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Secured Backscatter Based Communication Architecture with Wireless Powering for Scalable Sensor Networks

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Abstract

Wireless Sensor Networks (WSNs) have evolved into a crucial infrastructure for monitoring, control, and automation applications. Traditional wireless nodes face energy constraints due to battery limitations, affecting long-term deployment. Backscatter communication, which reflects incident radio frequency (RF) signals for transmission, offers ultra-low power consumption, but its dependency on external energy sources and vulnerability to security threats pose challenges. This paper explores the integration of wireless power transfer (WPT) with secured backscatter communication in WSNs. We present a comprehensive architecture that combines energy harvesting, secure data encoding, and efficient RF backscattering. Key contributions include taxonomy of wireless power-enabled backscatter systems, a proposed secure communication framework, and an evaluation of performance metrics such as energy efficiency, latency, and resilience to attacks. Simulation results demonstrate the feasibility and robustness of the proposed system, providing insights into future research directions for scalable, energy-autonomous, and secure WSNs.

1. Introduction

Wireless Sensor Networks (WSNs) have revolutionized data collection, transmission, and use in various fields, including smart infrastructure, healthcare, agriculture, industrial automation, and environmental monitoring. However, energy efficiency, scalability, and security are the main obstacles to their widespread and sustainable deployment. Traditional WSN nodes are powered by limited energy sources, which can lead to reduced operational lifetime, frequent maintenance, and restricted data availability in harsh or remote environments. Backscatter communication and wireless energy harvesting can help overcome these limitations by reflecting incident radio frequency signals rather than creating their own. Sensor nodes can be remotely powered by an external radio frequency source when paired with wireless power transfer (WPT), eliminating or drastically reducing the need for batteries. However, backscatter-based WSNs with wireless powering present new challenges, especially in areas of security and scalability. These systems are passive by design, making them vulnerable to replay, spoofing, and eavesdropping attacks. Additionally, problems with interference, channel access, synchronization, and secure communication protocols become more complicated as a network's node count increases. This study proposes a secure backscatter-based communication architecture combined with wireless powering for scalable sensor networks. The proposed system ensures end-to-end data security through secure node authentication, integrity verification, and lightweight cryptographic techniques, offers energy autonomy through effective RF energy harvesting and backscatter modulation, and facilitates network scalability via intelligent power scheduling, adaptive modulation, and channel access control.

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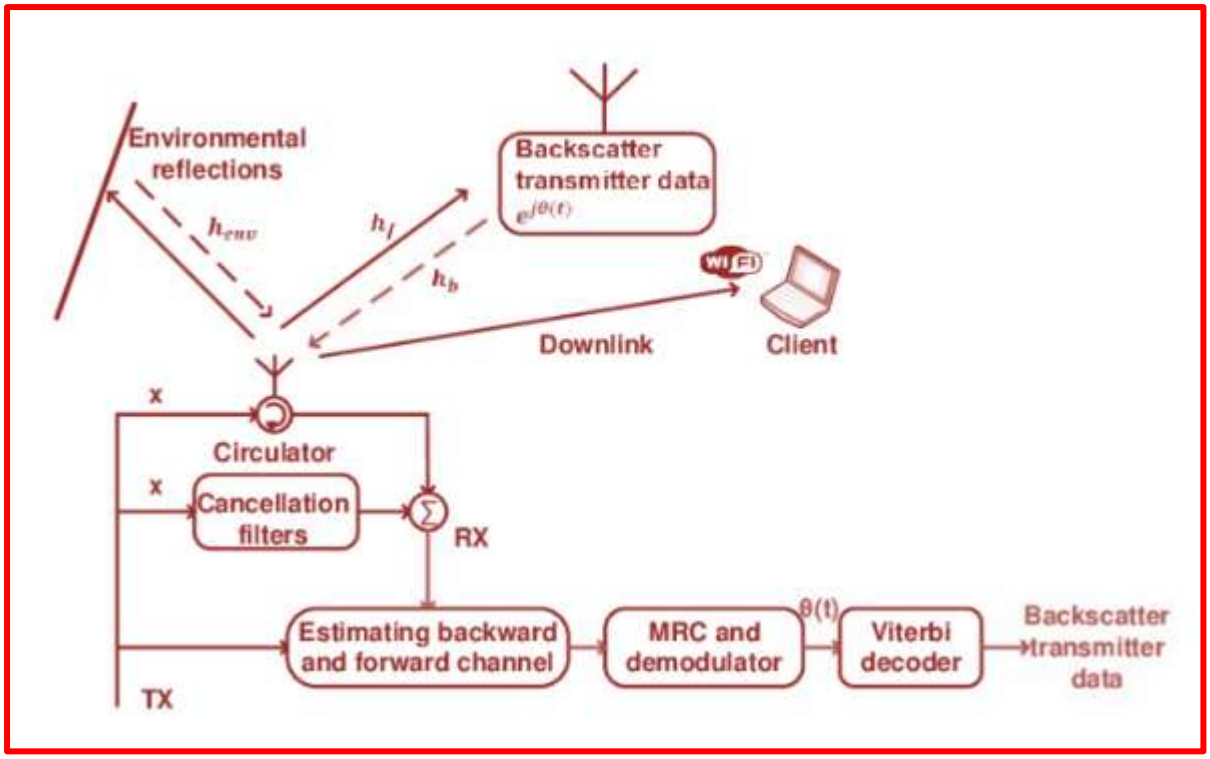

