

B^3 : Bistatic Backscatter Beamforming for mmWave IoTs

Zhenzhe Lin*
George Mason University
Fairfax, USA
zlin9@gmu.edu

Mingyo Jeong
George Mason University
Fairfax, USA
mjeong6@gmu.edu

Yoon Chae*
University of Texas at Arlington
Arlington, USA
yoon.chae@uta.edu

Parth Pathak
George Mason University
Fairfax, USA
ppathak@gmu.edu

Abstract

Millimeter-wave (mmWave) backscatter has emerged as a compelling low-power communication paradigm for high-bandwidth IoT applications. However, existing systems rely on specialized readers, such as FMCW radars, which limits their scalability and practical deployment. On the other hand, commodity mmWave backscatter integrates the tags directly into the mmWave networks with devices like APs and clients, and the protocol frames are retrofitted to enable seamless communication with the tags. Despite its potential, such bistatic backscatter communication suffers from low SNR and short communication range. In this work, we present B^3 , a bistatic backscatter beamforming framework that operates entirely on commodity mmWave infrastructure such as 802.11ad/ay. B^3 introduces a lightweight multibeam backscatter technique that enables tags to embed both ID and channel information directly into standard beamforming frames via pulse position and on-off keying modulations. The design yields high-gain beams towards the tag in bistatic settings and supports concurrent multi-tag beamforming within a single training round. We prototype a multibeam 60 GHz backscatter tag and achieve a 13 dB SNR improvement compared to codebook-based beamforming, supporting backscatter communication at distances of up to 11 m with $\text{BER} \leq 10^{-3}$. Our evaluation shows that B^3 enables high-SNR backscatter even with blockages and NLoS conditions. Our tag prototype consumes only 2.5 mW of power, making it a practical and scalable solution.

CCS Concepts

• Computer systems organization → Sensor networks.

Keywords

mmWave, Bistatic backscatter, Beamforming, Tags, IoT

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*Co-primary authors with equal contribution.



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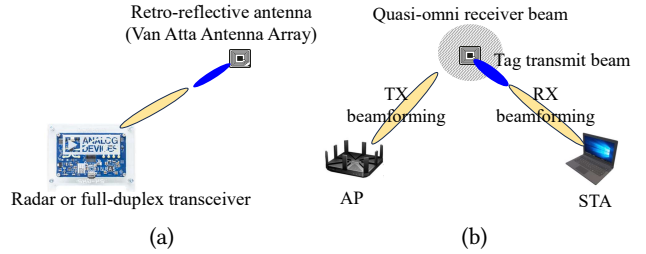


Figure 1: (a) mmWave backscatter using radar or full-duplex transceiver as dedicated readers; (b) bistatic mmWave backscatter where the tags are integrated in existing mmWave networks.

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1 Introduction

mmWave backscatter [8, 51] has emerged as a novel, promising paradigm that leverages the large bandwidths available at mmWave bands for improved sensing and high-speed communication, while ensuring low-power operation through backscattering. Recent research has explored mmWave backscatter across a range of applications. Millimetro [47], SuperSight [4], Hawkeye [5], and many others [10, 17, 26, 30, 46, 63], leverage mmWave's short wavelength and directionality to achieve fine-grained sensing and localization using mmWave FMCW radars. Systems such as BiScatter [39] Omniscatter [3], MilBack [32], and others [22, 34, 40] exploit the large mmWave bandwidth to support high-throughput and massive-scale concurrent communication, capabilities that are often beyond legacy IoT systems. These systems typically rely on mmWave radars as backscatter readers and use retro-reflective antennas on the backscatter tags, as shown in Fig. 1(a).

Different from these radar-based mmWave backscatter solutions, recent works [6, 7, 22, 27, 60] have integrated mmWave backscatter tags directly into mmWave wireless networks (e.g., 802.11ad/ay WiFi and 5G NR). As shown in Fig. 1(b), such commodity mmWave backscatter systems leverage a bistatic setup where WiFi access points (APs) or cellular base stations (BSs) collaborate with client devices (STAs/UEs) to communicate with backscatter tags. Here, the APs/BSs typically act as the transmitters (Tx) of the query signal, which are essentially protocol frames that are received by the STAs/UEs (Rx) after being backscattered from the tag, which also embeds its data during backscattering. These commodity mmWave

backscatter have been shown to achieve high-speed, low-power communication (for example, 55 Mbps at 87 microwatts as in [7]). Commodity mmWave backscatter systems eliminate the need to deploy dedicated radars or transceivers with full-duplex functionality, which is not commonly available in today's off-the-shelf devices. With direct integration of backscatter tags into mmWave networks, a range of new applications can be enabled. For example, a client device can retrieve video frames or a high-speed sensor stream from a low-power, camera/sensor-equipped tag using a nearby AP's query signal. These systems create a new era of IoTs that are also low-cost, as they reuse existing network infrastructure without the need for specialized hardware (such as mmWave radars) deployment.

