signal, and the energy of the tag determine the range of operation in BBWS systems. Techniques for improving the range revolve around addressing those factors. Sometimes tags are required to cover a particular area and collectively sense parameters in that region. Hence, techniques to enhance tags' coverage for sensing are employed.

Conventional BBWS systems are yet to provide long range and reliable sensing functionalities despite their low cost and operation at low power. This is due to the attenuation of signal from RF source to backscatter tag and then backscatter tag to receiver. Even with that, the attenuated signal at the receiver is interfered with a signal of higher strength directly form the RF source. In many RFID based sensing applications, a monostatic backscatter architecture is used. Though effective in sensing but the range limits its deployment. An approach to increasing the range by at least 29% is presented in Kimionis et al. (2012). The approach involves separating the carrier generator from the receiver. This allows backscatter nodes to be closer to carrier generators and hence enabling higher energy backscatter signals. In a quest to achieve true ubiquity, authors in Talla et al. (2017a) proposed a LoRA based backscatter that can enable sensing over hundreds of meters and even Kilometers. This requires deploying a backscatter node that will modulate information in a way that is decodable in the presence of a high tone signal. And the receiver needs to be a cheaply available commodity hardware. These challenges are addressed by; redesigning the physical layer of LoRA (most sensitive (−149 dBm) existing radio) in order to allow generation of Chirp Spread Spectrum (CSS) modulated packets and designing a harmonics cancellation mechanism that will reduce out-of-band interference and improve spectral efficiency. The LoRA backscatter integrated circuit (IC) achieved a power consumption of 9.25 μW and could operate at any point between an RF source and receiver separated by 475 m. The backscatter device could also achieve a range of 2.8 km when it is collocated with the RF source. While Talla et al. (2017a) extended the range for only devices that can decode LoRA packets, LoRea (Varshney et al., 2017a) proposed a Computational RFID (CRFID) based architecture that improves the power, cost and range of sensing allowing cross technology backscatter. To achieve that, a bistatic approach is adopted where multiple sources of RF carrier signals (at low bit rates) are generated to avoid self-interference at the reader. The signals are backscattered at different frequencies to different commodity devices to avoid cross technology interference (CTI). The system consumed 70 μW of power (at 868 MHz) and 650 μW (at 2.4 GHz) while costing 70 USD. When the tag is located within 1 m of carrier signal (28dBm) in 868 MHz band, a range of 3.4 km was achieved. In PolarScatter (Song et al., 2020), long range backscatter was achieved by polarizing the signals. Thereby, eliminating noise in the channels. Polar codes that are adaptive to channel quality were then used to transmit information with low error probabilities. In addition to modifying the architecture of backscatter systems to improve range, Amato et al. (2017, 2018) proposed the Quantum Tunnel Tags (QTT). The QTTs exploit the quantum tunneling effect to enable highly sensitive (−84 dBm) tags that have high return gain (35 dB). The carrier wave is amplified by setting biasing point conditions without increasing power consumption. Experiments at 5.8 GHz show that QTT can achieve 1.2 km backscatter range while consuming 20.4 μW.

Table 7
Summary of range and coverage enhancement techniques.

Reference	Approach	Implementation	Performance
Kimionis et al. (2012)	Enhance the coverage of RFID sensing	Separate the carrier generator from the receiver to enable higher energy for nodes	The range was extended by 29%
Talla et al. (2017a)	Achieve ubiquity (up to Km) with LoRA	Redesign the PHY layer of LoRA to allow CSS modulated packets and harmonics cancellation	The LoRA IC consumed 9.25 μ W and could achieve 2.8 km range
LoRea Varshney et al. (2017a)	Achieve long range cross technology	Design CRFID that can backscatter multiple excitation signals at different frequencies	The systems achieved 3.4 km, consumed 70 μW (at 868 MHz) and 650 μW (at 2.4 GHz)
PolarScatter Song et al. (2020)	Leverage polarization to enhance range	Develop polar codes that are adaptive to channel quality	Long range was achieved with low bit error rates
Amato et al. (2017) Amato et al. (2018)	Enhance the sensitivity of tags	Leverage quantum tunneling effect to develop backscatter tags	A range of 1.2 km was achieved with a 20.4 μW power budget
Alhassoun et al. (2017)	Enhance the coverage of RFID tags	Design a rat race coupler and attach to the tag to enable reflection in many directions (retrodirectivity)	Near ideal coverage at the tag
Alhassoun et al. (2018)	Enhance the performance of highly directive backscatter links	Deploy rate race coupler as a feeder to tags and tunnel diodes to enhance tags performance	A high (6 dB) gain tag that can address path loss in directive (microwave and mmWave) links
Varner et al. (2018)	Harness the array (MIMO-like) properties of directed links	Subdivide the retrodirective tag array and investigate; link budget, information theory and beam-forming	Properties investigated showed possibility to enhance coverage and range
PassiveVLC Xu et al. (2017)	Explore highly directive VL links (retroreflection)	Develop a trend based modulation and a code assisted demodulation	Achieved a data rate of 1 Kbps
RETROTURBO Wu et al. (2020)	Exploit channel capacity to improve VL links	Design novel modulation schemes (DSM and PQAM) to fully exploit time and polarization domains of the channel	A 7.5 m range was achieved and data rate of 8 Kbps
Zheng et al. (2018)	Leverage multiple hops for range and coverage enhancement	An algorithm that allows device far from source simultaneously harvest energy while backscattering to device closer to source	Increased coverage and throughput
NetScatter Hessar et al. (2019)	Enable multiple single hops from tags at various locations to an AP	Develop distributed CSS at the tag to modulate data and use FFT at the AP to demodulate	Enable 256 concurrent transmissions to an AP
X-Tandem Zhao et al. (2018b)	Two-hop backscatter sensing with WiFi	An MFS scheme that allowed tags to backscatter at different frequencies while using control signal to assign data fields to tags	Achieved a throughput of 200 bps and 8 m range at 0.4 m tag–tag separation
Majid et al. (2019)	Multi-hop network for enhanced coverage	Flooding based link-level and MAC protocol were designed	Increased range and decreased dead spots
Zhao et al. (2020a)	Range extension and decoding of signal in multi-hop backscatter	Use multiple excitation sources	Achieved 4.8 m tag–tag distance and up to 6 tat-tag hops