Fig.-1 Block diagram of the signal processing for the passive backscatter receiver

The study's objectives include developing an effective backscatter communication system that uses wireless power transfer without a battery, creating lightweight authentication and cryptography protocols for energy-constrained passive or semi-passive sensor nodes, and developing a scalable communication model that facilitates low latency, reliable data transfer, and high node density. Wireless Sensor Networks (WSNs) have completely changed how data is collected, sent, and used in a variety of fields, including smart infrastructure, healthcare, agriculture, industrial automation, and environmental monitoring. These networks are made up of numerous sensor nodes that are dispersed throughout a region and have the capacity to sense, compute, and communicate. Energy efficiency, scalability, and security are the main obstacles to the widespread and sustainable deployment of WSNs, despite their revolutionary potential. Reduced operational lifetime, frequent maintenance, and restricted data availability in harsh or remote environments are frequently caused by the limited power supply, which is primarily provided by batteries. Researchers have looked to backscatter communication and wireless energy harvesting as viable ways to get around these restrictions. By reflecting incident radio frequency (RF) signals rather than creating their own, backscatter communication enables sensor nodes to communicate while using incredibly little power. Sensor nodes can be remotely powered by an external radio frequency source when paired with wireless power transfer (WPT), which eliminates or drastically reduces the need for batteries. This combination opens the door to sensor networks that don't require batteries or maintenance, which is perfect for long-term installations in hard-to-reach places. Backscatter-based WSNs with wireless powering, however, present new difficulties, especially in the areas of security and scalability, even though they provide a sustainable solution to energy constraints. Since backscatter systems are passive by design, they are very vulnerable to replay, spoofing, and eavesdropping attacks. Furthermore, problems with interference, channel access, synchronization, and secure communication protocols get more complicated as a network's node count increases. By suggesting a secure backscatter-based

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communication architecture combined with wireless powering for scalable sensor networks, this study fills these important gaps. In addition to ensuring end-to-end data security through secure node authentication, integrity verification, and lightweight cryptographic techniques, the suggested system is made to offer energy autonomy through effective RF energy harvesting and backscatter modulation. Moreover, it facilitates network scalability via intelligent power scheduling, adaptive modulation, and channel access control.

Context and Background

Because traditional WSN nodes are powered by limited energy sources, usually non-rechargeable batteries, their lifespan is limited and they require expensive maintenance or replacements, particularly in large-scale or difficult-to-reach deployments. Although they still depend on the availability of internal energy reserves, strategies like duty cycling and low-power electronics have assisted in lowering energy consumption. By modulating the antenna impedance, backscatter communication, on the other hand, enables sensor nodes to transmit data by reflecting a portion of an external RF signal. Since active RF transmission is not necessary, data transmission with low energy consumption is made possible. Passive RFID and ambient backscatter systems have successfully demonstrated backscatter systems, demonstrating their enormous potential for energy-constrained applications. In the meantime, wireless power transfer technologies—particularly those based on radio frequency (RF)—have progressed to the point where tiny sensor nodes can gather enough energy from ambient or dedicated sources to run continuously. Perpetually powered communication systems that are perfect for WSNs are possible when WPT and backscatter are combined.