Despite its potential, commodity mmWave backscatter suffers from short range and low SNR due to high attenuation at mmWave frequencies and losses incurred by backscatter hardware (e.g., switch insertion loss). For example, prior works [6, 7, 35] demonstrate reliable communication only within a range of 8 meters at 24 GHz (5 meters at 60 GHz). Beamforming is a natural solution to the problem; however, beamforming in a bistatic setup (AP to tag to STA, as shown in Fig. 1(b)) necessitates separate beam alignments for both the AP and STA towards the tag, which not only complicates the beamforming process but also doubles its overhead. More importantly, the backscatter tags are designed for low-power operations and cannot directly demodulate the protocol frames or measure the channel to provide feedback, as typically done in beamforming protocols. Additionally, commodity mmWave devices often rely on wider codebook-based beams designed for better coverage, rather than narrow, high-gain beams necessary to support low-power tags. Such wider beams also increase multipath interference, which can be detrimental to mmWave backscatter communication. As the number of backscatter tags increases, the complexity and overhead of beamforming can become a key limiting factor in the future adaptation of mmWave backscattering. Existing solutions, such as [7], are limited to beamforming on one endpoint and do not scale well with the increasing number of tags.

To address these challenges, we introduce B^3 in this paper. B^3 is a novel bistatic beamforming framework that enables robust and scalable mmWave backscatter communication using existing mmWave infrastructure. Our key design objective in B^3 is to move the burden of the beamforming process from the low-power, resource-constrained tags to regular mmWave devices such as the APs and STAs. Instead of requiring the tag to measure signal strength or channel, and decode frames, B^3 uses a multi-beam backscattering that enables the tags to implicitly convey the channel information directly during the standard beamforming process. Furthermore, each tag encodes its unique identifier during the backscattering to support simultaneous multi-tag beamforming. The multi-beam operations ensure reliable communication from tags without any prior knowledge of the receiver's direction. Both the channel and ID information are conveyed entirely within the standard over-the-air beamforming frame, preserving its original functionality and ensuring protocol compliance. Finally, with the given information, the transmitter (i.e., AP) and receiver (i.e., STA) can collaboratively create high-gain beams towards the backscatter tags for reliable backscatter communication. B^3 supports detection and beamforming for multiple tags within a single beamforming process, eliminating the need for separate beam alignment for each tag. Since B^3

embeds tag channel and ID information in the preamble of wireless packets, it can be easily extended to a wide range of beamforming-based mmWave networks. It enables reliable high-speed backscatter communication. High-speed backscatter can support transmission of a large amount of data from sensors such as a video camera (i.e., video streaming over backscatter [38, 57, 58]). The wide bandwidth of mmWave can improve localization, gesture tracking, occupancy detection, and other sensing tasks via accurate tag angle estimation in B^3 . In Industrial IoT, tags can facilitate simultaneous monitoring and tracking of multiple items without wiring or frequent battery replacement. Therefore, this design enhances the practicality and scalability of mmWave backscatter communication in real-world deployments.

Challenges. Designing a bistatic backscatter beamforming requires us to address the following challenges: (1) In order to enable the Tx and Rx to create high-gain beams towards the tag, it is necessary for the tag to implicitly convey its observed channel during backscattering. How can a resource-constrained tag, which is incapable of directly measuring the channel, backscatter such that the receiver devices can infer its channel and use that for beamforming towards it? (2) Furthermore, the tag should explicitly convey its ID to support scenarios with multiple coexisting tags. How can the tag encode the ID while preserving compatibility with the existing mmWave beamforming frame structure and without modifying the BF protocol? (3) Using omni or quasi-omni backscattering on tags significantly reduces the SNR, while using narrow transmit beams on tags requires prior knowledge of the receiver's relative position, which is infeasible for a resource-constrained tag. How can a passive tag backscatter using its directional beams, but without prior knowledge of the receiver's direction? (4) Commodity mmWave phased arrays often produce non-uniform beams with large sidelobes [49], resulting in the receiver observing a mixture of backscatter and multipath signals. How can the receiver accurately isolate the backscatter path from these interfering components to reliably extract the channel and calculate the corresponding beam weight vectors that can increase the gain from AP/STA to the tag? (5) Performing separate bistatic beamforming for each tag introduces significant overhead, which grows rapidly with the number of tags. How can we support simultaneous multi-tag detection and beamforming in the given commodity bistatic setup?

