



Wi-Fi Backscatter for Low Power IoT: Review and Research Outlook

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Abstract: Wi-Fi backscatter communication offers a compelling solution for ultra-low-power and battery-free communication systems, especially within the Internet of Things (IoT) domain. By repurposing existing Wi-Fi infrastructure and ambient signals, backscatter systems achieve energy-efficient communication by reflecting signals rather than generating them. This review consolidates the current landscape of Wi-Fi backscatter technologies and highlights key areas of development such as feasibility on commercial hardware, antenna design, modulation techniques, synchronization, and safe Wi-Fi packet manipulation. Furthermore, the review identifies persistent research gaps and proposes future directions to bridge them, with emphasis on addressing four core challenges: hardware feasibility, antenna optimization, modulation reliability, and protocol-safe Wi-Fi packet analysis.

Index Terms: ambient backscatter, low-power wireless communication, packet analysis, Wi-Fi compatible modulation

1 INTRODUCTION

Wi-Fi backscatter has emerged as a transformative technology for enabling low-power and battery-free communication, particularly in the realm of the Internet of Things (IoT). By leveraging ambient or dedicated RF sources and reflecting signals rather than generating them, backscatter communication offers substantial energy savings. Backscatter devices do not generate their own carrier signals; instead, they modulate and reflect ambient signals from existing RF sources such as Wi-Fi routers or Bluetooth beacons. This principle allows for significant power savings, often reducing power consumption by several orders of magnitude compared to active radios.

Recent advancements have shown that backscatter can be implemented using off-the-shelf devices and innovative circuit designs, making it increasingly viable for real-world applications. However, technology is still emerging, and critical challenges remain particularly regarding scalability, reliability, and seamless integration with existing Wi-Fi infrastructure. This review synthesizes key contributions across foundational theory, technological advances, and practical implementations, with a focus on feasibility, antenna optimization, modulation techniques, synchronization, and packet-level integration.

2 WI-FI BACKSCATTER

2.1 Historical Context

Backscatter communication dates to early radar and identification systems in the mid-20th century, most notably used in the development of Radio Frequency Identification (RFID) technology. In recent years, this

approach has evolved through the introduction of ambient backscatters, where signals from legacy systems like TV and Wi-Fi are repurposed for communication. Liu et al. (2013) introduced ambient backscatter communication using TV signals [1]. This concept was later adapted to Wi-Fi with the seminal work of Kellogg et al. (2014) [2], which showed for the first time that RF-powered devices could communicate with commodity Wi-Fi hardware by modulating ambient Wi-Fi signals.

Despite this breakthrough, practical implementations often rely on specialized or modified hardware to achieve reliable backscatter performance. For example, systems such as BackFi use full-duplex access points to enable simultaneous signal generation and reception [3]. Other works like Passive Wi-Fi focus on achieving Wi-Fi compatibility while minimizing power, often through custom chipsets [4]. The emerging trend is toward solutions that can be integrated seamlessly into existing commercial hardware environments, though few have fully achieved this.

2.2 Antenna Design and Optimization

The antenna in a backscatter system serves a dual role: harvesting RF energy and enabling impedance modulation to reflect signals. Research by Song et al. [5] and others has demonstrated novel antenna architectures, including high gain printed designs and multiband rectennas that improve reflection strength and energy efficiency. Furthermore, recent advancements in printed electronics have made it possible to develop flexible, wearable antennas that can conform to surfaces, making them ideal for IoT and biomedical use cases.

Optimizing antenna design involves trade-offs between size, gain, directionality, and compatibility with low-power electronics. The ability to control radar cross-section dynamically enhances modulation capability, while impedance matching ensures minimal signal loss. A thorough understanding of material science and electromagnetic simulation is essential to developing antennas tailored for different application scenarios.

2.3 Modulation Techniques

Various modulation schemes have been proposed and tested in Wi-Fi backscatter systems. The simplest and most energy-efficient is On-Off Keying (OOK), which toggles between two impedance states. More advanced techniques like Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) provide better spectral efficiency and robustness, especially under noisy conditions. Sync Scatter [6] introduces single-sideband QPSK modulation, which enhances bandwidth efficiency while maintaining low power consumption.

Modulation also impacts receiver complexity. For example, CRC-based XOR modulation used in EEWSscatter [7] allows tag data to be inferred by comparing corrupted and uncorrupted packets. This clever reuse of Wi-Fi frame structure provides a means for efficient uplink without violating Wi-Fi protocol integrity. Future systems may blend multiple modulation approaches dynamically depending on network conditions.

2.4 Synchronization and Symbol-Level Alignment

Synchronization is essential for coherent demodulation and multi-device access. Traditional backscatter systems suffer from high bit error rates due to lack of precise symbol alignment. SyncScatter [6] addresses this by employing a hierarchical architecture with a low-power wake-up receiver and a secondary high-bandwidth synchronization module, achieving symbol-level accuracy within 150 nanoseconds. This precision enables higher data rates and multi-user scheduling.