RFID-based sensing systems have limited coverage in addition to their limited range. Since RFID-based sensing works with line of sight (LoS) carrier signal, the backscatter signal is only detected in the LoS of the carrier signal. In Alhassoun et al. (2017), the coverage of an RFID tag is enhanced by enabling retrodirectivity on the tag. To achieve that a rat-race coupler attached to the tag forms a retrodirective array which allows modulation and reflection of the carrier signal in multiple directions of respective incident carrier signals. Thereby, increasing the field view and coverage of the tag. The system achieved a near-ideal performance with a retrodirective ideality factor (RIF) of 1.003. Since retrodirective arrays on tags allow for highly directive backscattered signals, Alhassoun et al. (2018) proposed a high-gain (6 dB) tag that can address path loss in the microwave and mmWave backscatter systems. The system used a rat-race coupler as a feeding network on the tags whose performance can be further enhanced by adding tunnel diodes. In Varner et al. (2018), the retrodirective arrays on the tags are further divided into subarrays in order to enhance capacity and range. The system draws from the hardware and signaling advances of MIMO systems. The performance of the partitioned arrays under; link budget, information theory, and time-varying beamforming further underscores their potential in improving next-generation (microwave and mmWave) backscatter systems. A similar technique to retroreflection was used in PassiveVLC (Xu et al., 2017) to enable highly directive visible light backscatter. To improve the data rate, a trend-based modulation and code-assisted demodulation were implemented. The system achieved a throughput of 1 Kbps (8 x increase over state-of-the-art). In order to exploit the channel capacity of VL-based BackCom to enhance range and data rate, RETROTURBO (Wu et al., 2020) was proposed. RETROTURBO leveraged a high Signal-to-Noise Ratio (SNR) channel to implement novel modulation schemes (Delayed Superimposed Modulation (DSM) and Polarization-based Quadrature Amplitude Modulation (PQAM)) that fully utilize the channel in time and polarization domains. The system achieved 8 Kbps and 7.5 m range with a sub-mW power budget.

The range and coverage of sensing systems could also be enhanced by enabling single and multi-hop backscatter between tags. In Zheng et al. (2018), a single-hop backscatter was used to enhance the throughput of Wireless Powered Communication Networks (WPCN) by addressing the near-far effect. In a setting with two wireless devices at different distances from the Access Point (AP), the farther device will have less harvested energy for information transfer. As such, an algorithm that allows the farther device to simultaneously backscatter information to the nearer device while harvesting energy was designed. This allows increased throughput and coverage since backscatter allows the farther device to transmit its information with low energy. Similarly, NetScatter (Hessar et al., 2019) used single-hop transmissions between a tag and an AP to enhance coverage. The system utilized distributed CSS to modulate data at the tags and used Fast Fourier Transform

Table 8
Summary of throughput enhancement techniques.

Reference	Approach	Implementation	Performance
EkhoNet Zhang et al. (2014)	Enhance sensing by reducing computational overhead	Redesign the architecture of sensor by eliminating energy hungry components	Achieved a data rate of 780 kbps and consumed 35 μW of power
R2B Li et al. (2020b)	Eliminate computational overhead from sensing	Use SPI buses to directly connect radio to peripheral sensors	Achieved 200 kbps and consumed 25.9μW of power
BLINK Zhang et al. (2012)	Redesign backscatter link-layer	Design a mobility-aware backscatter link-layer with reduced probing overhead	Achieved mean goodput of almost 95 reads/second
CARA Gong et al. (2016)	Leverage channel diversity to enhance throughput	Design a light weight channel probing scheme for channel estimation	Achieved a better (4.1 x) goodput over BLINK
Gong et al. (2017)	Improve downlink channel to enhance overall throughput	Design a novel optimal rate adaptation protocol for both uplink and downlink	Achieved a better (1.9 x) goodput over CARA
Liu et al. (2014)	Enhance throughput with feedback channels	Designed an instantaneous feedback channel between transmitter and receiver	Reduced energy consumption and enhanced throughput
Zhao et al. (2019b)	Leverage concurrency of OFDMA to enhance throughput	Backscatter signals at tags using synthesized (analog domain) orthogonal subcarriers	Achieved a throughput of 5-16 Mbps
DigiScatter Zhu et al. (2020)	Scalable OFMA backscatter	Design synthesis (frequency-domain) of orthogonal carrier frequencies	High throughput and up to 1019 concurrent transmissions
TScatter Liu et al. (2021)	Address phase offset BackCom tags	Develop high granularity sample-level modulation	3-4 orders of magnitude higher throughput and 212x throughput over MOXcatter
MOXcatter Zhao et al. (2018a)	Exploit spatial multiplexing property of MIMO to enhance throughput	Develop MIMO transmitter and receiver for transmitting and receiving spatially multiplexed signal	Achieved 50 Kbps and 1 Kbps (single and multiple stream transmission respectively)
VMscatter Liu et al. (2020)	Fully enable spatial multiplexing on backscatter system	Develop MIMO transmitter, backscatter tag and receiver	The system achieved 500 Kbps and BER of 0.000011
FlipTracer Jin et al. (2019)	Exploit collision to improve throughput	Design OFG to track collision at the receiver	Aggregate throughput of 2 Mbps was achieved
Canon Jiang et al. (2018)	Exploit collision to improve throughput	Collided signals from different channels are extracted and clustered based on their states	Achieved a better (10 x) throughput over FlipTracer
Hubble Jin et al. (2018a)	Exploit collision to improve throughput	Develop an iterative model based on Gaussian process of collision to solve super clustering problem	Achieved a better (11.7 x) throughput over FlipTracer
Wen et al. (2019)	Enhance throughput by maximizing EH	A QL model was developed to attain sub-optimal scheduling between operation modes	Achieved 98% of optimal throughput