B^3 solutions. To address these challenges, B^3 introduces a multi-beam backscattering technique that forwards signals without knowing the receiver's direction, allowing the receiver to obtain the same result irrespective of its relative position. The tag rapidly switches between different beam directions to simultaneously modulate its ID and encode channel characteristics. This multibeam switching is performed within the Short Training Field (STF) symbols of the BF frame preamble, leveraging their redundancy to embed information without altering the BF frame structure. This ensures full compatibility with existing standards and preserves critical preamble functionalities such as packet detection, carrier frequency offset (CFO) estimation, and boundary detection. The multibeam backscattering creates a composite signal at the receiver that combines pulse-position modulation (PPM), used to convey the tag's ID, with on-off keying (OOK), used to isolate the backscatter path from multipath. By analyzing the pattern of these modulated STF

symbols, the receiver can determine both the backscatter channel and the associated tag ID. To achieve this, B^3 provides a simple yet effective solution through which it can identify prominent paths of reflections and backscatter from noisy cross-correlation of STF symbols. The backscattered STF symbols include carefully chosen reference symbols that can help demodulate the ID of different tags, enabling the receiver to simultaneously receive the mmWave channel from multiple tags. The extracted channel for each tag is then used to estimate the Angle of Departure (AoD) from AP and STA to the tag, which in turn yields high-gain beam weight vectors that improve the bistatic backscatter SNR compared to the default codebook-based beams.

Prototyping, implementation, and evaluation. We develop a 60 GHz PCB tag prototype¹ (2 cm × 4 cm) enabling tag channel and ID modulation through multi-beam operation using Hadamard matrices. We implement the backscatter channel and tag ID extraction on the mmWave software radio. The B^3 beamforming process is demonstrated using the BF frames transmitted by off-the-shelf 802.11ad/ay devices. Our evaluation shows that B^3 achieves up to 13 dB SNR gain compared to codebook-based WiFi beam patterns and maintains $\leq 10^{-3}$ BER with an effective communication range of up to 11 m. (1.5× improvement over the state-of-the-art [7], 3× improvement over the codebook-based WiFi beam patterns.) We evaluate B^3 in real-world indoor scenarios with tags blocked with different objects/materials. We find that B^3 achieves an SNR improvement of 8 dB on average compared to the default codebook-based beamforming, making mmWave backscattering possible even in scenarios with high attenuation losses, including blockages from obstructions like glass and wood and NLoS conditions. Our multi-tag experiments further demonstrate that B^3 can successfully embed and extract tag IDs within BF frames to support concurrent bistatic beamforming. Additionally, B^3 embeds backscatter signals within the preamble without degrading packet reception or CFO estimation, and outperforms baselines lacking backscatter path extraction by improving SNR by 13 dB through more accurate beamforming. Lastly, our low-power prototype consumes only 2.5 mW, including frame detection and modulation, demonstrating its practicality for mmWave IoT deployments.

Contributions. Our main technical contributions are:

- We present a first-of-its-kind bistatic backscatter beamforming framework for improving backscatter SNR while ensuring protocol compliance.
- B^3 employs a novel multi-beam backscatter tag design that can embed a tag ID and channel information in the preamble using unique PPM and OOK modulations to support concurrent multi-tag beamforming.
- We implement and evaluate B^3 using tag prototypes with software radios, and COTS APs, and show that it can determine a high-SNR beam even in practical scenarios with rich multipath and blockages.

2 Background

Commodity WiFi backscatter. A backscatter system typically consists of a reader and a tag. The reader transmits an excitation or query signal, which the tag reflects after modulating it to encode

data. The tag modulates the signal by switching between different impedance states, thereby altering the amplitude, phase, and/or frequency of the reflection to convey information. To decode the backscattered signal, the reader operates as a transceiver, comparing the original transmission with the reflected response. To eliminate the need for specialized hardware and reduce the deployment costs of the reader, commodity WiFi backscatter systems have been introduced. In these systems, existing WiFi devices—such as APs acting as RF sources and STAs serving as receivers—function as readers within a *bistatic configuration*. Here, standard WiFi protocol frames can be repurposed to act as query signals. B^3 leverages mmWave WiFi devices and protocol frames to enable scalable and reliable bistatic mmWave backscatter communication through beamforming.

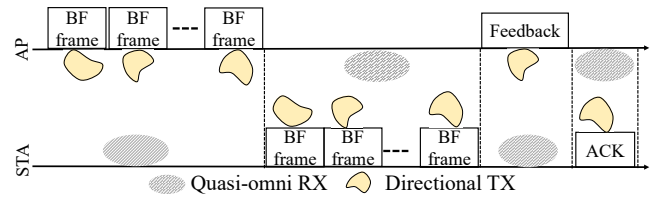


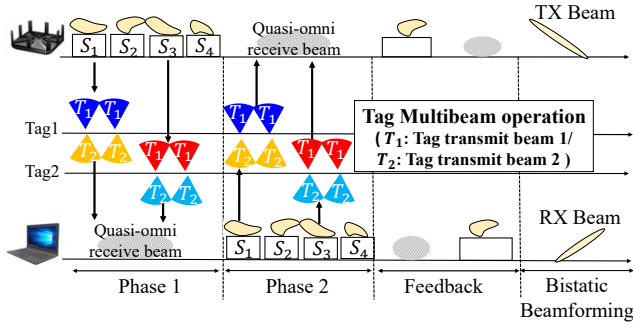
Figure 2: 802.11ad/ay beamforming training process.

