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Backscatter technologies and the future of Internet of Things: Challenges and opportunities

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Abstract: Energy source and circuit cost are two critical challenges for the future development of the Internet of Things (IoT). Backscatter communications offer a potential solution to conveniently obtain power and reduce cost for sensors in IoT, and researchers are paying close attention to the technology. Backscatter technology originated from the Second World War and has been widely applied in the logistics domain. Recently, both the academic and industrial worlds are proposing a series of new types of backscatter technologies for communications and IoT. In this paper, we review the history of both IoT and backscatter, describe the new types of backscatter, demonstrate their applications, and discuss the open challenges.

Key words: ambient backscatter; backscatter communications; battery-less sensor; Internet of Things (IoT); Large Intelligent Surface (LIS); Unmanned Aerial Vehicle (UAV)

1 History of IoT

The concept of the Internet of Things (IoT) originated in the 1990s. It first appeared in the book, *the Road Ahead*, written by Bill Gates in 1995, depicting many IoT devices being used in traffic management and daily life. In 1999, the MIT Auto-ID Center developed an Electronic Product Code (EPC) standard based on the global Radio-Frequency IDentification (RFID) item identification system and built a prototype of the IoT[1]. In 2005, the International Telecommunication Union (ITU) issued the "ITU Internet Report 2005: Internet of Things" in Tunisia[2], officially presenting the concept of IoT. Since then, many countries have attached great importance to the idea of IoT. In November 2008, the American government incorporated the "Smart Earth" plan into its national strategy. In 2009, European Union (EU) issued two plans: the "Internet of Things–An action plan for Europe" and the "Internet of Things Strategic Research Roadmap". Korea released its "IP-based ubiquitous sensor network infrastructure construction plan", focusing on sensor infrastructure construction. Meanwhile, Japan proposed the "I-Japan" strategy, which would promote the development of digital technology, after their "U-Japan" plan[3], which was meant to connect everything. In 2010, Chinese government announced that IoT would be part of its long-term development plan.

Governments have also promoted IoT applications in many fields, including military, industry, and agriculture. In 2011, the USA released the "Advanced Manufacturing Partners" plan. In 2013, the EU adopted the "Horizon 2020" scientific research plan and established the alliance for Internet of Things innovation in 2015. In 2016, the World Internet of Things (WIoT) Exposition was held in Wuxi, China and the "Smart Manufacturing Development Plan (2016–2020)" was published[4]. The

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NarrowBand cellular Internet of Things (NB-IoT) protocol was approved by the international organization 3rd Generation Partnership Project (3GPP) in the same year, indicating the start of large-scale commercial IoT usage. It is predicted that by 2021, approximately 28 billion devices, including more than 15 billion machine-to-machine and consumer electronic devices, will be connected to the IoT around the world[5]. In March 2019, 3GPP announced the first 5G standard, with one of the goals being the realization of large-scale IoT.

Figure 1 lists the milestone events during the development of IoT, showing that IoT has made significant progress over the past 30 years.

However, when comparing IoT with mobile communication systems, IoT has developed slowly. The first generation of mobile communication systems started in the 1980s and is currently evolving into the 5th generation. Regarding adoption, the 4th generation mobile communication networks, such as Long Term Evolution-Advanced (LTE-A), have been widely used in many countries, and the 5th Generation (5G) mobile communication system initiates its commercial applications in 2020. In comparison, IoT seems still in its infancy.

The question arises: what are the current main challenges for IoT? In general, challenges are seen in both the management and technology sectors. For example, there are currently no IoT operators that can earn money from potential clients due to high management costs, such as the establishment and maintenance costs of numerous access nodes or base stations. However, given many IoT users, operators can earn money through networking and selling data services.

When considering technical reasons, we hold that at least three key challenges limit the rapid development of IoT:

(1) Sensor energy issues: Currently, most sensors require a battery, which has a limited service life. Further, batteries necessitate replacement and cannot provide stable and continuous energy for various low-power wireless devices, especially in unique scenarios like pressure sensors embedded in walls and sensors underwater or along the seacoast.

(2) The high cost of wireless sensors: Most wireless sensors need Radio-Frequency (RF) circuits, such as oscillators, to transmit carrier signals. These RF circuits are expensive, thus limiting the extensive usage of IoT.