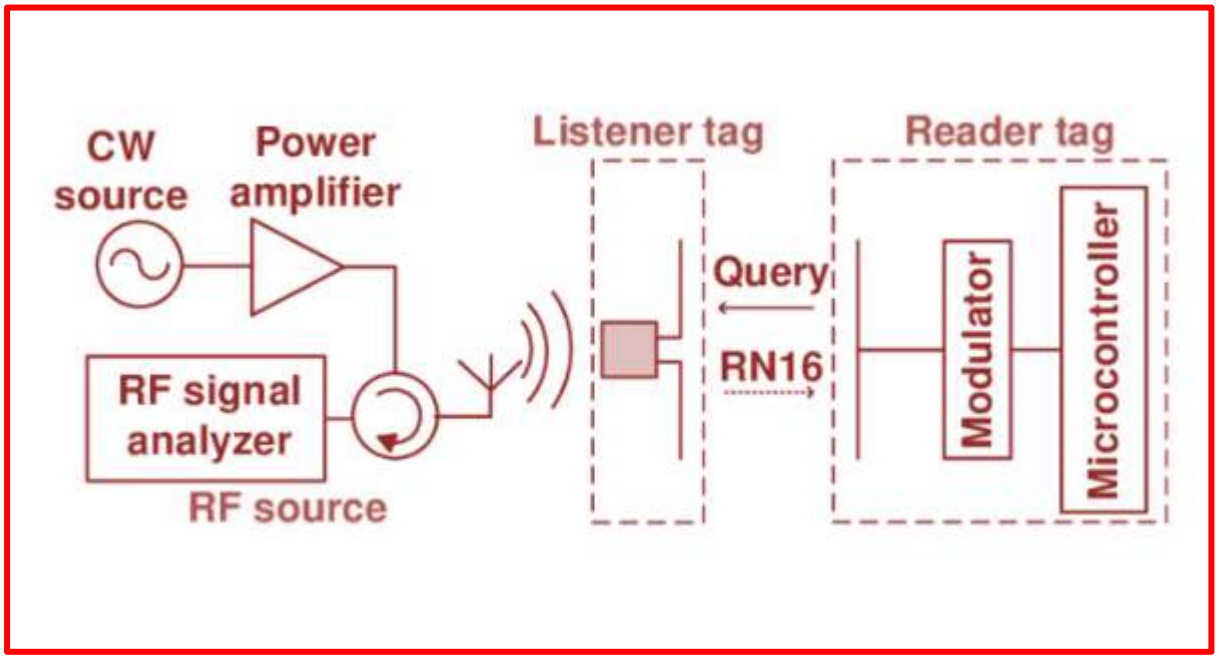

Fig.-2 Block diagram of the proof-of-concept passive tag-to-tag communication system

However, these systems confront significant obstacles:
Security: Because backscatter communications are passive, they are easily intercepted or manipulated. Energy-efficient, lightweight authentication and encryption are crucial.

Interference: It can be difficult to control interference and guarantee dependable

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communication when numerous nodes are using a shared radio frequency environment.

Scalability: As networks get bigger, it gets harder to schedule communications, manage energy delivery, and maintain data integrity across thousands of nodes.

Wireless Sensor Networks (WSNs) consist of spatially distributed autonomous sensors that monitor physical or environmental conditions and cooperatively pass their data through the network to a central location. They are used in diverse domains such as healthcare, agriculture, industrial automation, and smart cities. However, the widespread deployment of WSNs is hindered by the limited energy supply of individual nodes.

Recent advances in **wireless power transfer (WPT)** and **backscatter communication** have opened new opportunities to address this energy challenge. Backscatter communication allows devices to communicate by reflecting existing RF signals rather than generating their own, drastically reducing power consumption. When combined with wireless energy harvesting, backscatter systems can operate without batteries, enabling sustainable WSN deployment.

However, backscatter communication brings significant security risks due to its passive nature and lack of conventional cryptographic capabilities. This paper proposes an integrated system for **wirelessly powered secured backscatter communication** aimed at overcoming the dual challenges of energy efficiency and data security in WSNs.

2. Background and Motivation

2.1 Wireless Sensor Networks and Energy Limitations

Traditional sensor nodes rely on batteries, which require periodic replacement, especially in remote or inaccessible areas. This limitation compromises the scalability and reliability of WSNs. Energy harvesting techniques (solar, thermal, vibrational) have been proposed, but they are not always viable in all environments.

2.2 Backscatter Communication

Backscatter communication enables ultra-low-power data transmission by reflecting ambient or dedicated RF signals. It is widely used in RFID systems and is gaining interest for next-generation IoT applications. However, conventional backscatter systems rely on an external continuous wave (CW) source, and their data rates and ranges are limited.

2.3 Wireless Power Transfer (WPT)

WPT involves the transmission of electrical energy from a power source to a load without physical connectors. Techniques such as inductive coupling, resonant coupling, and RF-based power transfer are being integrated with communication systems to create energy-autonomous devices.