mmWave WiFi beamforming. To achieve high-gain directional links, WiFi devices must identify the best (i.e., highest SNR) beam from a set of predefined beam patterns. As shown in Fig. 2, the beamforming training process is used to determine the best transmit sector (i.e., beam pattern) pair between an AP and a STA. During this process, the AP first transmits beamforming (BF) frames sequentially across its available sectors, while the STA measures the received signal-to-noise ratio (SNR) for each beam with a Quasi-omni beam. Once the AP completes its sweep, the roles are reversed: the STA becomes the transmitter and performs its own sector sweep while the AP acts as the receiver. After both sides complete their respective sweeps, they exchange measured SNR values through feedback frames. Based on this mutual feedback, the AP and STA select the transmit sectors with the highest SNR and conclude the beam alignment with an acknowledgment.

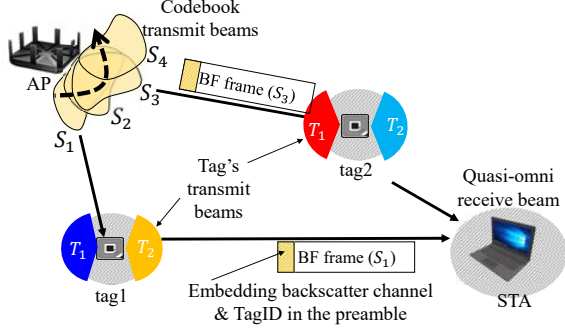
3 B^3 Overview

Fig. 3(a) illustrates the design of B^3 , which consists of four phases. (1) Phase 1: When AP initiates the beamforming process with a STA, it sends out beamforming frames across different sectors one by one. A B^3 tag receives these frames using a quasi-omni receive beam and backscatters them. As shown in Fig. 3(b), during the preamble of each beamforming frame, the tag performs a multibeam operation by alternating between beam directions. It encodes both its tag ID and channel information using a unique combination of PPM and OOK. Specifically, PPM across the preamble slots encodes the tag ID, while OOK within each slot captures variations in the backscatter path's channel state. *Notably, this multibeam operation serves a dual purpose: it is used to encode tag ID and channel information, and it also enables the B^3 tag to transmit directionally without the need for prior knowledge of the receiver's location or orientation.* After receiving the backscattered signals, the STA then extracts the backscatter path channel for each tag by cross-correlation-based

¹<https://github.com/Wireless-IoT-Sensing-Lab/B3-Bistatic-Beamforming-mmWave-Backscatter>.



(a) Bistatic backscatter beamforming process



(b) Phase 1 in action

Figure 3: B^3 performs bistatic backscatter beamforming within a single beamforming training process: (1) Phase 1: measuring the backscatter channel between AP and tags at STA, (2) Phase 2: measuring the backscatter channel between STA and tags at AP, (3) Feedback: exchanging feedback, including tag IDs and AoD information, and (4) creating a TX/RX beam for bistatic backscatter communication with each tag.

channel extraction and separates them using the embedded tag IDs. Given the cross-correlation result, the STA estimates the AoD from the AP to the tag by comparing the extracted backscatter channel with its respective codebook beam patterns. (2) Phase 2: The same process is repeated in the reverse direction from STA to AP. As a result of this process, the AP finds the AoD from the STA to the tag. (3) Feedback: Both the AP and STA share this information (tag ID and AoD) via feedback. (4) Bistatic beamforming: Using the estimated AoD, both AP and STA generate high-gain beam patterns towards the tag, which is optimized for bistatic beamforming, by computing the appropriate steering weight vector for their phased arrays.

4 Multibeam Backscatter Channel Encoding

A naive solution for embedding the backscatter channel is that the tag backscatters the incoming BF frame in an unmodified form to the receiver, which measures the SNR of the incoming BF frames. Since the power of the backscattered signal is proportional to the incoming signal from AP to the tag, the sector for which the BF frame is received with high SNR at the receiver can also be observed with high SNR from AP to the tag. However, in practice,

the BF frame from AP can traverse through multiple paths (including the backscatter path) before being received by a receiver due to the non-uniform beam patterns created by commodity phased arrays [13, 45, 48, 64]. This is demonstrated in recent mmWave backscatter works such as [7]. Hence, the backscattered signal and other multipath can combine constructively or destructively at the receiver, and the resultant signal's SNR can be very different from the SNR of just the backscattered signal (we evaluate this in Sec. 9.5). Furthermore, the tag is unaware of the relative position of the receiver, which means that it has to rely on omnidirectional transmissions when backscattering. This can result in a low SNR of the backscattered signal at the receiver, making it difficult to extract and use it for the backscatter channel extraction. Lastly, such a naive solution cannot achieve concurrent beamforming for multiple tags. To overcome these issues, we introduce a novel multibeam operation for mmWave tags.