(3) The lack of open IoT architectures or protocols: Unlike the Internet, where Transmission Control Protocol/Internet Protocol (TCP/IP) provides an open architecture that allows free access for different users, IoT does not have such open architectures or protocols. Various companies create individual applications based on proprietary IoT protocols, but most do not provide

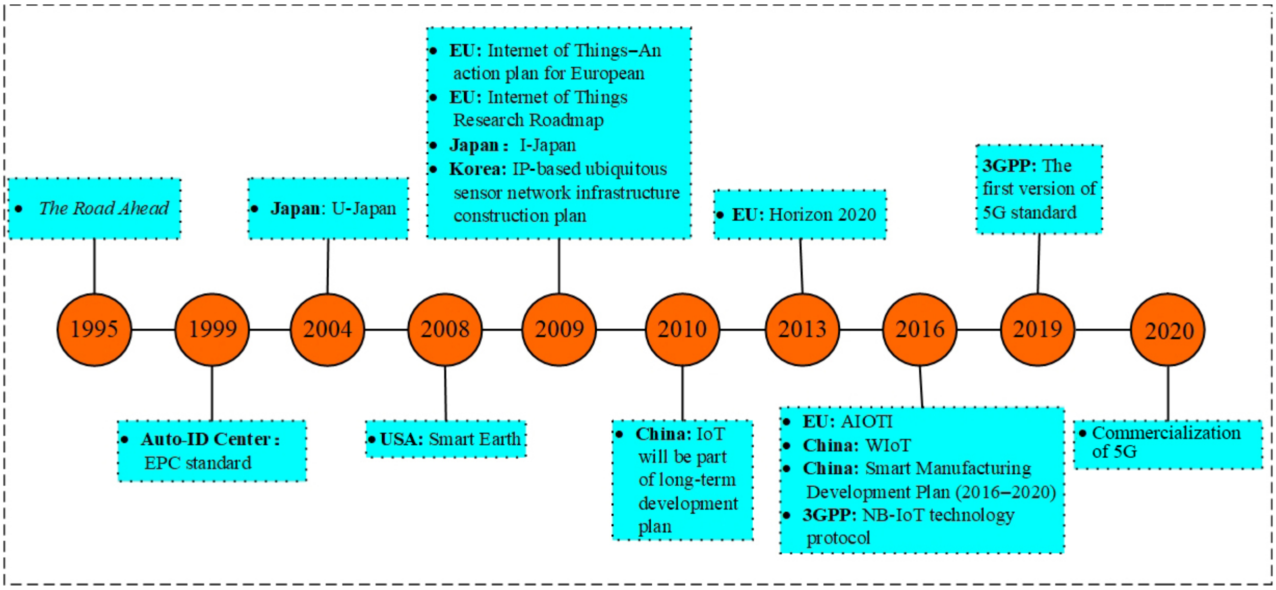


Fig. 1 Milestone events of the IoT development.

interconnection or universal interfaces between other companies' applications.

2 Backscatter technology

2.1 Traditional backscatter communication technologies

Backscattering technology was first used in World War II (1939–1945) to distinguish whether an incoming fighter plane was an enemy or not. Tags were installed on fighters that reflected RF signals emitted by radar as modulated special information. In 1948, the first academic paper on backscattering technology was published[6].

Subsequently, backscatter-related RFID products appeared and flourished, focusing primarily on commodity identification and supply. From 1990 to 2000, Electronic Toll Collection (ETC), a famous RFID product, was used extensively[7]. After 2000, with the improvement of integrated-circuit technology, RFID systems' cost has continuously reduced, further promoting the broad deployment of IoT applications.

Meanwhile, backscatter technology has attracted wide attention from the academic community, including channel fading characteristics, path loss models, tag impedance, encoding and detection, multi-antenna technology, and security.

2.2 New backscatter communication technology

Traditional backscatter communication requires an active RF source to power the backscatter tag. To eliminate such a requirement, scholars from the University of Washington first proposed ambient backscatter in 2013[8]. This technology directly collects the exiting RF signals in an environment to serve as the RF source. Ambient backscatter makes it easy to achieve flexible deployment of large-scale IoT while further reducing power consumption and cost, significantly promoting the development of backscatter communication technology. Figure 2 illustrates the number of papers about ambient backscatter and backscatter communications on the IEEE Xplore database.

