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BATTERY–FREE IOT: TRENDS, CHALLENGES, AND TECHNICAL IMPLICATIONS OF AMBIENT BACKSCATTER SMART TAGS

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Abstract: IoT sensing through wireless battery–free smart tags is growing rapidly with the development of enhanced communication protocols and various emerging pervasive data collection requirements, leading to the adoption of ambient backscatter technologies. While RFIDs have been widely used in transportation, logistics, industry, business, and other application fields due to their convenience and high efficiency, they are equipped with robust functionality and modules that enable them to evolve into smart tags. The future yearns for more, in terms of adaptability, functionality, and performance. The wireless, battery–free smart tags use ambient backscatter technology for energy harvesting and transmit information via radio–frequency signals. It focuses on advanced Tag–to–Tag (T2T) communication and network architecture, a key research area that extends beyond simple reader–to–tag systems. This paper analyzes both future trends and present–day technical challenges by comparing traditional and emerging wireless, battery–free smart tags, using an applied literature review and expert interviews (Hybrid Thematic Analysis) to complete the research.
Keywords: RFID, Battery–Free IoT, wireless battery–free smart tag, backscatter technology

1. INTRODUCTION

RFID tags are generally available in various shapes and are evolving toward miniaturization and diverse forms, making them suitable for a wide range of products. Traditional smart tags primarily consist of two types: tags with diagnostic or detection functions and tags that utilize information technology [1], [2]. While the former mainly include Time-Temperature Indicators, labels, freshness indicator labels, oxygen indicator labels, carbon dioxide indicator labels, packaging leak indicator labels, and pathogenic bacteria indicator labels, the latter are electronic devices that store identifiable data [3].

They are small, Bluetooth/UWB-enabled devices that attach to personal items (keys, bags, pets) or are placed in wallets, helping you find them via a smartphone app (like Apple Find My, Samsung SmartThings, or Google Find Hub) by making them ring, showing their last location, or even using them for simple smart home control [4]. Popular examples include Apple AirTags, Samsung Galaxy SmartTags, and various brands compatible with Android's Find My Hub, offering features such as proximity finding, directional guidance (UWB), and long battery life [5].

Battery-Free IoT paradigm: Contrast the Old Technology with the New

Traditional communication systems, including transceiver modules, have a roughly symmetric architecture with independent RF chains that contain high-power components, such as power amplifiers and oscillators, for generating and receiving RF signals [6]. Traditional smart tags typically do not require energy and instead rely on built-in batteries (e.g., active RFID tags) or readers (e.g., passive RFID tags) to power them. Backscatter communication technology offers an effective solution for communication among massive low-power nodes in battery-free IoT, garnering active attention and interest from numerous companies worldwide [7]. Wireless, battery-free smart tags use ambient backscatter technology [8]. They harvest energy from existing signals in the surrounding environment. Through a data acquisition unit, they sense information such as the location of the attached object or environmental information like temperature and humidity. Finally, they complete data transmission by switching between reflecting and non-reflecting states.

Wireless Battery-free Smart Tag

In recent years, with the development of IoT and various novel backscatter technologies, wireless, battery-free smart tags based on ambient backscatter (i.e., wireless smart tags) have gradually

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emerged [9], [10]. It is important to note that wireless battery-free smart tags differ from traditional smart tags.

A key distinction lies in their energy source, functional modules, and whether they employ novel backscatter technology. Researchers have conducted extensive studies on energy management for IoT nodes to improve energy efficiency [11], [12], which has extended network lifetime to some extent but has not fundamentally solved the problem of limited battery energy [8], [13]. If energy management is regarded as a "cost-saving" mechanism, then the method of harvesting energy from the surrounding environment proposed in recent years is a new "revenue-generating" mechanism [14], [15]. In theory, IoT nodes can continuously obtain energy from their surrounding environment through various means to maintain their basic functions, thereby eliminating their reliance on batteries [16], [17]. In view of this, novel battery-free IoT based on ambient energy harvesting has become a current research hotspot. The working principle of a wireless battery-free smart tag is shown in Figure 1.