4.1 Multibeam operation

B^3 tag employs directional transmit beams with a multibeam operation. Instead of backscattering with a low-gain omnidirectional pattern, B^3 tag cycles through multiple high-gain directional beams, enabling it to cover a broader spatial region and ensuring that the STA receives the backscattered frame. Our B^3 tag uses a quasi-omnidirectional receive pattern to receive BF frames and switches through multiple directional beams to transmit while backscattering.

Fig. 4 illustrates B^3 's multibeam operation using an example where the tag alternates between two transmit beams (we choose two for ease of explanation, but the design generalizes to more beams as we show in evaluation). In this setup, the tag receives a signal from the AP and backscatters it by switching between transmit beams 1 and 2, each directing the signal in a different spatial direction. This multibeam strategy provides three key advantages:

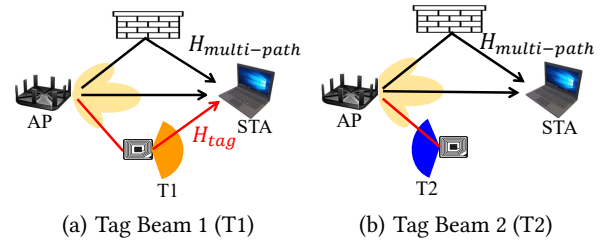


Figure 4: Channel change observed by a receiver due to the tag's multi-beam operation.

(1) It removes the requirement for the receiver to be in a specific direction relative to the tag. By sweeping across multiple beams, the tag increases the likelihood that the backscattered signal will reach the receiver, regardless of its position. (2) From the receiver's perspective, the tag's beam switching creates a distinct on-off pattern in the received signal, enabling the receiver to distinguish the backscattered component from other multipath signals, even in the presence of original frames directly received from the AP (Fig. 4). (3) The tag can encode data using PPM, where the beam switching pattern carries bit information. For example, switching from Beam 1 to Beam 2 could represent a binary '0', while switching from Beam 2 to Beam 1 could represent a '1'. Here, the received signal at the

receiver can be described as: $y_{receiver} = (H_{tag} + H_{multi-path}) \times x$ where H_{tag} denotes the channel corresponding to the backscatter path and $H_{multi-path}$ represents the channel for other multipath, excluding the backscatter path. As shown in Fig. 4, $y_{receiver}$ will either be $(H_{tag} + H_{multi-path}) \times x$ or $(H_{multi-path}) \times x$, while $H_{multi-path}$ remains constant in both cases. If the receiver can estimate $(H_{multi-path}) \times x$, it can isolate H_{tag} , which can be leveraged to precisely determine the SNR of the backscattered signal and, in turn, use that to estimate the AoD of a transmitter. We note that depending on the receiver's position, it can receive H_{tag} through beam 2, but the underlying operations remain unchanged.

4.2 Embedding tagID on the preamble

To enable multi-tag backscatter communication, it is crucial to incorporate tag identification (tag ID) within the backscattered BF frames while embedding the tag's channel information. We achieve this by encoding the tag ID into the preamble symbols of the BF frame, while simultaneously leveraging the known preamble symbols to convey the tag's channel information. However, embedding the tag ID using multibeam operation introduces abrupt channel variations within the preamble and presents two primary challenges: (i) preserving the original structure and functionality of the preamble, and (ii) ensuring that the receiving station can consistently detect the same tag ID regardless of the tag's spatial position.

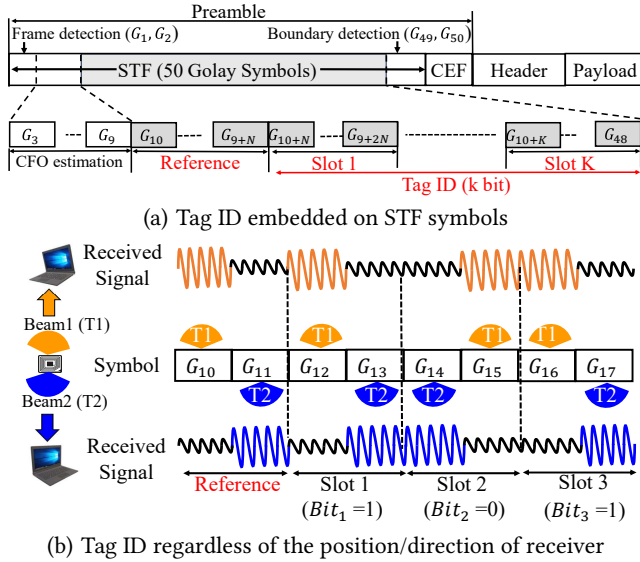


Figure 5: Slot-based multi-beam tag operation.