(FFT) at the receiver for decoding. However, timing/synchronization and near/far effect affect the communication protocol. Therefore, a careful selection of FFT bin frequencies and power-aware cyclic shifting of signals were used to overcome the problems in NetScatter. The system enabled concurrent communication between 256 devices and an AP. Further, X-Tandem (Zhao et al., 2018b) proposed a two-hop backscatter that allows sensing tags to modulate their data onto a WiFi packet which is decoded at the receiver. Achieving this requires addressing tag–tag interference, order of modulation by the tags, and order of packet reception. X-Tandem designed a multiple frequency scheme (MFS) that makes each tag backscatter at a different frequency to avoid interference. Also, the tag uses control signals to allocate fields for the modulation of data. Lastly, the modulated packet is verified at the receiver by checking its Received Signal Strength Indicator (RSSI) to avoid out-of-order reception. At a 0.4 m tag–tag distance, X-Tandem achieved a throughput of 200 bps and an 8 m range. Similarly, authors in Majid et al. (2019) presented a multi-hop tag-to-tag (T2T) network to enhance range and coverage. T2T transceivers were designed with a flooding-based link-level protocol that allows multi-hop transmission of packets. A medium access control (MAC) protocol was also designed that minimized the listening energy of backscatter tags. The result of the experiment with four T2T hops showed an increase in range by a factor of two over single-hop networks and a significant decrease in dead spots. To avoid the decay of signal strength (short-range) and the inability for tags to decode in a multi-hop scenario (due to noise), Zhao et al. (2020a) used multiple excitation sources for tags. Thereby achieving up to 4.8 m tag-to-tag distance and up to 6 tag-to-tag hops.

-Lessons Learnt

- We can observe that the existing literature has discussed several techniques for enhancing the range and coverage, including redesigning the PHY layer, MAC layer, and multiple excitation sources.
- Though high range was achieved, future research in this direction should target BBWS nodes with high gain antennas. Further, modulation techniques that can achieve long-range with low power are required.

4.4. Throughput of BBWS

Applications of BBWS have varying throughput requirements ranging from a few Kbps to rates of up to tens of Mbps. Hence, techniques for improving the throughput of systems have been developed. Some enhance specific components of the BackCom system to increase throughput while others re-design the BackCom system.

Existing WS systems consider communication to consume far more energy than sensing and computation and hence see communication as the bottleneck for sensor design. However, BBWS systems have proved otherwise by enabling communication at microwatt power levels by backscattering a carrier signal. Therefore, with low power sensing and communication in BBWS, computation becomes the bottleneck in achieving low power and high throughput. Hence, EkhoNet (Zhang et al., 2014) proposed an end-to-end reduction of energy consumption by eliminating energy-hungry computation blocks between sensing (sensor) and communication (RF frontend) components of a sensor. It also proposed a re-design of the computational architecture of a sensor to achieve higher throughput. The components to be eliminated between the sensor and RF frontend were selected after considering the energy consumption of each block. Also, a bandwidth scalable network stack was designed with a minimalist design approach that can support raw data (hundreds of Kbps) transmission and tens of nodes. The MAC layer of EkhoNet optimizes data rates and slot sizes by leveraging resources at the reader. EkhoNet achieved a power consumption of 35 μW (3.3 x better than WISP 5.0) and a throughput of 780 Kbps. Further, authors in R2B (Li et al., 2020b) proposed complete elimination of computation from the backscatter device. They proposed a novel design that allowed a backscatter radio to communicate with peripheral sensors over a serial peripheral interface (SPI) bus. R2B achieved 200 kbps and consumed 25.9 μW (26% less than EkhoNet).