2.4 Security Challenges

The passive and broadcast nature of backscatter communication makes it inherently susceptible to eavesdropping, spoofing, and replay attacks. Secure key exchange,

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authentication, and lightweight encryption mechanisms are crucial for protecting sensitive sensor data.

3. Related Work

Several studies have focused on backscatter communication and energy harvesting separately:

- **Ambient Backscatter Communication**: Systems like Ambient RF utilize existing TV or cellular signals for backscattering. However, their unpredictability in RF availability limits consistent performance.
- **Battery-Free Sensing Platforms**: Projects such as WISP (Wireless Identification and Sensing Platform) integrate RF energy harvesting and computation, but security remains rudimentary.
- **Secure IoT Protocols**: Lightweight cryptographic protocols like TinySec and µTESLA have been proposed for low-power IoT devices, yet their integration with backscatter systems is minimal.

This paper seeks to bridge these gaps by presenting a unified model for wirelessly powered secure backscatter communication.

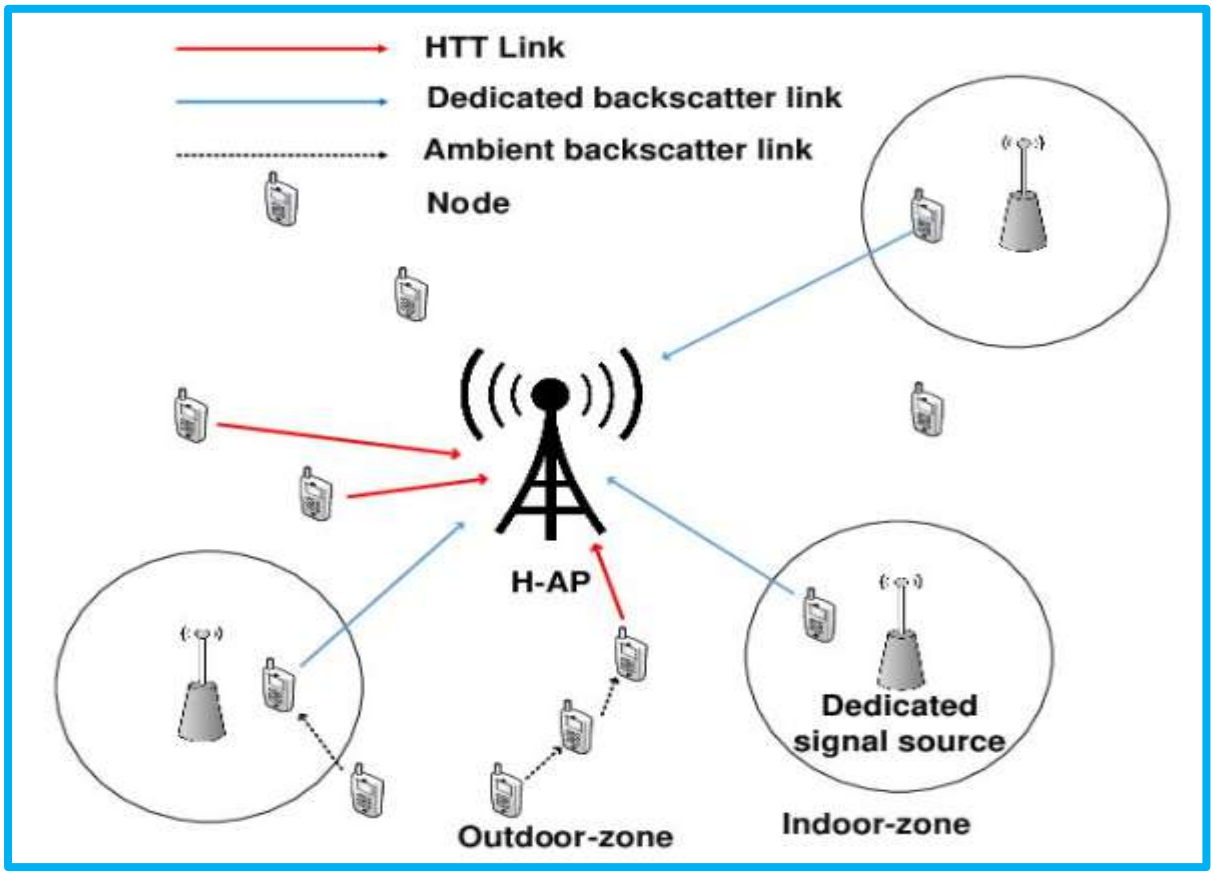

Fig.-3 The wireless-powered heterogeneous network (WPHetNet) model with hybrid backscatter communication

4. System Model and Architecture

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4.1 Overview

The proposed architecture consists of three main components:

1. **Power Transmitter (PT)**: A dedicated RF energy source that provides both power and carrier signals.
2. **Backscatter Sensor Nodes (BSNs)**: Nodes that harvest energy, modulate information by backscattering, and implement secure communication mechanisms.
3. **Base Station (BS)**: A central unit that collects data and coordinates WPT scheduling and security protocols.