B^3 addresses the first challenge by leveraging the STF within the frame preamble. The STF consists of 50 known Golay symbols (Fig. 5(a)), where the first 2 symbols detect a frame, the last 2 symbols detect the boundary (the end of the STF), and the remaining 46 symbols are employed for CFO estimation. To exploit the redundancy within these 46 Golay symbols, we draw from recent studies indicating that 7 Golay symbols suffice for robust CFO estimation [15, 25, 29, 31]. Remarkably, even under low SNR conditions of less than 5 dB, the CFO estimation incurs less than 2% error [15] when using 7 Golay symbols only ($G_3 \sim G_9$). To embed our tag ID, we utilize the remaining 39 Golay symbols in the CFO estimation

section ($G_{10} \sim G_{48}$), minimizing the impact of our tag's operation on the existing 802.11ad/ay function. Additionally, recognizing that the backscatter signal is weaker than other multipath signals, the influence of the backscatter channel on CFO estimation is minimal.

The second challenge is addressed by introducing a slot-based tag ID where the multibeam switching in a specific way creates a PPM modulated signal across different slots. We partition the 39 Golay symbols into slots, where each slot consists of N (number of tag beams) symbols. As shown in Fig. 5(a), N symbols immediately following the CFO estimation symbols serve as a reference slot. During the reference slot, the tag switches sequentially over the N beams for backscattering. Following that, during the tag ID slots, if the tag ID bit in a slot is '1', the tag uses the exact same switching sequence as the reference slot (i.e., beam pattern 1 to N). If the tag ID bit in a slot is '0', the tag sequentially switches from beam pattern 2 to N and then back to 1 in that order. For example, when a tag has four beams, the reference slot cycles through beams 1–4 in order. In the following tag ID slots, the tag sweeps beams {1, 2, 3, 4} if the bit is 1, or {2, 3, 4, 1} if the bit is 0. This is demonstrated using an example with 2 beam patterns in Fig. 5(b). Depending on whether the receiver is located in the direction of beam 1 or beam 2, it will experience different sequences of channel variations as shown in Fig. 5(b). However, the receiver can receive the same tag ID because bits are demodulated compared to the reference slot. We also see that within each slot, the resultant signal has both ON and OFF, which is leveraged by the receiver for calculating the backscatter channel of each tag.

Detecting BF frames and synchronization at tags. B^3 makes sure that the tags backscatter only BF frames and not any other types of frames, such as data frames, to avoid interfering with ongoing communication. However, directly demodulating the frame on the tag is not possible due to hardware constraints and power limitations. To address this problem, we integrate a power detector into our tag. The power detector is a passive device that can provide the voltage readings of incoming received signals. Although the power detector has a limited bandwidth (0.5% of 802.11ad channel bandwidth), we find that the distorted signal received using the power detector still exhibits different patterns for STF and following Channel Estimation Field (CEF) due to the use of different Golay symbols in the two. Since the length of the STF is much shorter for data frames ($1.24 \mu s$) compared to the control frames ($3.64 \mu s$), as shown in Fig. 6, we use the length to determine the type of the frame by calculating the auto-correlation of the output voltage, achieving a 98.5% true positive rate and a 1.4% false negative rate. When the power detector observes the short STF (i.e., data frame), the tag stops embedding its ID to avoid corrupting a data payload. We note that the high-correlation detection approach with a power detector can be extended to 5G NR, where the Synchronization Signal Block (SSB) also uses an M-sequence offering strong correlation.

Given that the tag lacks the ability to demodulate the received signal, achieving perfect synchronization with Golay symbols (72.9 ns) also poses a challenge. This out-of-sync operation can lead to a reduced SNR of the backscattered signal as received on the respondent. B^3 adopts a strategy by setting the length of the switching period to twice the length of the Golay symbol, ensuring complete coverage of at least one Golay symbol even in the worst case. If

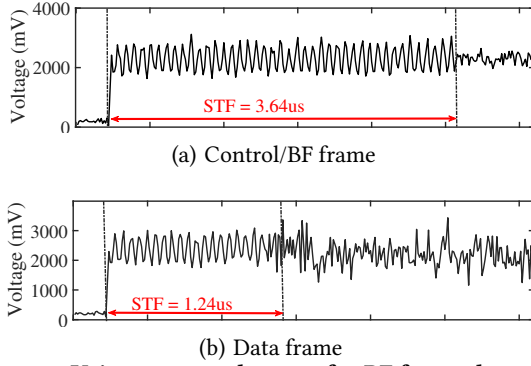


Figure 6: Using a power detector for BF frame detection.

each tag has 2 beams, which means each slot (i.e., bit) occupies 4 Golay symbols with a doubled length of the switching period, 39 Golay symbols can support 8-bit IDs. In principle, 8-bit IDs provide a theoretical upper limit of 256 tags for beamforming.