While EkhnoNet leverages resources at the reader based on energy-utility and channel awareness, BLINK (Zhang et al., 2012) and CARA (Gong et al., 2016) exploit novel backscatter link layer design and channel diversity (spatial and frequency diversity) respectively to enhance the throughput of backscatter systems. BLINK designed a mobility-aware link layer with a reduced channel probing overhead. The probing of channels provides information on packet loss rate and RSSI. The information is used to assign channel rates. BLINK achieved a mean goodput of almost 95 reads/second. But BLINK assumes that backscatter nodes experience the same channel quality. So, to exploit the channel diversity, CARA requires knowledge of varying channel information at fine granularity. As a result, CARA designed a lightweight channel probing scheme to obtain important metrics (packet loss rate and RSSI) for channel estimation. Optimal data rates are then selected based on coverage of nodes and nodes with the best channel condition. CARA achieves better (4.1x) goodput gain over BLINK. Further to CARA's adaptation of data rates based on varying channels between nodes and reader (uplink), Gong et al. (2017) considers the effect of the reader-to-node channel (downlink) to improve the uplink data rate and hence overall throughput. A novel (C1G2 protocol) rate adaptation algorithm with low probing overhead was used to implement optimal rate adaptation for both uplink and downlink. An improved (1.9 x better than CARA) throughput was achieved. To have information on the channel between transmitter and receiver, Liu et al. (2014) deployed an instantaneous feedback channel between a backscatter transmitter and receiver. The feedback channel aids in reducing packet collision provides efficient retransmissions and a better rate adaptation of channels. Thereby reducing the overall energy consumption and enhancing throughput.

Drawing from the concurrency of orthogonal frequency division multiple access (OFDMA), Zhao et al. (2019b) developed a technique that improves the throughput of WiFi-based backscatter sensing systems. The concurrent links are generated by using WiFi backscatter tags to modulate sensing data unto excitation signal and reflect it at non-digitally synthesized orthogonal subcarrier frequencies, which are obtained from the tags. The phase offset of backscatter signals at the receiver is addressed using tight synchronization at the tags. Throughput of 5–16 Mbps was achieved after implementing the developed techniques. The analog domain synthesis of orthogonal carrier frequencies limits the scalability of OFDMA-based backscatter systems. Hence, DigiScatter (Zhu et al., 2020) proposed a frequency domain synthesis of orthogonal carrier frequencies. This supports up to 1019 concurrent transmissions. Similarly, authors in Liu et al. (2021) developed TScatter to address the phase offset generated by backscatter tags. Evaluations of TScatter in different environments showed 3–4 orders of magnitude lower BER and 212 times higher throughput over MOXcatter. Though high throughput was achieved in preceding OFDMA systems, the backscatter tags and the receiver have single antennas. Hence, the spatial multiplexing property of MIMO systems could be further exploited to enhance throughput. MOXcatter (Zhao et al., 2018a) proposed a MIMO-based WiFi backscatter with multiple antennas at the transmitter and receiver. The sensed data at the tag is modulated onto the spatially multiplexed ambient carrier generated at the source (transmitter) and backscattered to a commodity WiFi device (receiver). The sensed data is decoded at the receiver by comparing the received ambient backscatter signals from the source and the MOXcatter tag. The problem of changes in the order of OFDM symbols received due to the number of spatial links used and synchronization at the tag is addressed by designing a decodable modulation scheme that conveys information by changing the phase of symbols. Then, a logic for automatically selecting the number of streams to use was also implemented at the receiver. MOXcatter achieved a throughput of 50 Kbps (single-stream) and 1 Kbps (multi-stream) at the tag-receiver range of 14 m. Despite the data rates achieved by MOXcatter, it does not fully exploit the channel diversity properties of MIMO since the backscatter tag always produces the same phase changes at the receiver. Hence, VMscatter (Liu et al., 2020) employed a versatile (independent of the number of sender antenna) MIMO backscatter tag to fully exploit the channel diversity of MIMO by reducing bit error rate and increasing throughput. VMscatter addressed the challenge of enabling MIMO transmissions on a tag and decoding it at the receiver by using on/off switching to generate space–time coding and channel estimation of sender-tag-receiver, respectively. The system achieved a bit error rate (BER) of 0.000011 (862 x improvement over MOXcatter) at 6 ft (tag-reader). 2x4x4 VMscatter (two sender antennas, four tag antennas, and four receiver antennas) achieved 500 Kbps (4 x improvement over MOXcatter) at 20 m (tag-reader).

The receiver of a BBWS system experiences a lot of colliding signals due to the multiple parallel paths taken by signals in both MIMO and non-MIMO architectures. A widespread assumption is that the colliding signals are perfectly separable in the in-phase and quadrature (IQ) planes. However, the super clustering phenomenon shows otherwise and proves the colliding signals as a bottleneck to achieving high throughput. Colliding signals form clusters based on the states of collision. Moreover, the size of the cluster depends on the noise level. FlipTracer (Jin et al., 2019) exploits the peculiarity of collided signals to address the problem and improve throughput. The peculiarity is: that though the collision of signals is irregular and time-varying, the transition probabilities between signals' collided states are stable. Therefore, One-Flip-Graph (OFG) was designed and used to track collided signals at the receiver. FlipTracer achieved an aggregate throughput of almost 2Mbps. Canon (Jiang et al., 2018) addresses the super clustering problem by designing a Multi-Carrier Backscatter Module (MCB) that extracts collided signals from different channels. Moreover, a Multi-Channel Clustering Union (MCCU) algorithm separates collided signals based on their states. Canon achieved a better (10 x) throughput over state-of-the-art (FlipTracer). On the other hand, Hubble (Jin et al., 2018a) designed an iterative travel model based on the underlying Gaussian process of collided signals to address the super clustering problem. Hubble extracts collided signals based on states and then applies the Markov model to study their transitions. Lastly, error correction techniques are applied to improve the reliability of the decoding process. Hubble achieves a better (11.7 x) throughput than FlipTracer.