Apart from ambient backscatter, a series of new backscatter types has been proposed in recent years. Typical models for new backscatter communications are depicted in Fig. 3.

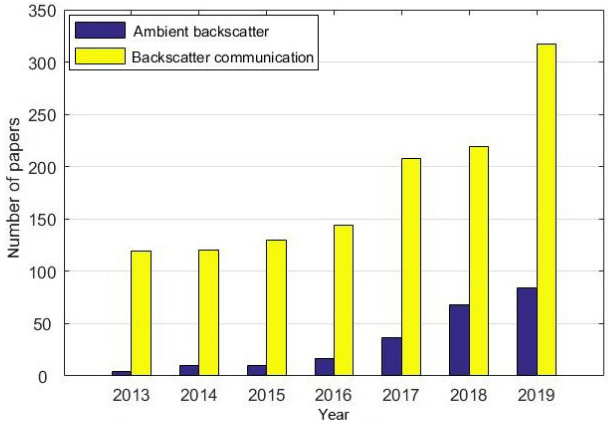


Fig. 2 Number of academic papers on backscatter and ambient backscatter.

As shown in Fig. 3a, one disadvantage of traditional backscatter technology is the need for a dedicated RF signal source. To overcome this requirement, various new backscatter technologies have been proposed, including bistatic backscatter[9], full-duplex backscatter[10], inter-technology backscatter[11], LoRa backscatter[12], Large Intelligent Surface (LIS)-aided backscatter[13], Piezo-Acoustic Backscatter (PAB)[14], and NetScatter[15].

(1) Bistatic backscatter: This technology locates a carrier generator near the backscatter tag and transmits fixed carrier signals. Due to the short distance between the carrier generator and the tag, the corresponding path loss is reduced, so the tag can obtain more power from the carrier generator, thus expanding the communication range between the reader and the tag. However, this technology requires a fixed carrier generator.

(2) Ambient backscatter: This version exploits existing wireless signals, like wireless TV signals, radio broadcast signals, and Wi-Fi Access Points (APs), for both energy and communications. Ambient backscatter communications systems employ two main steps. First, a tag backscatters or absorbs the received wireless signals, which indicates a "1" or "0" state, respectively; Second, a reader adopts well-designed signal processing methods to detect these two states. Reference [16] proposed an energy harvest circuit that uses wireless digital TV broadcast signals for sensors. Reference [8] designed a prototype that averages the received signal energy, realizing the mutual

