Survey of Detector Research Trends for BER Minimization in Ambient Backscatter Communication Systems

Seonghun Hong
School of Computer Science and Engieneering
Chung-Ang University
Seoul,Korea
shhong@uclab.re.kr

Chunghyun Lee
School of Computer Science and Engieneering
Chung-Ang University
Seoul,Korea
chlee@uclab.re.kr

Junsuk Oh
School of Computer Science and Engieneering
Chung-Ang University
Seoul,Korea
jsoh@uclab.re.kr

Thanh Phung Truong
School of Computer Science and Engieneering
Chung-Ang University
Seoul,Korea
tptruong@uclab.re.kr

Manh Cuong Ho
School of Computer Science and Engieneering
Chung-Ang University
Seoul,Korea
hmcuong@uclab.re.kr

Sungrae Cho
School of Computer Science and Engieneering
Chung-Ang University
Seoul,Korea
srcho@cau.ac.kr

***Abstract*—Backscatter communication (BackCom) technology is an emerging ultra-low-power communication method that passively scatters/reflects an incident RF signal to transmit data to an intended receiver (Rx). Since no active transmission is required, the power consumption of BackCom devices (tags) is in the microwatt level and the tags can be manufactured very cheaply. These advantages make this technology one of the most competitive tools to support battery-free Internet of Things (BF-IoT). Furthermore, AmBC, one of the types of BackCom, supports flexible deployment and provides better coverage and flexibility by utilizing ambient RF signals without configuring a separate RF signal emitter. In this paper, we survey the recent trends in detector research for BER minimization in AmBC communication.**

Keywords—Backscatter, Detector, Energy efficiency

I. INTRODUCTION

The Internet of Things (IoT) has been making remarkable strides over the past several decades, transforming the way we interact with our environment by enabling the wireless connection of a vast array of devices, from household appliances to large-scale infrastructure in smart cities and logistics systems. This evolution is underpinned by the vision of creating a world where ubiquitous connectivity between humans, machines, and objects is seamlessly integrated into daily life. The global IoT market continues to expand rapidly, with projections estimating that its market size will soar to $1.55 trillion by 2026. Furthermore, the number of IoT devices in use worldwide is expected to exceed a staggering 30 billion by 2025, showcasing the vast scale of this technological revolution [1].

However, this exponential growth in connected devices has brought about significant challenges. Chief among these are the increasing energy consumption and maintenance costs associated with the operation of billions of devices, many of which rely on batteries. The widespread use of batteries not only drives up operational costs but also raises environmental concerns, particularly as it pertains to the disposal and replacement of these power sources. Addressing these issues has become a priority, leading to the emergence of innovative solutions such as battery-free IoT (BF-IoT). BF-IoT devices represent a revolutionary shift in IoT design, as they can harvest and store ambient energy from their surroundings instead of relying on conventional batteries for power. This ability to extract energy from the environment significantly reduces the need for battery use and maintenance, making it a more sustainable approach to IoT.

One of the most promising technologies enabling BF-IoT is backscatter communication. Unlike traditional communication technologies that depend on expensive, power-hungry devices to transmit and receive signals, backscatter communication works passively. It leverages existing RF (radio frequency) signals by scattering or reflecting these signals to transmit data. The receiver (Rx) demodulates the reflected signals by analyzing changes in power levels or employing more advanced methods, which enables ultra-low-power communication. This makes backscatter communication one of the most competitive and attractive tools for BF-IoT systems, as it significantly reduces the energy demands of connected devices [1].

Backscatter communication can be categorized into three main types. The earliest form is Monostatic BackCom, in which the RF source and backscatter receiver are integrated into the same device. A more advanced version, known as Bistatic BackCom, separates the RF source and backscatter receiver into two distinct devices, offering more flexibility in network deployment. The most cutting-edge and efficient form of backscatter communication is Ambient BackCom, which utilizes ambient RF signals present in the environment, such as TV broadcasts, Wi-Fi signals, or cellular communication waves. Ambient BackCom is especially advantageous in terms of cost and energy efficiency, as it eliminates the need for dedicated components to generate RF signals. Instead, it capitalizes on the ambient RF signals already available in the surroundings for communication purposes. Given these advantages, Ambient BackCom is rapidly emerging as the most effective solution for energy-constrained IoT systems.