Outage-free BBWS requires efficient system-level scheduling between energy harvesting and sensing operation modes because tags have limited energy storage. In Wen et al. (2019), the throughput of a backscatter communication system is maximized by adaptively selecting between the two operation modes (communication and EH) based on a channel fading environment. The problem is modeled as an infinite-horizon Markov Decision Process (MDP). Where the channel distribution is known, the value iteration algorithm was used to obtain the optimal decision strategy. But in many practical scenarios, the channel distribution is not given. So, a Q-learning (QL) based reinforcement learning approach was used to select the sub-optimal strategy that

Table 9
Summary of security techniques.

Reference	Approach	Implementation	Performance
NICscatter Yang et al. (2017)	Leak information from devices using backscatter (covert) channels	Use few software commands to exploit the changing impedance of WiFi NICs and leak information	System could leak information at 1.6 bps throughput over a 2 m range
ShieldScatter Luo et al. (2018a)	Secure AP with multi-antenna structure	Assign fine grained signatures to legal and attacking devices at the AP using tags	Accurately detect 97% of attacks
SecureScatter Luo et al. (2018b)	Exploit on-body signal propagation to secure backscatter networks	Develop algorithm to separate between on-body and off-body signal in the presence of noise	Achieved 93.2% true positives and 3.18% false positives
Han et al. (2019)	Secure backscatter tags with random artificial noise	Generate noise and transmit with backscatter signal. And use SIC at legal receiver	Achieved high secrecy rate which increases with increase in tag-reader channel gain and number of tags
RF-Cloak Hassanieh et al. (2015)	Secure RFID systems with randomization	Create random carrier for modulation and randomly switch antenna to create random channel	Defend against MIMO and non-MIMO attackers
RF-Rhythm Li et al. (2020a)	Two-factor RFID tag security	Randomly create unique phase changes at the tag. Authenticate using saved sequence at the reader.	Achieved near zero false positives and false negatives
Van Huynh et al. (2019b)	Defend against jamming attacks on devices with backscatter	Utilize the high tone jamming signal as a carrier to communicate with receiver	Continuous energy harvesting and transmission by jammed devices
Dinh et al. (2019)	Secure against smart jammers	Deceive the jammer by using false transmission	Defend against jamming and improve performance
Van Huynh et al. (2019a)	Secure against smart jammers	Learn the operation of jammer and use it to adapt BackCom	Improved throughput (426%) and lower (24%) packet loss rate
Han et al. (2020)	Secure against jamming in a multi-tag AmBC network	Leverage artificial noise from tags and tag cooperation	Improved BER and secrecy rate of AmBC network

Table 10
Summary of backscatter signal enhancement techniques.

Reference	Approach	Implementation	Performance
Bletsas et al. (2010)	Investigate effect of tag's antenna on tag efficiency	Estimate the tag antenna structural mode	Proved the tag's antenna structure as the most important metric for tag efficiency
TunnelScatter Varshney et al. (2019)	Generate carrier signal in the absence of one	Leverage the RNR property of tunnel diodes to generate carrier signal	Achieved a transmission range of 18 m and consumed 57 μW of power.
Tunnel Emitter Varshney and Corneo (2020)	Eliminate dependence of carrier emitter on dedicated power supply	Leverage back injection phenomenon of tunnel diode oscillators	Backscatter across multiple floors of building while consuming tens of μW

achieves the maximum throughput. The QL-based algorithm achieved an average throughput of 98.17% of the optimal throughput.

-Lessons Learnt

- We can observe that the existing literature has discussed architecture re-design, enhancement of communication links, and adoption of ML techniques to enhance the throughput
- Though high (Mbps) throughput was achieved, future research in this direction should include the integration of other technologies such as intelligent reflecting surfaces (IRS) into the BBWS architecture. Further, highly sophisticated deep learning techniques could be deployed at the receiver to enhance the throughput.

4.5. Security of BBWS

The low power budget of BackCom systems makes them vulnerable to security threats due to the non-adoption of high power-consuming encryption protocols. To validate the vulnerability of BBWS, NICScatter (Yang et al., 2017) showed how information can be leaked from mobile devices using backscatter-based covert channels. The system exploits the changing impedance of WiFi network interface cards (NICs) due to different working states with few/no extra software commands to establish the covert channels. NICScatter could achieve 1.6 bps throughput over a 2 m range. Therefore, deploying low-power physical layer security techniques (ElHalawany et al., 2021; Wang et al., 2022) is direly needed.

In ShieldScatter (Luo et al., 2018a), backscatter tags attached to an AP in a multi-antenna-like structure were used to secure IoT devices. The structure at the AP allows for a fine-grained multipath signature assignment to a legal user and an attacker. When interacting with a user, the AP uses dynamic time warping (DTW) and support vector machines (SVM) to identify and prevent attacks. ShieldScatter could accurately detect 97% of attacks. Similarly, SecureScatter (Luo et al., 2018b) used the propagation signature of on-body signals to secure backscatter networks. Since the signals refracted due to body tissues are different from off-body signals, attacks could be easily identified. But the challenge of separating on-body propagation signatures from noise (caused by body movement) is addressed by comparing the backscatter signal with a direct path on-body signal. SecureScatter experiments showed 93.2 % true positives and 3.18% false positives. Another physical layer solution based on leveraging a random artificial noise at the tag was presented in Han et al. (2019). The system randomly generates a noise signal at a tag and transmits it to a user and an eavesdropper. This results in receiving a backscatter signal corrupted with noise. The receiver then applies successive interference cancellation (SIC) to eliminate the noise. The system showed a high secrecy rate which improves with increasing tag-reader channel gain and number of tags.