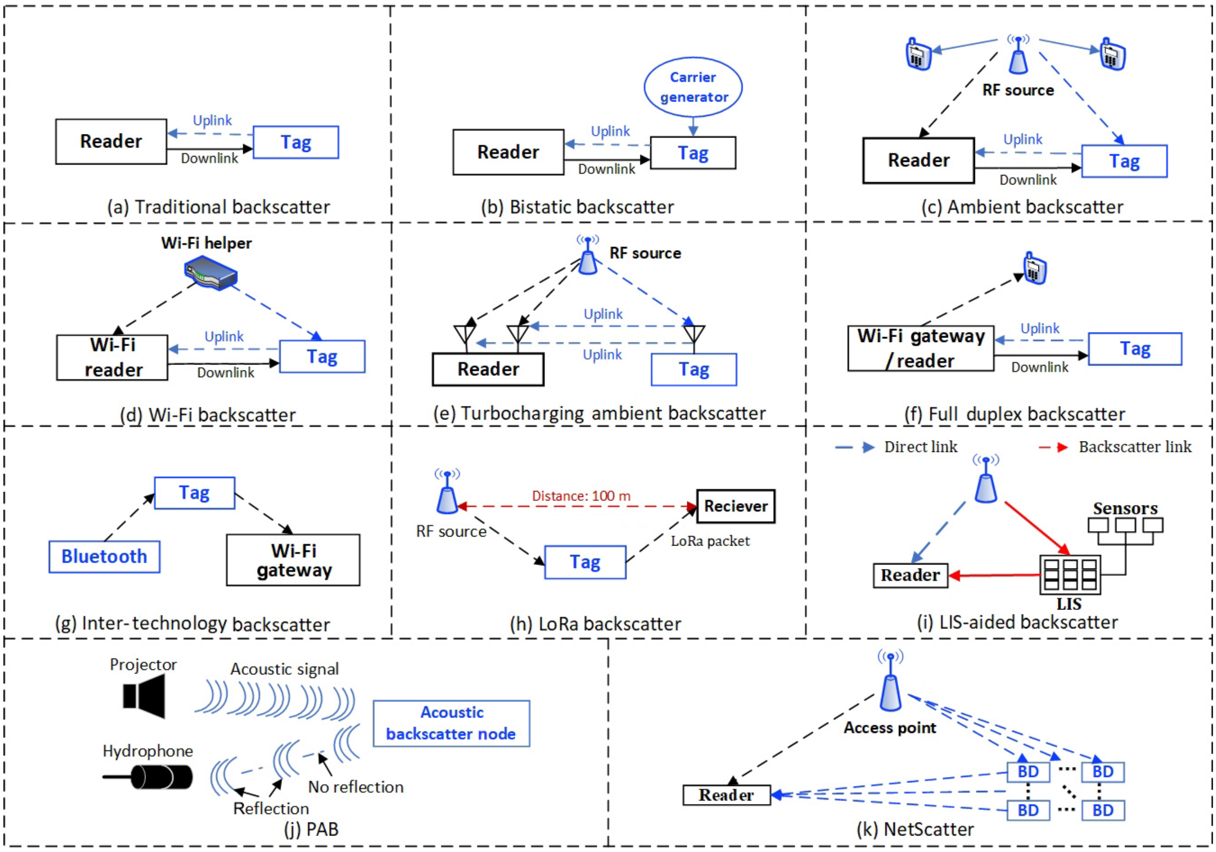


Fig. 3 Typical models for backscatter communication systems (BD means backscatter device).

communication between two passive tags. References [17, 18] proposed new approaches to improve the transmission rate. Specifically, Ref. [17] proposed a new signal detector based on the change of channel parameters and built a physical circuit platform, which obtains a higher transmission rate and has a larger communication range of up to 20 meters. Reference [18] investigated high-order modulation (M-Phase Shift Keying (PSK)) for backscattering, and its hardware prototype can achieve a data transmission rate of 20 kbps, which is higher than most binary ambient backscatter communications. Reference [19] offers a physical circuit and a communication protocol that enable passive tags and commercial Wi-Fi devices to communicate, although this prototype's communication speed is relatively low.

(3) Full-duplex backscatter: Backscatter based on full duplex enables Wi-Fi gateways with multiple antennas to simultaneously communicate with laptops or smartphones while collecting information from backscatter sensors. When a gateway antenna transmits signals to a laptop or a smartphone, these signals can also be reflected as modulated information by a tag or a sensor. Next, the Wi-Fi gateway can recover the tag's or the sensor's modulated information after canceling its own signals by using full-duplex technology.

(4) Inter-technology backscatter: This technology can convert Bluetooth signals into Wi-Fi signals or ZigBee signals.

(5) LoRa backscatter: Reference [12] is based on the high sensitivity of LoRa signals as low as –149 dBm. It also employs spread-spectrum coding to achieve long-distance communications up to 475 meters.

(6) LIS-aided backscatter: LIS is a meta-surface equipped with many nearly passive reflectors that can be programmed to alter the phase of incoming signals. It can be considered a centralized node with massive backscatter units. LIS enables high data rate transmissions, making it a contender for the technology that will fulfill visions for the next generation of communication systems and IoT[20]. Reference [21] first investigates the fading of LIS direct links and backscatter links. It reveals that LIS can strengthen wireless signals

to become stronger than even direct link of line of sight connections.

(7) PAB: PAB is the first technology that enables underwater backscatter communication and senses without need for a battery by harvesting energy from underwater acoustic signals through the piezoelectric effect. Reference [14] shows that PAB can achieve single-link throughputs up to 3 kbps and power-up range, where the tags can be activated, up to 10 meters.

(8) NetScatter: This technology enables hundreds of backscatter devices to communicate concurrently with the wireless protocol proposed in Ref. [15], which is in line with the vision of massive IoT adoption. Based on this protocol, improvements latency and throughput increase by about 20 and 40 times, respectively.

