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Exploration of Low-Power Communication Technologies in Passive Internet of Things (IoT)

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Abstract

Passive IoT enables battery-free communication by harvesting ambient energy, offering a revolutionary pathway for building green and sustainable massive IoT networks. This paper explores the principles of key low-power technologies such as ambient backscattering and energy harvesting, and analyzes their application value and challenges in scenarios including retail, logistics, and industrial monitoring. The research indicates that this technology will drive the evolution of IoT towards ultra-low cost and maintenance-free operation. However, its large-scale adoption still depends on overcoming bottlenecks related to communication range and the standard ecosystem.

Keywords

Passive IoT; Low-power Communication; Ambient Backscattering; Radio Frequency Identification (RFID); Energy Harvesting.

1. Introduction

The power consumption and battery replacement/maintenance costs of IoT terminals have long hindered large-scale commercial deployment. Passive IoT, which utilizes widely available ambient energy sources like RF signals and light for communication, makes it possible to achieve "permanently online" connectivity among a vast number of nodes anytime, anywhere. This not only solves the power supply problem of existing devices but also, due to its low-cost characteristics, enables widespread application in retail, agriculture, infrastructure, and other fields. Studying its low-power communication methods and development prospects is conducive to advancing the entire IoT industry towards a more environmentally friendly and economical direction.

2. Concept and Connotation of Passive IoT

With the development of wireless communication and electronic manufacturing, the Internet of Things (IoT) has made significant progress in recent years, spawning innovative products and applications in smart homes, healthcare, agriculture, logistics, and many other fields. The number of IoT devices is growing exponentially. Market forecasts predict that the total number of active devices worldwide will reach 29.7 billion by 2027, a 78% increase from 16.7 billion in 2023, highlighting the transformative impact of smart technology on global connectivity. Passive IoT is a disruptive technological concept where each node does not require a battery or connection to an external power source. Instead, it powers its own operation by harvesting various forms of energy abundantly present in the surrounding environment. These energy sources are diverse, such as radio waves in shopping malls, indoor light, vibrations from machinery in factories, or even differences in body temperature. Using miniature devices like RF energy harvesters or photovoltaic cells, this weak energy is collected, converted, and stored for use by integrated circuits and sensors. This completely eliminates the issues associated with active IoT, such as short lifespan due to regular battery replacement, high maintenance costs, and environmental pollution. Furthermore, passive nodes utilize novel

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communication methods, most notably ambient backscattering technology. Instead of generating its own wireless signal, a node acts like a mirror, reflecting and modulating existing ambient signals like Wi-Fi or cellular signals for communication, thereby drastically reducing communication energy consumption [1].

3. Application Value of Low-Power Communication Technologies in Passive IoT

3.1 Creating Economic Value: Driving Cost Revolution and Business Model Innovation

The most prominent advantage of low-power communication technologies in passive IoT is the fundamental transformation of the cost structure associated with IoT deployment and maintenance, thereby enabling many previously unimaginable application scenarios. In traditional IoT solutions, the costs of batteries, the labor for regular battery replacement, and managing/charging numerous devices are high and ongoing. Since passive technology eliminates the need for batteries or extends their lifespan to several years or even permanently, it removes this major expense. Consequently, the hardware cost per sensor or communication node can be extremely low. For instance, the price of a high-performance passive tag is far lower than the combined cost of a Bluetooth module and a battery. This drastic cost reduction makes the "Internet of Everything" no longer a fantasy but a practical business model. In the retail industry, companies can afford to equip every product, even each beverage bottle or snack pack, with a smart tag at a low price, enabling real-time, accurate inventory tracking from warehouse to shelf. This significantly reduces product loss and out-of-stock situations, improving inventory turnover. In logistics, low-cost passive sensors can be attached to every package or even items inside, monitoring temperature, humidity, and impacts during transit. Previously, such fine-grained management was only feasible for valuable goods, but now it can be applied to ordinary parcels. More importantly, passive IoT creates new business opportunities, such as time-based insurance based on an item's current location or precise supply chain financing based on actual usage. Therefore, passive IoT is not just about cost savings; it provides various industries with the opportunity to leverage data for refined operations, reduce costs, increase efficiency, and create new revenue streams.