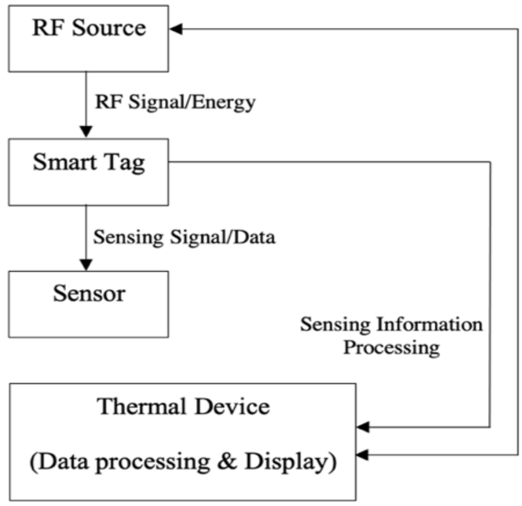

Figure 1. Working Principle of Wireless Battery-free Smart Tags

2. RESEARCH APPROACH

Focusing on the axes of Trends and Technical Implications within the Battery-Free IoT domain, an Applied Literature Review (ALR) and 8 Expert consultations (EC)—an approach (Hybrid Thematic Analysis) that uses a mix of Deductive (theory/literature-driven) and Inductive (data-driven) coding —were adopted. The consultations were conducted under an agreement of anonymity, with participant identities categorized by their primary domain (e.g., E1, E2, E3), as shown in Table 1 and following the six phases [18] outlined by Braun and Clarke (Table 2), adapted to integrate both secondary (literature) and primary (interview) data sets. The inference was on two themes. Theme 1: The Transition from Discrete Tags to Pervasive Sensing (Trend); Theme 2: The Practical Limits of the RF Energy Budget (Technical Implication/Challenge).

Table 1: Profile and Core Expertise of Industry Expert Consultants (n=7)

Expert ID	Primary Role / Organization Type	Core Expertise Area
E1	VP of Engineering (Semiconductor Manufacturer)	Backscatter IC design, Ultra–low power hardware
E2	Chief IoT Architect (Major Technology Company)	IoT platform development, Connectivity standards
E3	Senior Market Analyst (Global Consulting Firm)	Market forecasting, Investment, and adoption trends
E4	CTO (Industrial System Integrator)	Large–scale enterprise deployment, Real–world channel challenges
E5	Professor of RF Systems (University Research Lab)	Fundamental physics, Advanced backscatter modulation
E6	Director of Logistics (Global E–commerce/End–User)	Asset tracking, Supply chain digitization needs
E7	VP of Product Management (Smart Tag Vendor)	Software integration, Data utilization, Product lifecycle

3. STATE OF THE ART

Since the concept of ambient backscatter communication systems emerged, academic researchers have conducted extensive studies in related directions. Early research focused on building prototype systems for feasibility verification and performance evaluation.

Researchers have built a basic ambient backscatter communication verification system, achieving short-range communication between two passive tags and specifically designing data packet formats and carrier-sensing mechanisms. Ref. [19] proposed using two antennas at the receiver to exploit differences in received signals to cancel interference from ambient RF signals. Prototype verification results demonstrated that this method can effectively enhance system data rate and communication distance. Ref. [20] implemented the LoRa protocol using backscatter communication technology, achieving ultra-long-distance communication with very low energy consumption using commercial LoRa receivers. To further enhance the performance of ambient backscatter communication systems, academia has proposed a series of new detection theories and transmission methods.

Starting from the classical single-antenna ambient backscatter communication system model, Ref. [21] established a basic theoretical model for signal detection and derived the optimal semi-coherent detector via the maximum likelihood ratio under the assumption of a Gaussian ambient signal. Based on this, to avoid dependency on channel state information, Ref. [22] introduced a differential encoding mechanism and derived a non-coherent detector. To improve coding gain, Ref. [19] proposed using FMO encoding at the tag and designed a detector that demodulates tag information by utilizing the carrier frequency offset. Ref. [23], [24] proposed a simple information coding method, using positive/negative phase and non-reflection states at the tag to enhance the system transmission rate.

Due to interference from ambient RF signals, a class of detectors that use energy as the decision variable exhibits an error floor in their bit-error-rate (BER) performance at high signal-to-interference ratio (SIR) scenarios. For Orthogonal Frequency Division Multiplexing (OFDM) ambient RF signals, Ref. [25] utilized the cyclic prefix property of OFDM signals, cleverly canceling ambient RF signal interference by subtracting received signals from different cyclic prefix time intervals. Ref. [26], [27] proposed using frequency modulation at the tag and shifting the reflected signal to a frequency band that does not overlap with the ambient RF signal via backscatter technology to eliminate interference.