Symbol-level synchronization not only improves robustness but also facilitates coexistence with

traditional Wi-Fi traffic. Systems like HitchHike[8] and FreeRider[9] have attempted coarse synchronization, but their reliance on high bit redundancy makes them inefficient. Future research may explore machine learning approaches for adaptive synchronization under dynamic channel conditions.

2.5 Wi-Fi Packet Integration and Safe Manipulation

For backscatter systems to coexist with standard Wi-Fi traffic, they must safely manipulate packet contents without violating protocol specifications. Researchers have found ways to encode data into unused portions of packets, such as padding or cyclic redundancy check (CRC) fields. SyncScatter[6] and BackFi[3] demonstrate how CRC manipulation combined with XORing can embed data in a way that is both detectable and reversible.

However, few tools exist to guide developers on which fields are modifiable and under what constraints. Tools like Wireshark help visualize packet structures but do not validate protocol compliance. Establishing a reference framework for packet-safe modulation remains a critical step toward large-scale adoption.

2.6 Energy Harvesting and Circuit Diagrams

One of the key advantages of backscatter systems is their potential for battery-free operation. This requires efficient energy harvesting circuits that can power sensors and logic even under weak ambient signals. EEWSscatter [7] and other systems integrate RF rectifiers with minimal quiescent current, enabling energy storage and reuse.

Flexible and stretchable circuit designs are also gaining interest for wearable applications. Power gating techniques, where certain modules are activated only during transmission windows, help conserve energy. Future backscatter tags may incorporate hybrid energy harvesting mechanisms combining solar, kinetic, and RF sources.[11]

2.7 Theoretical Limits and Emerging Techniques

Korn et al. (2022) [10] have modeled the upper bounds of achievable data rates, ranges, and power budgets in mono-static and bi-static backscatter setups. These theoretical insights are crucial for benchmarking real-world systems and identifying areas where performance lags behind potential [11, 1].

In addition, research into hybrid backscatter systems that combine Wi-Fi with Bluetooth, LTE, or LoRa [12] for extended coverage and robustness is ongoing. Some exploratory work also considers mmWave backscatter [13] and even quantum-enhanced signal detection. As the ecosystem matures, cross-technology coordination will become an increasingly important topic in backscatter communication design.

3 ADDRESSING THE FOUR CORE GAPS IN FUTURE RESEARCH

Four critical gaps identified based on the literature, serving as the foundation for future experimental and theoretical contributions:

- **Feasibility Assessment:** The potential for implementing Wi-Fi backscatter using only commercially available hardware has to be considered. This includes leveraging programmable Wi-Fi chipsets (e.g., ESP32, Atheros) to experiment with firmware-level control for backscatter modulation. Comparative performance analysis of custom solutions should be conducted in terms of throughput, error rate, and compatibility.

- **Antenna Optimization:** Custom antennas have to be designed using simulation tools such as CST Microwave Studio and HFSS, followed by fabrication on flexible substrates and PCB boards. Return loss, S-parameters, gain, and radiation patterns measuring by using a vector network analyzer. Both directional and omnidirectional designs should be evaluated for different IoT environments (e.g., indoor smart home, wearable health monitoring).
- **Modulation Techniques:** The modulation schemes including OOK, BPSK, QPSK, and CRC-based XOR on testbed should be designed and tested. Each has to be evaluated under the controlled interference, variable distance, and environmental noise. Energy consumption per transmitted bit and achievable bit error rate (BER) should be used to assess reliability. At the end, particular focus should place on the trade-offs between complexity, decoding speed, and power efficiency.
- **Wi-Fi Packet Analysis:** A detailed mapping of the IEEE 802.11 packet structure has to be considered. Identification of safe fields for data embedding (e.g., padding, CRC, or unused header fields) using packet sniffing tools such as Wireshark should be included. A simulator designing and development to model packet corruption and test backscatter techniques without physical hardware should be evaluated. This framework aims to help new researchers avoid protocol violations and foster safer integration with existing networks.

Additionally, future work should be proposed a general methodology that combines the above aspects to form a cohesive design cycle: starting from hardware selection and antenna design, through modulation and packet-layer integration, and ending with real-world evaluation. This full-stack approach addresses both theoretical gaps and practical deployment barriers.

4 CONCLUSION

Wi-Fi backscatter represents a promising direction for enabling low-power, battery-free communication in future IoT systems. By leveraging existing Wi-Fi infrastructure and ambient RF signals, it offers a practical path toward energy-efficient connectivity. This review has highlighted recent progress across key areas—modulation schemes, antenna design, synchronization, and packet integration—while also identifying core research gaps.

Challenges remain, particularly in deploying solutions using commodity hardware, standardizing modulation techniques, and ensuring safe packet manipulation. The proposed work aims to directly address these challenges through systematic experimentation and integrated design approaches.

As the field matures, solving these issues will be essential for transitioning Wi-Fi backscatter from research labs into real-world, scalable applications. With continued innovation, it has the potential to become a foundational technology for sustainable and pervasive wireless communication.

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