5 Extracting Channel and Tag ID at Receiver

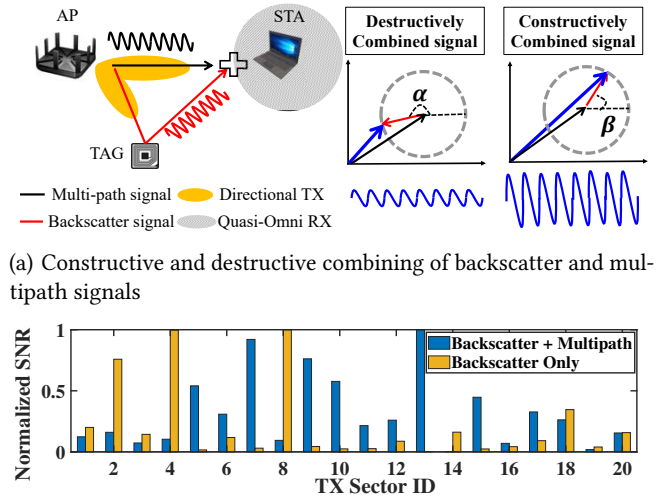
In this section, we propose a novel backscatter channel and tag ID extraction technique for mmWave tags.

5.1 Extracting channel information

B^3 receiver (STA in Phase 1 & AP in Phase 2) is designed to estimate the channel between a transmitter (AP in Phase 1 & STA in Phase 2) and a tag by receiving a packet forwarded by the tag. A straightforward approach would be to estimate the channel by directly measuring the signal variation caused by multibeam operations. However, in practice, accurately estimating the channel is challenging because BF frames from the AP can travel along multiple paths—including both direct and backscatter paths—before reaching the receiver, along with the complex and non-uniform beam patterns of commodity phased arrays [13, 45, 48, 64]. This behavior is further confirmed by recent mmWave backscatter studies such as [7]. As a result, the backscattered signal and other multipath can combine constructively or destructively at the receiver, and the resultant signal's channel can be very different from the channel of just the backscattered signal, as depicted in Fig 7(a). The impact of multipath can be severe, especially when the beamforming sectors in the codebook are non-uniform and have non-trivial side-lobes. This means that simply measuring the amplitude of each STF symbol at the receiver and using that to determine the backscatter channel from the transmitter to the tag can result in incorrect AoDs. To validate this, we measure the SNR for different transmitter sectors directly on the tag and compare that with the SNR measured at a receiver. Fig. 7(b) shows that the two SNRs have very different patterns for different sectors, indicating the role of multipath. This means that for correct backscatter channel estimation, we need to isolate the backscattered signal from multipath.

5.2 Cross-correlation-based channel extraction

To separate each path from the combined signal received at a receiver, we employ cross-correlation using STF. The STF (50 Golay symbols) is composed of predetermined identical 48 Golay symbols (G_{b128}), followed by one $-G_{b128}$ and $-G_{a128}$. We leverage the fact



(b) SNR measured at tag (backscatter only) and at receiver (backscatter + multipath)

Figure 7: Impact of multipath and the need for backscatter channel extraction

that each path, having distinct propagation delays, produces a high correlation during the cross-correlation process, which can help us extract different paths. Furthermore, due to the presence of an ample number of symbols within the STF, the method remains robust even in the presence of noise. However, extracting precise channel information from the STF is still challenging because the STF does not use a complementary set of Golay symbols like the CEF. The complementary set of CEF generates its out-of-phase aperiodic autocorrelation coefficients, which sum to zero, except for the zero shift (Fig. 8(a)). The CEF performs a one-time channel measurement of a frame, and it presents combined channel information, including multi-path and backscatter. Since it is difficult to distinguish between the multipath and the backscattering path with only the one-time channel measurement, at least two beamforming processes are required to detect the channel change if we use CEF instead of STF. However, we cannot guarantee the channel coherence during the two beamforming processes. Therefore, B^3 uses STF instead of CEF for beamforming.