Table 2: Six–Phase Hybrid Thematic Analysis Framework

S/N	PHASE	CORE ACTIVITY	DATA SOURCE INPUT	OUTPUT AND ALIGNMENT TO TOPIC
1	Data Management and Familiarization	Input Preparation & Immersion	ALR: Extracted findings (technical specs, applications, existing challenges) and core manuscript context. EC: Verbatim transcripts of 8 expert interviews.	A unified, text–based data, aligning both context from ALR and EC on the Battery–Free IoT.
2	Generating Initial Codes (Hybrid Approach)	Systematic Labeling	Combined data set (ALR findings + EC transcripts).	A comprehensive Codebook containing codes generated directly from the research on Trends and Technical, and unique expert insights.
3	Searching for Themes	Code Clustering & Pattern Recognition	Codebook and all coded data extracts.	Preliminary Theme Clusters and a Thematic Map to group "Trends" and "Technical Implications."
4	Reviewing Themes	Refining and validating	Thematic Map and all underlying data extracts.	Themes are validated for internal coherence, ensuring they accurately and comprehensively reflect the challenges and opportunities of Ambient Backscatter Smart Tags as viewed by both the literature and industry.
5	Defining, Refining, and Naming Themes	Interpretation & Finalization	Finalized thematic structure.	Clear definitions and publishable names for the final set of themes and sub–themes, which provide the interpretive narrative on the subject matter: Battery–Free IoT
6	Producing the Report	Narrative Construction	Final Themes, definitions, and supporting quotes/citations.	Findings and Discussion with integrated evidence (expert quotes + literature citations)

While in-depth research on signal detection is ongoing, several studies have begun to investigate other key issues in ambient backscatter communication systems. Considering the difficulty in acquiring channel state information in such systems, as noted in Refs. [29], [30] proposed an adaptive estimator based on the Expectation-Maximization algorithm. Since the tag operation depends on energy harvesting efficiency.

Ref. [31] examined the impact of different receiver architectures and demonstrated that system throughput is maximized when conjugate matching and maximal ratio combining are employed. Furthermore, due to the spatial propagation characteristics of wireless signals, communication between the tag and the reader is vulnerable to eavesdropping. Considering this, Ref. [32] studied physical layer security issues in multi-tag ambient backscatter communication systems and designed a new secure transmission protocol to improve system security performance. Table 3 summarizes key performance metrics of selected backscatter communication research projects.

Table 3. Key Performance of Selected Backscatter Communication Research Projects

Name	Frequency Shift Achieved?	Minimum Power/µW	Maximum Bit Rate	Distance/m	Transmitter to Tag/m	Transmitter	Receiver
BackFi [19]	Digital (QPSK)	N/A	5 Mbit/s	1	7	7	Ambient Wi–Fi
Ambient Backscatter [20]	Digital (ASK)	0.79	10 kbit/s	0.4	N/A	2.5	Ambient TV
Wi–Fi Backscatter [28]	Digital (ASK)	9.65	1 kbit/s	N/A	N/A	2.1	Commercial Wi–Fi
HitchHike [21]	Digital (GFSK)	28 (IC)	11 Mbit/s	N/A	0.9	27.4	Commercial BLE
Intertechnology Backscatter [22]	Digital (GFSK)	28 (IC)	11 Mbit/s	N/A	0.9	27.4	Commercial BLE
Battery–free Phone [23]	Analog (AM)	3.48	N/A	N/A	N/A	15.2	Custom Hardware
LoRa Backscatter [25]	Analog (CSS)	9.25 (IC)	37.5 kbit/s	N/A	5	2.8 km	Custom Hardware
FM Backscatter [26]	Analog (CS)	11.07 (IC)	32 kbit/s	4.9	N/A	18.3	Ambient FM

4. TRENDS IN BATTERY-FREE IOT: WIRELESS BATTERY-FREE SMART TAGS

The primary driver of trends in the Battery-Free IoT ecosystem is the economic unsustainability of deploying and maintaining billions of battery-reliant devices (such as those used in consumer trackers or LPWAN) for massive-scale applications [33], [34]. Backscatter technology addresses technical—energy-based supply issues by operating at the microwatt (μW) scale, thereby enabling a transition from an active node with high maintenance requirements to a maintenance-free, passive sensing [35], [36].

The Pivot to Pervasive Sensing and Data Generation

The nascent IoT market trend is a shift in value proposition from traditional identification (RFID) to embedded, continuous, and stable operation, while further improving wireless energy-harvesting efficiency and reducing power consumption [37]. With the rapid development of electronic design, tags are evolving from merely carrying an ID to functioning as distributed systems, and the power consumption of processing and sensing modules is expected to continue decreasing. Accordingly, E3 *"The true inflection point for this technology isn't replacing barcodes; it's enabling disposable, pervasive sensing. Companies are moving from basic temperature logging to monitoring chemical changes, strain, and humidity on every perishable item or structural component."*

The technicality and the need for this shift are due to energy constraints. While pervasive sensing may require multi-sensor integration, the need to minimize the energy floor and drive future research on highly efficient backscatter circuits is timely.