3.2 Expanding Technological Boundaries: Unlocking Extreme and Massive Application Scenarios

The significance of this technology lies in overcoming the physical constraints and deployment limitations of traditional IoT, enabling digital sensing in previously hard-to-reach areas. Because they don't need a power supply or support, passive devices can be made very small, light, thin, even flexible or implantable. This opens possibilities for deploying sensors in special environments or on specific objects. In industry, they can be placed inside rapidly rotating aircraft engine blades, embedded within reinforced concrete structures, or attached to high-temperature, high-pressure petrochemical pipelines to monitor strain, vibration, and heat in real-time, enabling true preventive maintenance without worrying about battery depletion or wiring complexity. In agriculture, thousands of passive soil moisture and temperature sensors can be scattered like seeds across a field to form a high-density monitoring network for precision irrigation, requiring no retrieval or recharging, truly integrating with nature. Moreover, due to its "permanently online" advantage, passive IoT is an ideal choice for creating digital twins. Imagine a future where every bridge, road, and fire hydrant in a city has a passive health monitoring sensor. The health status of the entire urban infrastructure could be monitored around the clock without blind spots, providing city management with a new real-time and holistic perspective. This ability to "awaken physically silent entities" greatly enriches the scope of IoT, allowing everything from tiny implantable medical devices to massive buildings to be connected, sensed, and controlled [2].

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3.3 Practicing a Sustainable Future: Building a Green and Low-Carbon IoT Ecosystem

In the context of the global pursuit of "carbon peak" and "carbon neutrality" goals and sustainable development, low-power communication technologies in passive IoT offer significant environmental benefits and social value, representing a green technical solution. Their greatest advantage is the complete elimination of environmental pollution caused by the batteries of numerous IoT devices, including the natural resource consumption and pollution from battery production and use, as well as the risk of heavy metal contamination in soil and groundwater from improper disposal of spent batteries. Passive devices themselves consume almost no power and effectively utilize ambient energy (like RF signals or light), so their carbon emissions are negligible. If this technology is widely adopted, the resulting IoT systems will be cleaner and more sustainable. Furthermore, this green attribute complements its enabling function. For example, in smart grids, passive sensors deployed on power lines can more effectively monitor line conditions, preventing power losses due to faults. In smart buildings, widely distributed passive occupancy sensors can better regulate lighting and air conditioning, achieving significant energy savings. Thus, passive IoT is inherently green while also using the data it collects to empower other sectors to improve resource efficiency. It represents a change in mindset: technological development does not necessarily entail greater energy consumption and more electronic waste; instead, through more ingenious methods, it can harmonize with nature and resources, leaving a cleaner digital legacy for future generations.

4. Application Pathways for Low-Power Communication Technologies in Passive IoT

4.1 Starting with Scenario Definition and Energy Supply Strategy

The first step in using passive IoT low-power communication technology is not selecting a chip, but conducting a detailed "examination" or "profiling" of the target application scenario. This is the foundation for subsequent work. Key considerations include the characteristics of the physical environment: What forms of usable ambient energy are available? Are there dense Wi-Fi or cellular signals, stable indoor light, vibrations from machinery, or significant temperature differences? Different energy sources determine different harvesting methods. The friendliness of the physical environment for radio signals must also be assessed: Are there issues like severe multipath reflections, metal shielding, or water attenuation? These problems affect backscatter communication performance and range. The deployment form factor of the nodes is also important – will they be attached to high-speed moving packages, embedded in concrete, or implanted in living organisms? This influences device size, shape, and packaging.

More critical is the data requirement: Which parameters need sensing (e.g., temperature, humidity, location)? What is the required data update frequency (once per second or once per day)? What is the permissible communication latency? How high is the requirement for data reliability? For example, warehouse inventory counting might require reading hundreds of tags within one second but can tolerate some read errors, whereas a medical implant device might require very low-frequency data transmission with extremely high reliability. By comprehensively considering these four aspects – energy, environment, form factor, and data – the basic requirements for passive nodes in that application scenario can be determined. This provides clear, quantitative justification for subsequent technology selection and solution design, avoiding the pursuit of advanced but unsuitable technology. For instance, in industrial control scenarios, the application of passive IoT devices mainly involves temperature, humidity, and vibration detection for industrial equipment. In a factory environment, motors and other equipment inevitably generate vibrations. Devices can use vibration energy harvesters to convert the kinetic energy of vibrations into electrical power. The devices then send data via Bluetooth or Wi-Fi to a gateway, which forwards it to a backend server [3].