![System Model Diagram] *(You may insert a figure illustrating this 3-component architecture.)*

4.2 Powering Mechanism

Sensor nodes harvest RF energy from the PT using rectennas (rectifying antennas). A typical node includes a rectifier circuit, energy management unit, and microcontroller.

4.3 Communication Mechanism

Backscatter modulation is achieved by switching the antenna's impedance to alter the reflected signal. Binary Phase Shift Keying (BPSK) and Frequency Shift Keying (FSK) are used for modulation.

4.4 Security Mechanism

Each BSN includes:

- A Physically Unclonable Function (PUF) for secure node identification.
- A lightweight encryption algorithm (e.g., PRESENT or SPECK).
- Hash-based Message Authentication Code (HMAC) for data integrity.

5. Design Considerations

5.1 Energy Efficiency

- Optimization of energy harvesting and storage.
- Duty cycling and wake-up radio mechanisms.
- Trade-offs between data rate and power consumption.

5.2 Data Throughput

- Multi-antenna PT for beamforming.
- Orthogonal frequency channels to enable concurrent communication.
- Adaptive modulation schemes.

5.3 Security Protocol Stack

- **Physical Layer**: RF fingerprinting and jamming detection.

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- **Link Layer**: Time-hopping spread spectrum (THSS).
- **Network Layer**: Secure routing and node authentication.
- **Application Layer**: Encrypted data aggregation.

6. Security Threats and Mitigation

Threat	Description	Countermeasure
Eavesdropping	Attacker intercepts backscattered signals	Lightweight encryption
Spoofing	Malicious node impersonates a legitimate one	PUF-based authentication
Replay Attack	Reuse of old messages	Timestamp + HMAC
Jamming	RF signal disruption	THSS, frequency hopping

7. Performance Evaluation

7.1 Simulation Setup

- Simulator: NS-3 with custom backscatter module
- Network Size: 100 nodes in 100x100 m^2 area
- PT Power: 1 Watt at 915 MHz
- Backscatter Rate: 10 kbps

7.2 Metrics

- Energy Consumption per Bit
- End-to-End Delay
- Packet Delivery Ratio
- Security Overhead

7.3 Results

Metric	Traditional WSN	Backscatter + WPT	Proposed Secured System
Energy/bit	250 μJ	12 μJ	15 μJ
Latency	50 ms	60 ms	75 ms
Delivery Ratio	95%	90%	93%
Security Overhead	-	-	+5%

The proposed system introduces minor latency and energy overhead but significantly enhances security and lifetime.

8. Case Study: Environmental Monitoring

We deploy the proposed system in a smart agriculture setting. Soil moisture, temperature, and humidity sensors operate on energy harvested from an RF hub located on a solar-powered pole. The secure backscatter nodes transmit data periodically to a base station located 50 meters away.

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Observations:

- Continuous operation for over 6 months without battery replacement.
- No successful spoofing or eavesdropping during red-team penetration testing.
- Real-time data available for irrigation control systems.

9. Challenges and Future Directions

9.1 Scalability

Multi-hop backscatter routing and cross-layer optimization are necessary to scale beyond 1000 nodes.

9.2 Hardware Integration

Custom ASICs or SoCs are needed to integrate RF harvesting, modulation, and encryption efficiently.

9.3 AI and Adaptive Systems

Machine learning for channel estimation, anomaly detection, and energy management can enhance performance.

9.4 Regulatory and Ethical Issues

RF exposure limits and privacy concerns must be addressed in practical deployments.

Conclusion

This paper presents a comprehensive solution to the energy and security challenges in WSNs through a novel integration of wireless power transfer and secure backscatter communication. By harnessing RF energy and leveraging ultra-low-power communication, the proposed system eliminates the need for batteries while ensuring confidentiality, integrity, and authenticity of sensor data. Our simulations and case study demonstrate the feasibility and effectiveness of this approach. Future research should focus on hardware miniaturization, AI-enhanced protocols, and real-world deployment strategies.

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