For securing RFID-based sensing systems, RF-Cloak (Hassanieh et al., 2015) leveraged randomization to secure RFID tags without adding any components. RF-Cloak randomizes modulation by generating a random carrier at the reader every time it wants to sense the tag. This leads to a random modulation. Then, the wireless channel for backscatter is also randomized by randomly switching between

Table 11
Summary of modulation and coding techniques.

Reference	Approach	Implementation	Performance
Durgin et al. (2013)	Performance of modulation schemes on backscatter channel	Deploy various Modulation schemes on an orange colored noise channel	Energy-limited tag sensitivity and range improved by low transition modulation
Durgin (2015)	Draw from optical and magnetic recordings to modulate BackCom	Consider the spectral properties of backscatter and develop balanced codes	Enhanced RFID throughput by at least 50%
Vougioukas and Bletsas (2018)	Develop a universal modulation technique for BackCom	Pseudo-FSK and S-BPSK (digital domain) while FM radio remodulation (analog domain) were developed	Efficient universal modulation with frequency switching. Also, 26 m range was achieved with 24 μW (analog domain)
Wang et al. (2012)	Increase reliability of BackCom system	Develop sparse and rateless code by allowing collision from BackCom nodes.	Increased throughput and reduced message loss rate
Parks et al. (2014)	Enhance BackCom range with multi-antenna based coding	Develop μ code based on the periodic sequences of sinusoidal signals	Achieved a range of 80 ft
Daskalakis et al. (2018a)	Modulate BackCom underlaying analog FM signal	Develop 4-PAM for modulation and transmission with a simple architecture	A throughput of 328 bps and range of 2 m were achieved with a 20 μW power budget
Varner et al. (2017a) Varner et al. (2017b)	Enhance demodulation in modulated carrier BackCom	Develop perfect pulses a carrier to communicate with receiver	Better range and signaling in the presence of noise and interference
LuxLink Bloom et al. (2019)	Modulate ambient visible light carrier signal	Develop frequency based modulation to avoid flickering	Achieved a throughput of 80 bps. And ranges; 4 m (indoor) and 60 m (outdoor)

moving antennas at the tag. RF-Cloak could defend against MIMO and non-MIMO attackers. Similarly, two-factor authentication was proposed in RF-Rhythm (Li et al., 2020a) to secure RFID tags. The first-factor authentication is generated by making a special tapping on the tag by the user. This causes unique phase changes to the backscattered signal, which are decoded by the reader. For the second factor, the reader compares the extracted sequence and compares it with the stored tapping sequence of the user. If both factors are okay, then the user passes the authentication. Experiments with RF-Rhythm achieve near-zero false positives and false negatives.

The vulnerability of BBWS can be used to defend against a jamming attack, as shown in Van Huynh et al. (2019b). Since a jamming attack prevents the transmission of signals, a backscatter device can utilize the jamming signal as a carrier to modulate information. Thereby continuously harvesting energy and communicating with a receiver. To address the uncertainty of using the jamming signal by the transmitter, a reinforcement learning approach is used to attain an optimal policy. Unfortunately, some jammers are intelligent in a way that they only attack the BackCom channel when a legitimate transmitter is operating. To prevent such intelligent jamming attacks, authors in Dinh et al. (2019) developed intelligent techniques that deceive the jammers by transmitting fake signals from legitimate devices. When the jammers attack, the jamming signal is used for backscatter or EH. Rather than deceiving the intelligent jammers, authors in Van Huynh et al. (2019a) leveraged deep neural networks first to learn the operation of the intelligent jammer. Then, the AmBC device adapts its operation parameters (such as transmit power and data rate) based on the operation of the jammer to avoid attacks.

For BackCom networks with multiple tags, authors in Han et al. (2020) developed security techniques based on artificial noise generation and tag cooperation to defend against jamming attacks. In the former, the BackCom network selects some tags to randomly generate noise and transmit together with the valid packet, making the eavesdropper experience interference. In the latter, the tags cooperate to transmit the same information to assist in decoding at the receiver in case of packet loss from some of the tags.

-Lessons Learnt

- We can observe that the existing literature has investigated have shown the possibility of defense against eavesdropping and jamming attacks. However, some BBWS applications require continuous sensing and transmission of signals.
- Therefore future applications where continuous sensing is required, a promising solution could be continuously randomizing the carrier, modulation technique, or assigning a unique signature to the signals themselves during transmission at the BBWS node.

4.6. Quality of backscatter signal in BBWS

The amplitude difference between the reflection coefficient of states (0 and 1) is usually regarded as the most important metric for a tag's efficiency. The authors in Bletsas et al. (2010) proved otherwise by showing the effect of a tag's antenna structural mode also significantly affects tag performance. However, correctly estimating the tag's antenna structural mode is challenging. Hence, the authors derived a closed-form expression to estimate the tag antenna structural mode, which can be implemented for passive and semi-passive tags. When the BBWS system is deployed in an environment with weak or no ambient carrier signals, the tags cannot transmit sensed parameters. Hence, TunnelScatter (Varshney et al., 2019) proposed the use of tunnel diode-based backscatter tags to achieve transmission in such environments. The tunnel tags leverage the region of negative resistance (RNR) property of tunnel diodes to make them behave like an RF oscillator. The tunnel tags can then generate carrier signals to transmit sensed environmental parameters at the tag. TunnelScatter achieved a transmission range of 18 m across walls with 57 μW peak-biasing power. While TunnelScatter allows tags to operate in weak signals, the BackCom exciter is still largely dependent on a battery or a dedicated power source. Hence, Tunnel Emitter (Varshney and Corneo, 2020) exploited the back injection phenomenon of tunnel diode oscillators to design a battery-free emitter for BackCom. The system could transmit across multiple floors of a building while consuming tens of μW.