(9) Turbocharging ambient backscatter: Reference [17] employs backscatter readers with multiple antennas, exceeding the communication rate and distance of ambient backscatter systems by 100 and 40 times, respectively.

(10) Wi-Fi backscatter: Reference [19] is a novel backscatter communication system that reuses existing Wi-Fi infrastructure to bridge RF-powered devices with the Internet. It can achieve communication rates up to 10 kbps and range up to 2.1 meters.

2.3 Basics of backscatter communication

It is widely assumed that backscatter communications most often utilize amplitude shift modulation, with the most common mode being on-off keying. However, other modulations, including PSK and frequency shift keying, can also be used in backscattering circuits. Furthermore, analog modulation can be used instead of digital modulation for tags that receive analog input data.

A tag modulates information on a received signal by controlling its reflection coefficient $F_T(t)$ to adjust the signal's amplitude, phase, and frequency. The reflection coefficient $F_T(t)$ is determined by the antenna impedance R_A and the load impedance R_L[22]. It can be calculated as

$$F_T(t) = \frac{R_L - R_A}{R_L + R_A} \tag{1}$$

If the incoming signals are denoted by $S(t)$, the backscattered signals can be represented by $F_T(t)S(t)$.

Figure 4 depicts the system structure of one reader and two backscatter tags: one tag with digital modulation and the other with analog modulation. The reader is equipped with an antenna and a circulator that can separate transmitting signals and backscattered signals to avoid self-interference. The tag with digital modulation has several fixed states of $F_T(t)$, while the tag with analog modulation aims to use continuously time-varying reflection coefficients of $F_T(t)$.

3 Application of backscatter technologies in IoT

In this section, we discuss the potential applications of backscatter technologies in IoT. We limit our discussion to the following three scenarios: smart homes, smart

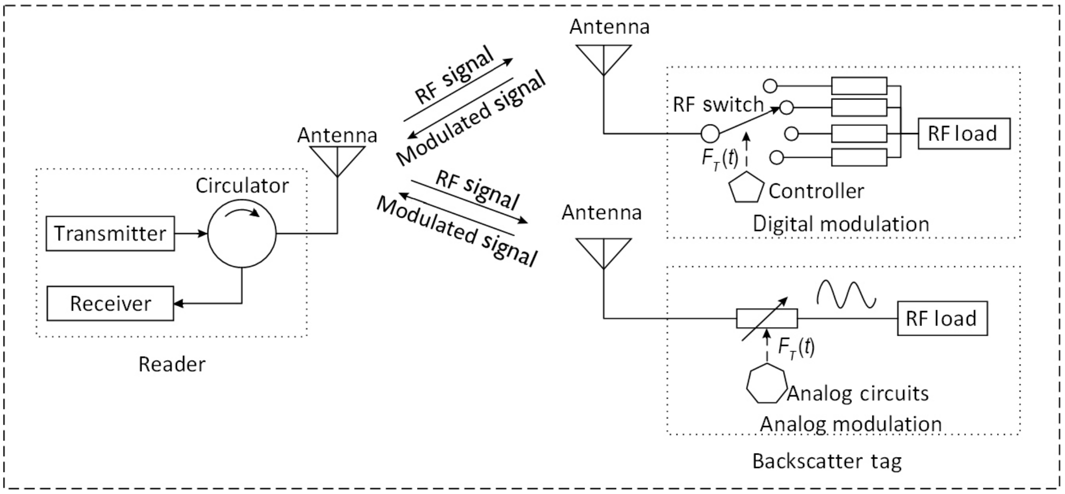


Fig. 4 System structure for a reader and a digital/analog tag.

cards, and Unmanned Aerial Vehicle (UAV)-aided communications.

3.1 Smart home

Smart homes use sensors and smart devices, such as cameras, pressure sensors, and light sensors, to reduce resource consumption and improve quality of life[23]. These small devices can employ backscatter technology for both obtaining power and conducting communications.

Figure 5 depicts such a system, consisting of many battery-less sensors and a reader with multiple antennas. When the reader transmits wireless signals, these devices can be powered and motivated to work. Next, the sensors can backscatter signals from the readers with modulated information. The reader can then receive these signals and use them to make decisions. Moreover, the reader can connect to a local server or an Internet server. The server would enable interaction with client applications running on smartphones, allowing access to the smart home from anywhere. For example, clients could send commands to the air conditioner in their house before arriving home, or order their windows to close in case of unexpected wind.