This paper will delve into recent research trends focused on detectors for AmBC, highlighting the latest advancements and innovations that are propelling this field forward. Through this investigation, we aim to provide a comprehensive overview of how AmBC detectors are shaping the future of

BF-IoT, offering insights into their potential applications and implications for the broader IoT ecosystem.

II. Proposed Detector

When designing an AmBC system, a signal detector is a key component. Accordingly, much research effort has been invested in designing signal detectors for AmBC. For example, [2], [3] assumed Gaussian surrounding signals, applied differential encoding to the transmitted signal, and then derived an ML detector using Gaussian approximation.

A. *Optimal Non-coherent Detector*

In [4], a highly innovative optimal noncoherent detector for AmBC systems was proposed and thoroughly analyzed. This detector addresses a critical challenge by functioning without requiring any prior knowledge of the communication channel information, which is typically needed in traditional systems. The design process began with the derivation of a joint probability density function (PDF) for the signal vector received by the receiver. This derived PDF was then used as a foundation to develop two distinct types of detectors. The first detector, referred to as the direct approach, operates by directly utilizing the joint PDF to derive test statistics and decision thresholds. The method proceeds with these derived values to determine whether a signal has been correctly received. The second detector assumes an unknown communication channel, which varies depending on the specific symbol being transmitted by the backscatter tag (denoted as the k-th tag symbol). In this case, the PDF is recalculated to take into account the effects of noise and the varying signal strength present in the received signal. Additionally, this second detector uses a maximum likelihood estimation (MLE) approach, combined with a likelihood ratio test (LRT), to establish a decision threshold that accounts for the unknown channel conditions.

Both detectors showed superior performance compared to traditional methods. Specifically, experimental results revealed that both of these newly proposed detectors achieved significantly lower Bit Error Rates (BER) than the conventional energy detector. The direct approach detector, which utilizes the joint PDF, demonstrated a particularly strong performance, while the indirect approach, although computationally simpler, also maintained a high level of accuracy. By designing these detectors to operate without requiring any prior channel information, they provide a more flexible solution for AmBC systems, enabling them to function effectively even in environments where channel conditions are unpredictable. This approach ensures that the system can maintain high communication reliability and efficiency without the need for frequent recalibration or detailed channel state information, which is often difficult or impossible to obtain in practical scenarios.

B. *Adaptive Dual-Threshold Detector*

In [5], researchers proposed an adaptive detector for AmBC that leverages FDA (Frequency Diversity Array) technology. A novel system model was developed by incorporating the time-varying characteristics of the FDA RF signal source into the AmBC system. The initial approach involved the use of a Maximum Likelihood (ML) detector; however, the ML detector typically required prior knowledge of the backscatter tag's location, posing a limitation. To overcome this drawback, an adaptive dual-threshold detector was introduced. This new detector intelligently selects different thresholds depending on whether the direct link signal from the FDA and the backscatter tag signal overlap or not. By doing so, the system operates independently of the tag's location, ensuring stable performance even as the tag moves. Unlike the ML detector, which suffers from performance degradation due to unknown or shifting tag positions, the adaptive dual-threshold detector continues to maintain accurate detection. The experimental results demonstrated a significant advantage of the adaptive dual-threshold detector, particularly when the tag's angle exceeds 56 degrees. Under such conditions, the BER (Bit Error Rate) of both the single-threshold detector and the ML detector rises considerably, whereas the adaptive dual-threshold detector is able to maintain a consistently low BER, underscoring its robustness and efficiency in challenging scenarios.