4.2 System Integration and Communication Architecture Design

After defining the scenario, the next step is to build a robust, reliable, and easily scalable overall communication system. This is not simply placing some passive tags; the entire system needs to be

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designed holistically. The primary task is establishing a collaborative framework of "exciter – passive node – reader/receiver gateway". The exciter (which could be a dedicated RF transmitter or an existing ambient signal source) needs to be strategically placed and optimized to provide sufficient energy radiation range and good signal strength, ensuring all nodes in the area are activated and can communicate effectively. This is like setting up an invisible "energy field" or "signal lighthouse" for the area. The design of the reader/receiver gateway is crucial; it must possess strong signal processing capabilities to correctly demodulate the weak signals reflected by passive nodes in noisy environments. Typically, this requires complex reception methods like multiple antennas and coherent detection.

More importantly, a good communication mechanism is needed. Given the extremely limited resources of passive nodes, they cannot run complex network protocols, so all intelligent design should reside on the gateway. This includes having a good collision avoidance method to resolve conflicts when hundreds or thousands of nodes are awakened simultaneously, a reasonable allocation and access strategy to ensure high data rates while minimizing node energy consumption, and simple node authentication and data encryption methods for basic system security. The system architecture should also be scalable, allowing for increased coverage or adaptation to complex environments by adding more gateways or increasing exciter power. Successful completion of this step links individual passive technology components into a reliable, controllable, and operable network system.

4.3 Hardware Implementation and Energy Management Optimization

Once the system architecture is determined, the focus shifts to hardware implementation and the art of extreme energy management-the "what" and "how". Hardware design for passive IoT devices is an extreme challenge at the milliwatt or even microwatt power level. It primarily involves a highly integrated, miniaturized system: The energy harvesting part (e.g., RF rectifying antenna or small photovoltaic panel) must be optimized for the specific application scenario or energy source. The energy storage part (typically a small capacitor or thin-film battery) must support frequent charge and discharge cycles within a minimal volume. The control and sensor part requires ultra-low-power processors or custom circuits that spend most of their time in sleep mode. The backscatter communication module is typically implemented using a smartly switchable impedance modulation circuit [4].

True intelligence lies in energy management, which acts as the "brain" of the entire system. It constantly monitors harvested energy and storage status, controlling device behavior based on pre-defined, intelligent policies. For example, when energy is abundant, the device might wake up more frequently, collect sensor data, and attempt communication. When energy is low, it might only maintain basic functions or communicate only when significant events occur (e.g., a sensor reading exceeds a threshold). To improve communication success probability, the algorithm might also allow the device to backscatter only when it senses the strongest ambient signal (e.g., when a reader is nearby). This synergistic hardware-software approach and dynamic, adaptive energy management is the crucial bridge moving passive devices from "theoretically feasible" to "truly practical," ensuring they can operate correctly and complete essential tasks even with extremely unstable and limited power supply.

4.4 Data Closed-Loop and Business Value Realization

The ultimate goal of technology application is value creation. This requires effectively integrating the data generated by passive IoT into business processes, forming a complete "sense-decide-act" data flow. The final step is to smoothly transform data into insights and actions. Therefore, the passive IoT system should not become an information silo. Its reader/gateway needs to use standard interfaces (e.g., Ethernet, 4G/5G) to upload collected data (e.g., "Tag ID A, Location B, Temperature 25°C") to the cloud or a local server in a timely manner. Data cleaning, correlation, and fusion operations are performed here. A passive tag ID must be linked to the asset number in the enterprise's asset management system; its location information must be correlated with the digital map of the warehouse or store layout; its sensor readings must be compared with historical data or process parameters.

Subsequently, within the business platform's rule engine or machine learning models, this information is converted into actionable operations or alerts. For example, if the system detects an excessively high temperature in a cold-chain package, it immediately issues an alert and notifies relevant personnel. In a retail system, when the inventory of a certain product on the shelf falls below a safe level, a purchase order is automatically generated. In a factory management system, based on trend analysis of equipment vibration, the system can predict that a specific fan will require maintenance in one month, allowing preventive maintenance to be scheduled proactively. The outcome of this process is quantifiable business benefits: inventory accuracy might increase from 93% to over 99.9%, product loss rate might decrease by 15%, unplanned equipment downtime might be reduced by 30%, and overall enterprise productivity significantly improves. Only when passive IoT technology, using data as a link, integrates into and drives the improvement and innovation of core business processes can its application path be considered complete, and its immense potential fully realized.

5. Conclusion

Low-power communication technology for passive IoT is transitioning from concept to product, and its effectiveness in reducing energy consumption and expanding application scenarios is already recognized. With the development of new technologies like 5G and AI, it may also overcome challenges related to long distance and high data rates, fostering a healthy ecosystem. Continued collaborative efforts are needed in standardization, energy efficiency optimization, and application scenario exploration to drive its development, making the IoT more environmentally friendly and intelligent.

Acknowledgments

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