-Lessons Learnt

- We can observe that the existing literature has investigated the effects of antenna and carrier signal and how they impact BackCom.
- Since BBWS nodes contains an antenna and a switch. Hence, future research could enhance antenna properties, such as using a meta-material antenna and dielectric resonator antennas (DRAs) for the BBWS nodes.

4.7. Modulation and coding in BBWS

Maintaining efficiency and reliability of operation in applications of BBWS requires rapidly transforming the existing traditional (amplitude, frequency, and phase-based) modulation and coding schemes. Modulation schemes that use constant carrier signals for modulation have shown better range and throughput performance than those that use modulated ambient carrier signals (e.g., TV and WiFi) for modulation (Harms, 2017). Hence, BBWS applications with modulated carriers require more complex modulation and coding schemes.

As applied in conventional communication systems, the modulation schemes in BBWS needs to match the noise model in the backscatter channels for optimal performance. In Durgin et al. (2013), the colored (orange) noise in the backscatter channel was modeled. Additionally, how matching a colored BackCom channel with various modulation schemes affects the tag's sensitivity and range of operation. Experiments with energy-limited tags showed that low n-transition bit rate modulation schemes are required for high sensitivity and range. At the same time, power-limited tags need to adopt high switching rate modulation to enhance tag sensitivity and range. Taking into account the colored noise model of backscatter systems, Durgin (2015) drew from coding concepts in optical and magnetic recordings to develop balanced codes for improving the throughput of backscatter links. Balanced codes have a codebook with an equal number of balanced and unbalanced codes. Due to spectral considerations, the balanced codewords are further tuned to allow mapping any combination of L bits to a sequence of K-coded bits. The balanced codes have L/K as rates and showed at least a 50% increase in throughput of an RFID channel. Due to the pervasiveness of ambient signals, a universal technique (based on frequency switching) for analog and digital modulation was proposed in Vougioukas and Bletsas (2018). Scenarios with a constant envelope carrier and a non-constant envelope carrier were considered in the digital domain. A pseudo- frequency shift keying (FSK) was designed for the constant envelope carrier signal. In contrast, a shifted binary phase-shift keying(S-BPSK) was designed for a non-constant envelope carrier. Both modulation techniques showed performance gains. In the analog domain, FM remodulation principles were used to modulate information. The analog modulation achieved a 26 m range while consuming 24 μW.

In Wang et al. (2012), the reliability and efficiency of backscatter systems were enhanced by designing a novel coding technique. It involves allowing a small random section of the backscatter nodes to continuously collide and regarding the collision as a sparse and rateless code. The receiver then applies compressive sensing techniques to decode the transmitted message. The transmission is terminated when the receiver has enough information to decode the transmitted message. The sparseness of the code eliminates the node identification overhead during communication. In contrast, ratelessness leads to the automatic adaptation of data rates. The system achieved a throughput gain and decreased (from 50% to zero) the message loss rate. Further, Parks et al. (2014) proposed a multi-antenna-based coding technique (μ code) to improve the range of backscatter systems. Since conventional coding schemes (such as Code Division Multiple Access (CDMA)) require computationally expensive synchronization, μ code exploits the periodic sequences of sinusoidal signals to form codes thereby eliminating the need for synchronization. μ code achieved a communication range of 80 ft between RFID tags. In Daskalakis et al. (2018a), a high-order pulse amplitude modulation (4-PAM) underlaying an ambient analog FM radio signal was designed. The coding technique allows sensor data at RFID tags to be modulated and transmitted using a simple architecture (transistor, antenna, and micro-controller unit). A low-cost SDR was used as a reader. The system achieved 328 bps over a tag-reader range of 2 m while consuming 20 μW. Generally, decoding backscatter signals with ambient modulated carrier signals is affected by noise and interference. Hence, perfect pulses (antipodal binary waveforms with DC-nulling effect) were designed in Varner et al. (2017a) and used enhance the performance tags in modulated backscatter applications (Varner et al., 2017b).

LuxLink (Bloom et al., 2019) presented a frequency modulation-based technique that uses ambient light as a carrier to establish a wireless link. The wireless link is used to transmit information to the user's field view. Since ambient light from passive sources suffers from flickering (due to information changes) when used for communication, frequency modulation is used to eliminate that bottleneck. The modulated signals can be easily decoded using photosensors as receivers. LuxLink implementation using a 6 × 8 cm liquid crystal display (LCD) achieved 80 bps throughput and ranges of; 4 m (indoor) and 60 m (outdoor).

-Lessons Learnt

- We can observe that the existing literature has discussed several modulation schemes that have been developed for BackCom. Though they have allowed modulation and coding at low power budgets, they are mostly restricted to the RF domain. Further, they do not achieve high data rates.
- Hence, future research on modulation and coding schemes should emphasize the achievement of high (>1 Mbps) data rates. Also, schemes that are effective for underwater and light BBWS environments should be developed.

5. Future applications and research issues in BBWS

This section discusses possible future applications of BBWS and possible research issues that can be exploited in achieving such applications.