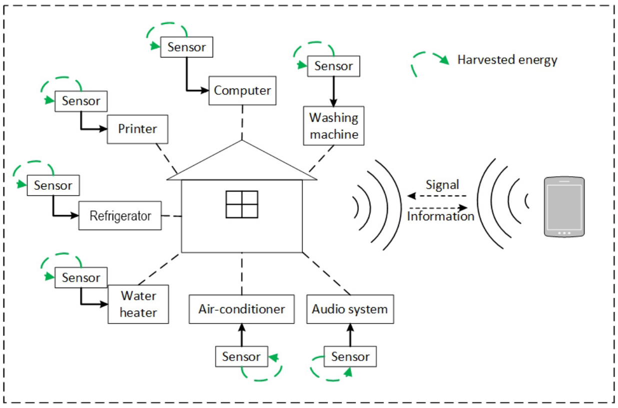


Fig. 5 Smart home architecture.

3.2 Smart card

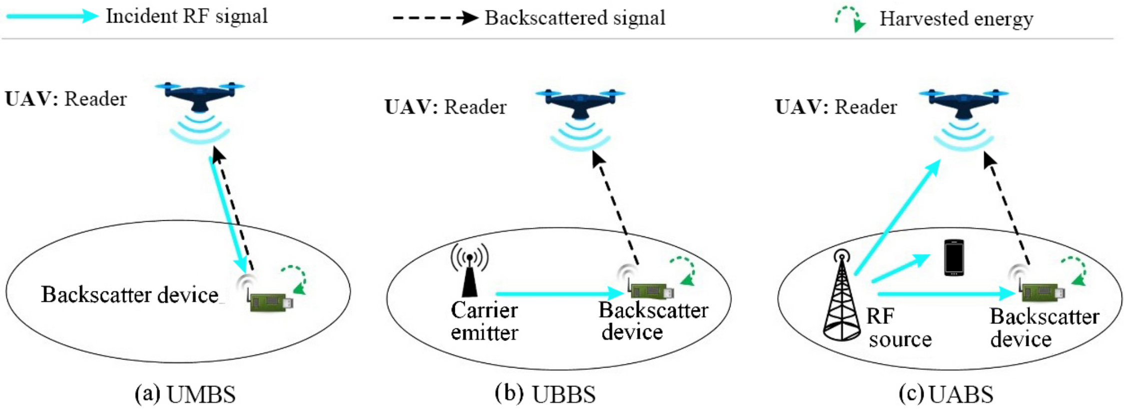
Due to the low security of traditional cards, from 2006 to 2010 the cases of global credit and debit card fraud have increased of 288%, with an expected of 57% for the next three years[24]. Ambient backscatter can help remedy this by powering security-enhancing hardware in smart cards. These cards are capable of using existing RF sources to recharge and then store the harvested energy for use in computing and communications. For example, two passive cards could quickly transfer funds through ambient backscatter.

Typical models of UAV-aided backscatter communication systems are shown in Fig. 6.

(1) UAV-aided Monostatic Backscatter System (UMBS): In UMBS, there are two main components: a backscatter reader, i.e., a UAV and a BD. The UAV transmits the incident RF signal to the BD and receives the backscattered signal from the BD. Due to the double path loss between the two components, this model is mainly used in low-altitude UAV applications.

(2) UAV-aided Bistatic Backscatter System (UBBS): In UBBS, a separated carrier emitter is located near the BD, with the UAV acting as a backscatter receiver in the sky. Using a dedicated RF source can avoid the severe path loss found in UMBS. However, UBBS deployment is costly, especially when a large number of BDs need RF signal.

(3) UAV-aided Ambient Backscatter System (UABS): In this model, BDs can backscatter signals from ambient RF sources, like TV towers, Wi-Fi APs, and UABS base



(a) UMBS (b) UBBS (c) UABS

Fig. 6 Typical models for UAV-aided backscatter systems.

stations. This model uses existing RF sources instead of relying entirely on deploying carrier emitters, reducing the model's cost and power consumption.