C. *Direct ratio detector with phase information preserved*

In [6], a highly efficient AmBC system utilizing a novel ratio detector was proposed to address the limitations of conventional average-based energy detectors. Traditional energy detectors rely on averaging, which tends to reduce the system's data rate and introduces a persistent error floor, thus hampering performance. The newly proposed system takes a different approach by utilizing the complex ratio of the signal magnitude between two reader antennas. Unlike the conventional detector that only considers the magnitude ratio, this new method preserves both phase and magnitude information, which is crucial for maintaining accuracy in signal detection. By retaining phase information, the design allows for a more precise and linear channel model to be developed for the ratio detector. This linear model enables the use of more advanced signal processing techniques, including the implementation of channel coding techniques that improve overall system performance. These coding techniques enhance error correction by extending the bit sequence through code repetition, which offers better protection against data loss.

Based on the newly constructed channel model, a minimum distance detector was proposed, providing a much-improved framework for signal detection. This minimum distance detector operates by calculating the minimum difference between received and expected signals, making it more robust in comparison to conventional methods. Moreover, the performance of this detector was further enhanced by deriving a closed-form expression for Bit Error Rate (BER), offering a more streamlined process for analyzing and predicting system performance. Experimental results demonstrated that, as the Signal-to-Noise Ratio (SNR) increased, the BER of conventional maximum likelihood (ML) detectors relying on perfect Channel State Information (CSI) decreased only gradually. However, the BER of the proposed efficient ratio detector decreased rapidly, showing its superior adaptability and efficiency in handling real-world ambient backscatter signals.

III. Conclusion

In this paper, we explored recent research trends in detectors for AmBC systems. The proposed detector demonstrated better performance than existing methods, thanks to its ability to estimate channels accurately, even when the tag location is unknown or perfect channel state information (CSI) is unavailable. This allows the detector to maintain low bit error rates (BER) and function effectively in scenarios where tag location is variable.

In the future, developing detectors that can keep BER low in information-limited environments will be essential. Such advancements will help support the flexibility and efficiency of future battery-free IoT (BF-IoT) systems, especially in low-power or unpredictable conditions.

Acknowledgment

This work was supported in part by the National Research Foundation of Korea (NRF) grants funded by the Korea government (MSIT) (RS-2023-00209125).

References

[1] T. Jiang et al., "Backscatter Communication Meets Practical Battery-Free Internet of Things: A Survey and Outlook," in IEEE Communications Surveys & Tutorials, vol. 25, no. 3, pp. 2021-2051, thirdquarter 2023, doi: 10.1109/COMST.2023.3278239.

[2] G. Wang, F. Gao, Z. Dou and C. Tellambura, "Uplink detection and BER analysis for ambient backscatter communication systems", Proc. IEEE Global Commun. Conf. (GLOBECOM), pp. 1-6, Dec. 2015.

[3] K. Lu, G. Wang, F. Qu and Z. Zhong, "Signal detection and BER analysis for RF-powered devices utilizing ambient backscatter", Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP), pp. 1-5, Oct. 2015.

[4] S. Guruacharya, X. Lu and E. Hossain, "Optimal non-coherent detector for ambient backscatter communication system", IEEE Trans. Veh. Technol., vol. 69, no. 12, pp. 16197-16201, Dec. 2020.

[5] Y. -Q. Hu, H. Chen, S. -L. Ji, W. -Q. Wang and H. Chen, "Adaptive Detector for FDA-Based Ambient Backscatter Communications," in IEEE Transactions on Wireless Communications, vol. 21, no. 12, pp. 10381-10392, Dec. 2022, doi: 10.1109/TWC.2022.3183688.

[6] W. Liu, S. Shen, D. H. K. Tsang, R. K. Mallik and R. Murch, "An Efficient Ratio Detector for Ambient Backscatter Communication," in IEEE Transactions on Wireless Communications, vol. 23, no. 6, pp. 5908-5921, June 2024, doi: 10.1109/TWC.2023.3328935.