1. Human and plant physiological sensing: A lot of research effort has been put into designing wearable devices for monitoring vitals in humans, such as; systems in Zhao et al. (2019a), Bandodkar et al. (2019). However, they do not provide a battery-free and long-range means of continuously monitoring human vitals. On the other hand, implantable devices employ invasive sensing methods in humans. Hence, battery-free, long-range, and non-invasive monitoring techniques, including sweat monitoring patches and glucose monitoring, would be prevalent in the next generation of wireless sensing systems. This would allow for the early detection of diseases in humans through analyzing electrolyte imbalance. Further, the next generation of healthcare systems will require highly reliable and low latency sensing systems for telemedicine and surgery applications. The sensing systems can be employed during long-duration robot-assisted surgeries to monitor key human signals and enhance haptic feedback. Therefore, a future approach to achieving this is using BBWS, where tags can sense human vitals and electrolytes in sweat or haptic signals and backscatter them effectively. Plant physiological monitoring with wireless signals (Ding and Chandra, 2019) provides a cost-effective means of ensuring optimal growth of plants or optimal use of water for irrigation. Hence, applications (such as a greenhouse) will rapidly adopt BBWS techniques. However, to enable pervasiveness and inter-technology operation, BBWS has shown prospects in moisture sensing (Wang et al., 2020a). Research to enable large-scale, battery-free, and long-range monitoring of plants is still open.
2. Vehicular Sensing: WS is becoming a big part of the automotive industry, with many manufacturers adopting sensors to ensure optimal performance of vehicles. For instance, cars have used proximity sensors to avoid collision when a car is in reverse motion, air pressure sensors for tires, and inertia sensors for safety. The deployment and use of sensors in the next generation of intelligent vehicles will be enormous because the vehicles will have to interact with other vehicles and roadside infrastructure at meager power budgets and high data rates (Wang et al., 2020b; Khan et al., 2021). Hence, large amounts of heterogeneous data will need to be processed. However, battery size and computational power will limit the next generation of vehicles. Though efforts such as; Osprey (Prabhakara et al., 2020) exploit mmWave for sensing tire wear in vehicles, they do not address such challenges. Hence, BBWS for enabling 'vehicular sensing' is a promising area that needs to be exploited to address sensing challenges in the next generation of transportation systems.

3. BBWS with heterogeneous signals (HetBackCom): Many practical scenarios are heterogeneous (consist of different types of excitations) in nature. An environment where a BBWS device would be deployed could contain ambient RF, VL, and acoustic signals. These types of signals could be exploited simultaneously to provide better sensing operation. For example, RF signal reception is usually poor when traveling through long underground tunnels. However, these tunnels have excellent light illumination. Future BBWS applications will seek to combine RF and visible techniques to enhance performance. Another application scenario is combining acoustic signals with RF signals for sensing in oil and gas. The underwater (acoustic) signals could be used to sense underwater parameters (such as vibration, temperature, and turbidity) and transmit over the air to achieve long onshore distances using RF signals. Recent systems such as TwotoTango (Galisteo et al., 2020) where a hybrid RF and visible light-based BackCom was designed, lay the foundation for future research in that area.
4. BBWS with a universal tag: Existing BBWS systems are usually limited to operation in the band of the carrier signal. This significantly limits sensing operation because of limited excitation sources and limited receivers on the said band. Next-generation BBWS would incorporate tags with a broader range of excitation sources. Though, ultra-wideband backscatter allows for a more comprehensive band operation of tags. It does not eliminate the dependence of tags on a particular technology. Therefore, further research on designing universal tags such as; AnyScatter (Kim and Lee, 2020) is needed to enhance the ubiquity of deploying BBWS.
5. Intelligent BBWS: The complex nature of BackCom in comparison to conventional communication system call for stringent design requirements. To enhance various aspects of BBWS, intelligent (machine learning and deep learning) techniques will be adopted soon. Though power-consuming intelligent techniques cannot be deployed on the tag due to its power budget, they can be used to enhance the processing of backscatter signals at the receiver. A future research challenge related to BBWS is identifying how the intelligent techniques can be used to enhance metrics of BackCom. For instance, authors in Wen et al. (2019) employed reinforcement learning to enhance the throughput of BackCom. Recently intelligent reflective surfaces(IRS) are being leveraged to enable more applications of BackCom (Zhao et al., 2020b; Zuo et al., 2021).
6. BBWS for smart city: WS has shown promise in sensing activities on an urban scale to enable smart cities. However, employing conventional wireless sensing for smart sensing comes with the downside of inherited limitations for WS. Hence, future applications where BBWS is employed to achieve low-cost monitoring of structures and environments will be prevalent. BBWS tags could also be used to monitor the stress in pedestrian bridges and buildings. Signals leveraged for sensing the various environments can be received on different channels based on the tags or receiver. Existing research such as building scale sensing (Zhang et al., 2019a; Buffi et al., 2021), frequency-shifted backscatter (FS-BS (Zhang et al., 2016b), and xSHIFT (Rostami et al., 2020)) provide foundation for further investigation into leveraging BackCom for sensing in smart cities. Similarly, leveraging the widely deployed LTE traffic in cities for BBWS is a promising solution. A recent work, LScatter (Chi et al., 2020) lays a good foundation for further work in this regard.

6. Conclusion

Wireless sensing will surely enhance sensing in the next generation of IoT, where millions of sensing devices will be connected. However, to achieve ubiquity and battery-free operation, this paper discussed how BackCom could be used to improve sensing tasks. The paper also discusses the various categories and application scenarios of BBWS. Further, existing works of literature that discuss techniques for enhancing the performance of certain aspects of BBWS were presented. Lastly, future applications of BBWS and open research issues related to future applications were highlighted.

Declaration of competing interest

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.

Data availability

No data was used for the research described in the article.

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