UAV-aided backscatter systems were studied recently in Refs. [25–28]. Specifically, the throughput of the UAV-backscatter networks was maximized in Refs. [25, 26]. An energy efficiency optimization problem was discussed along with analyzing the average system outage probability in Ref. [27]. Reference [28] considered a UAV trajectory design problem in UAV-enabled backscatter systems.

However, dynamic global state information is hard to obtain in practice due to the dynamic distance between the UAV and the BDs. Thus, Ref. [29] proposed a Deep Reinforcement Learning (DRL)-based approach to solve the energy efficiency optimization problem in UAV-aided backscatter communication systems. The method is model-free and can dynamically optimize UAV trajectory to maximize the system's energy efficiency.

4 Challenge and open problem

This section provides some key challenges for future IoT devices that employ backscatter technologies.

4.1 Channel estimation

Accurate channel estimation is essential for wireless communication systems[30], and a backscatter communication system's performance increases with better channel estimates. However, channel estimation is challenging for backscatter-based IoT systems due to their limited power and minimal training symbols[31]. Tags or sensors in backscatter-based systems obtain low-power levels through energy harvesting and are typically too small and simple to transmit their own training symbols.

Reference [31] first addressed the lack of training symbols for backscatter-based systems by offering an expectation-maximization algorithm to blindly estimate composite channels. Later, Ref. [32] exploited channel parameters' sparsity in angle domain and designed an estimator for massive antenna readers. These current studies about channel estimation focus on one tag or sensor, and all assume perfect synchronization. Designs for channel estimators when considering multiple tags or asynchronous states are open problems. Currently, only combined channels in backscatter-based systems can be estimated, so obtaining individual channel parameters to facilitate beamforming is an interesting research topic.

4.2 Signal detection

Signal detection for backscatter communication was studied in Refs. [33–35]. Specifically, Ref. [33] proposed a signal detector that uses differential encoding and achieves an error rate lower than 0.01. The paper shows that the difference in signal detection between backscatter communication systems and traditional wireless systems is a central challenge that limits extensive application. Three reasons for this argument are in the following:

First, sensors are energy-limited, especially sensors that rely on wireless energy harvesting. Sensors do not collect much energy, and they use it on both communication and computing. Therefore, in most cases, sensors cannot transmit their own training symbols.

Second, sensors use a reflection mechanism to load information onto existing RF signals, instead of generating its own signals. Hence the channel characteristics are different from traditional point-to-point wireless channels. For example, whether tags reflect received signals or not, there are different combinations of channels and an accordingly increasing detection complexity.

Finally, the received signals come from both backscattered links and other paths, including a direct link from the source, which can cause strong interference for backscattered signals.

4.3 Multiple access

Multiple access technology aims to address the decision who can use a channel when there are several users trying to communicate simultaneously with a central node on the same channel.

This problem can be solved in either the physical or Medium Access Control (MAC) layers. The difference between the physical and MAC layers is that the physical layer deals with bits within a single packet, whereas MAC works with packets.

Multiple access can be divided into two types:

grant-based and grant-free. Grant-based multiple access approaches require that users obtain authorization from other users or base stations before transmission. Widely used grant-based multiple access algorithms include Carrier Sensing Multiple Access (CSMA), which consists of Carrier Sense Multiple Access with Collision Detection (CSMA/CD) and Carrier Sense Multiple Access with Collision Avoid (CSMA/CA), and Random Access CHannel (RACH) in Long-Term Evolution (LTE) technology (LTE RACH).

Grant-free algorithms allow users to start transmissions freely without any grant, which offers a low control overhead but can result in collisions. Therefore, the key challenge is solving the collision between data transmission from different users. Typical grant-free algorithms are Non-Orthogonal Multiple Access (NOMA) and Multi-User Shared Access (MUSA) in the physical layer, and ALOHA and Coded Slotted ALOHA (CSA) in the MAC layer.

Compared with cellular networks, IoT has a low data rate, a short packet length, and a high user density. When many IoT devices require access at the same time, congestion quickly arises[36].