Competitive Positioning and Hybrid System Adoption

The present research corroborates the literature with expert opinions on the possibility of future deployment of battery-free tags capable of competing with, or complementing, existing connectivity technologies, particularly Low-Power Wide Area Networks (LPWAN) [35], [38] based on the following hybrid system adoption.

- *Strategic Positioning Against LPWAN:* Backscatter technology carves out a unique market niche by optimizing for ultra-low power and cost over long-range, high-throughput communication. This strategy is essential when considering the total cost of ownership (TCO) for large-scale deployments.
- *Competitive Positioning against LPWAN:* A key strategic trend involves defining the key target area for backscatter against Low-Power Wide Area Networks (LPWAN), such as LoRaWAN and NB-IoT. Table 4 confirms the superior capability of backscatter technology over general long-range IoT, particularly in its high-density, ultra-low-cost, and sustainable segments of the application domain.

Table 4. Comparative Analysis of IoT Connectivity Technologies: Ambient Backscatter vs. Low–Power Wide Area Networks (LPWAN)

Metric	Ambient Backscatter (BackCom)	LPWAN (LoRaWAN/NB–IoT)	Specific Application Domain
Power Budget	∼1–100μW (Battery–Free)	mW (multi–year battery life)	Ideal for truly disposable, high–volume deployment where batteries are impossible.
Data Rate	Low (<1 Mbps)	Low to Moderate (1 kbps to 1 Mbps)	Optimal for small, intermittent data packets (e.g., ID, temperature) across large populations.
Deployment Cost	Lowest (No battery, simple circuitry)	Low to Moderate (Battery, more complex modem)	Dominates in simple asset tracking, supply chain, and innovative packaging.

- *Hybrid Communication Systems:* Another major trend is the integration of backscatter with traditional active communication (LPWAN or Wi-Fi) to form Hybrid Communication Systems. Here, the strengths of both are evident: the backscatter tag uses μW of power for low-speed sensing and short-range transmission, while an active node (e.g., a gateway, a mobile reader, or a cellular IoT module) is used for high-speed, long-range data collection. Thus, optimizes energy efficiency across the network while extending the battery life of the active components by offloading the simple, frequent tasks to the passive tags.

Trends in Scalability and Network Integration

To meet the industrial demand for mass deployment, backscatter research is being driven by trends in network efficiency and scalability [21], [26], [32], [39].

- Demand for Multi-Tag Access: Practical applications in logistics and manufacturing require the simultaneous reading of tens of thousands of tags. This drives the trend away from inefficient Time Division Multiple Access (TDMA) and toward orthogonal/non-orthogonal anti-collision protocols to ensure high throughput in dense environments. Our industrial system integrator has this to contribute: E4 *"Our biggest challenge isn't the tag's complexity; it's guaranteeing enough ambient RF energy to wake up and reliably read 50,000 tags simultaneously at 10 meters."*

- Distributed Large-Scale Backscatter: A strategic move is underway to utilize the spatial dimension of wireless resources to overcome propagation challenges. This involves leveraging Reconfigurable Intelligent Surfaces (RIS) or Large-Scale Intelligent Surfaces (LIS) as smart reflectors. This trend aims to convert the chaotic, ambient RF environment into a controllable energy source, thereby creating vast, low-power coverage areas.

5. CHALLENGES AND IMPLICATIONS OF DEVELOPING WIRELESS BATTERY-FREE SMART TAGS

The development of ambient backscatter-based wireless, battery-free smart tags face several challenges, primarily related to wireless security. Due to the spatial propagation characteristics of wireless signals, it is necessary to consider how to prevent eavesdropping on communication between wireless battery-free smart tags and terminals [32], [38], [39].

According to the professor (E5): "There is a fundamental physics wall when designing backscatter systems: you are constantly sacrificing read range for data throughput, or vice versa, based on the fixed energy density. The only way forward is highly efficient modulation schemes or leveraging ambient sources like Wi-Fi, not just dedicated RFID readers".

Furthermore, the energy harvested by a wireless battery-free smart tag is partly used for its own operation and partly for backscatter information transmission. Optimizing the use of this limited energy needs to be considered [40]. However, many key issues in signal detection and practical applications are presented.