Traditional Orthogonal Multiple Access (OMA) technologies, such as Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA), divide communication resources into orthogonal units in one of three fields: time, frequency, or code domain. The orthogonality between resource blocks ensures that signals from various users do not conflict with each other, thereby simplifying the receiver's signal recovery process. The number of users is limited by the maximum available resources and the granularity of resource scheduling in OMA. For the massive scale of IoT access, wireless resources, such as frequency spectrum and resource granularity, have been exceedingly scarce[37]. Therefore, efficient random multiple access methods with autonomous, dispatch-free, and contention-based characteristics are especially favorable.

One potential solution in the physical layer is NOMA, which actively introduces controllable interference to enable a non-orthogonal transmission with different transmit powers, thus breaking the limitation of orthogonality in resource allocation. Most NOMA technologies can achieve a higher system capacity[38, 39].

Future implementations of IoT with 5G could allow many connections, up to 300 000, in a single cell tower. Although NOMA and MUSA outperform OMA, they still cannot serve so many potential connections. Therefore, new access methods await further investigation.

Figure 7 lists various existing access algorithms.

4.4 Source allocation

Several technologies were proposed to enhance the transmission quality of backscatter-enabled devices. Specifically, Ref. [17] introduced a multi-antenna technique and a novel coding scheme to improve

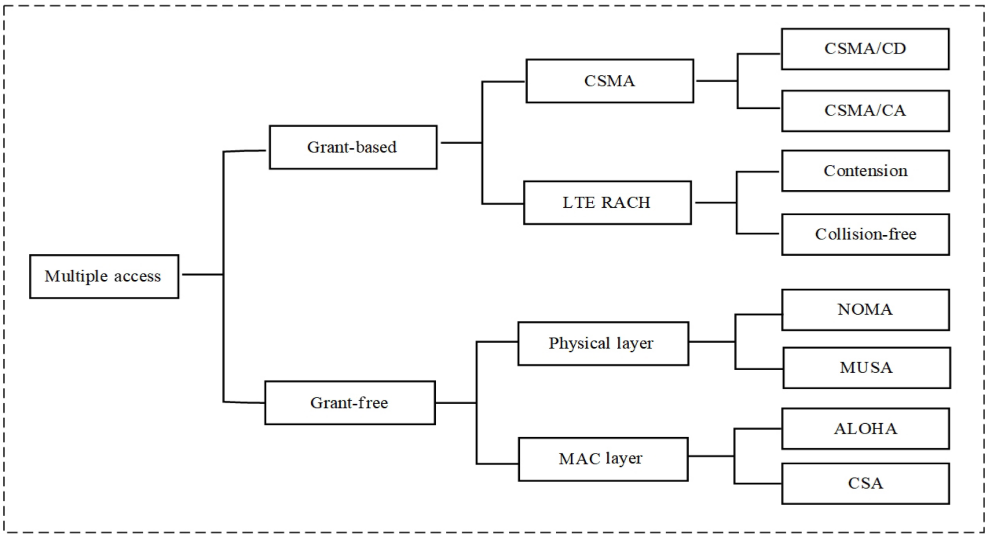


Fig. 7 Multiple access algorithms.

transmission rates and range, respectively. Reference [40] developed a Backscattering Tag-to-Tag Network (BTTN), which addressed the phase cancelation issue, thus enhancing transmission reliability.

The resource allocation strategies of backscatter transmissions also play an important role in improving backscatter transmission quality[41]. These strategies can bring more users into IoT services by efficiently utilizing the resources of IoT systems[42]. For example, an intelligent power management strategy could be studied to balance the proportion of harvested energy split between transmission and working. In the future 5G IoT, numerous smart devices will be interconnected, and the density of IoT networks will increase rapidly. In such scenarios, the allocation of energy and spectrum resources for transmission remains an open problem. Accordingly, optimal resource allocation strategies for 5G IoT await further study.

5 Conclusion

In this paper, we first provide a brief overview of the history of IoT and backscatter technology. We then introduce new types of backscatter communications and their applications. Finally, we suggest open problems with backscatter's use in future IoT.

Backscatter is a rising technology with extensive potential applications in IoT, but it also faces many challenges. It is important to remember that opportunities and challenges always coexist. Let us wait and see if backscatter technology can successfully be utilized in the future of IoT.

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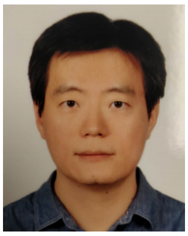

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