- Detection Delay: The energy detector compares the decision variable to a specific threshold to make a decision, and the threshold is estimated from all symbols transmitted within the coherence time. Therefore, decisions can only be made after all symbol transmission is complete, resulting in an unavoidable communication delay.
- Equiprobable Input Assumption: Most of the literature assumes that the tag sends "0" and "1" with equal probability and designs transmission schemes accordingly. In practical systems, the probabilities of sending "0" and "1" may not be equal, so methods developed under the equiprobable assumption can lead to significant performance loss in practice.
- Parameter Estimation Errors: Demodulation often requires estimating specific system parameters, such as noise power and channel gain. Practical estimation processes frequently introduce errors, degrading system performance.
- Error Floor: For the reader, the ambient RF signal is interference. When the ambient RF signal energy increases, the reader experiences greater interference, and its effective interference ratio cannot be improved, leading to an error floor in high SIR scenarios.
- Low System Throughput: Limited by tag cost and energy consumption, the symbol rate of tags in ambient backscatter systems is much lower than the ambient RF signal rate. Meanwhile, most existing literature is based on On-Off Keying (OOK) modulation, meaning each symbol sent by the tag can only carry 1 bit of information, making it challenging to improve system throughput. The low transmission rate severely limits the scope and use cases of tags. Therefore, adopting more advanced modulation schemes, designing new tag modulation methods and corresponding detectors, and improving system throughput have significant practical value.
- Short Communication Distance: Due to path loss, ambient RF signals reaching the tag are generally weak. If the distance between the tag and the reader is far, the signal reaching the reader after reflection will be even weaker, posing a great challenge for reliable signal detection.

While wireless charging technology has made significant progress, RF energy harvesting devices still face many limitations in practical applications for battery-free devices [41], [42], [43], [44], [45], [46]. This is contextualized from the mathematical principal domain. Firstly, energy conversion efficiency is one of the essential performance indicators of RF energy-harvesting devices. When RF signal energy is low, conversion efficiency can decrease rapidly. In the design of RF energy-harvesting devices, current methods to improve conversion efficiency mostly involve reducing the threshold voltage of rectifier diodes composed of Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) to reduce cascaded leakage current; however, this approach is not ideal. Further improvements or the development of other new methods are needed [47], [48], [49], [50], [51], [52], [53], [54].

Secondly, the sensitivity requirement, which also determines the maximum operating range of an RF energy-harvesting device. The sensitivity of P2110B is approximately -11 dBm, meaning that a tag integrated with P2110B needs to receive a signal with a power level of at least -11 dBm to be activated and begin energy harvesting. This dramatically limits the tag's operating range. However, while improving sensitivity, RF-to-DC power conversion can be achieved at greater distances from the RF energy source. However, as the distance between the tag and the high-power node increases, the received power at the tag decreases, reducing conversion efficiency. The tag's charging time also significantly lengthens. Designing a high-gain tag antenna can alleviate the limitation of sensitivity on working distance to some extent, as corroborated by:

E4: *"In a real warehouse environment—with metal racks, concrete, and heavy machinery—the RF propagation models from the lab simply break down. Our biggest challenge isn't the tag's complexity; it's ensuring sufficient ambient RF energy to wake up and reliably read 50,000 tags simultaneously at a distance of 10 meters.*

Thirdly, Ultra-wideband Ambient Backscatter Communication: Ambient RF signals are highly dynamic in the time domain, irregularly distributed in the spatial domain, and unevenly distributed in the frequency domain. At specific times and locations, ambient excitation signals might be unavailable. Ultra-wideband backscatter communication allows signals across an ultra-wide frequency range to serve as excitation signals, effectively broadening the application scope of ambient backscatter communication. However, developing low-cost tags capable of transmitting ultra-wideband signals, as well as designing transmission methods and detection techniques suitable for ultra-wideband ambient signals, are primary problems that need urgent resolution.

6. CONCLUSION

This paper provides a brief introduction to RFID technology and smart tags, comparing traditional smart tags with wireless, battery-free smart tags. It posits ambient backscatter communication technology as a key technology for expanding the application scope of battery-less IoT. However, due to the unknown and uncontrollable nature of ambient RF signals, ambient backscatter communication technology faces key challenges, including long signal detection delay, high BER, low transmission rate, and short communication distance. These challenges include RF energy harvesting, the impact of backscatter on wireless channels, and multitag coordination and processing. In summary, emerging wireless, battery-free smart tags hold significant market potential but also face numerous challenges. With the continuous development of the IoT market, the application of this technology in various fields is poised for further exploration.

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