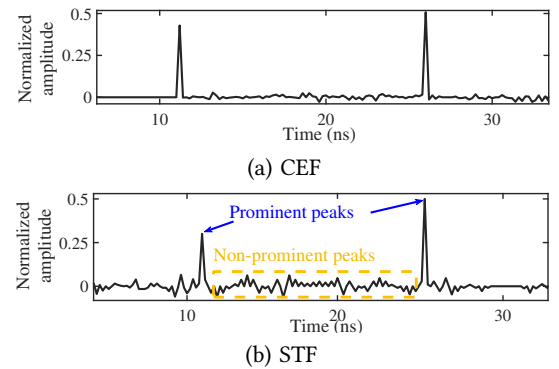


Figure 8: (a) Auto-correlation coefficient of CEF; (b) cross-correlation coefficient of STF.

When a receiver performs a cross-correlation of STF, the same cross-correlation result is repeated because of a sequence of 48 repeated symbols. However, the STF suffers from the residual aperiodic correlation coefficients. As shown in Fig. 8(b), the cross-correlation coefficient contains two types of peaks: prominent peaks, which are due to multi-path and backscatter signals, and non-prominent peaks, which correspond to residual aperiodic correlation coefficients. We observe that STF cross-correlation produces significantly more non-prominent peaks than the autocorrelation of the CEF, which explains why STF is typically avoided for channel estimation. In B³, however, these non-prominent peaks can be effectively suppressed during the backscatter channel extraction process, *as our objective is to capture channel variations induced by tag activity rather than reconstructing the complete channel response*. This approach will be elaborated in the next section.

5.3 Backscatter-channel isolation and Tag ID extraction

With all paths extracted from STF, B³ receiver isolates the backscatter channel and tag ID using the following process (shown for 2 beams in Fig. 9):

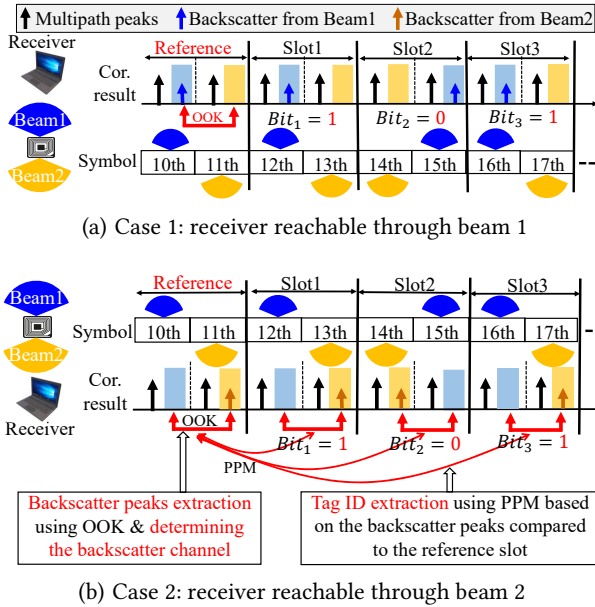


Figure 9: Regardless of receiver location/direction (which is unknown to the tag), a receiver can (1) observe the backscatter peak position and amplitude during the reference slot, and (2) extract the same ID information.

(1) Identifying backscatter peaks using OOK: While the tag backscatters, the receiver identifies only backscatter peaks using OOK from the cross-correlation of the reference slot. As shown in Fig. 9, the receiver can observe fixed and changing peaks during the reference symbols. This is because the multipath and non-prominent peaks appear in all symbols of the reference slot, while the backscatter peak only appears in one of them due to OOK modulation. Thus, by calculating the difference in the cross-correlation results of each Golay symbol in the reference slot, B³ can effectively remove strong multipath and non-prominent peaks while

preserving the backscatter peaks (also shown with measurement data in Sec. 9.3), essentially performing OOK demodulation.

(2) Backscatter channel extraction: The receiver can then use the time and amplitude from the backscatter peaks to calculate the backscatter channel (H_{tag}).

(3) Tag ID extraction using PPM: To map the measured channel to specific tags, the receiver performs slot-based PPM demodulation to extract the tag ID bits received in the subsequent slots after the reference slot by comparing the received symbols in each slot with those of the reference slot. Because our PPM demodulation depends on the reference symbols, the same tag ID can be observed irrespective of the beam through which the receiver is reachable (beam 1 or 2 in Fig. 9). Furthermore, just like the modulation, the demodulation also naturally extends to any number of beams on the tag without any modifications.

Beyond tag identification and channel estimation, the receiver can also infer the tag's best transmit beam by identifying the beam corresponding to the highest peak observed in the reference slot. For example, in Case 1 and Case 2, the strongest peak aligns with Beam 1 and Beam 2, respectively, indicating that these beams are best aligned with the receiver. Since each symbol index in the reference slot can be translated into a specific beam index, the receiver can directly map the peak amplitude to the corresponding tag transmit beam. Crucially, this is required to enable the tag to utilize its strongest beam for backscatter communication instead of multibeam operation once the beamforming process is complete.

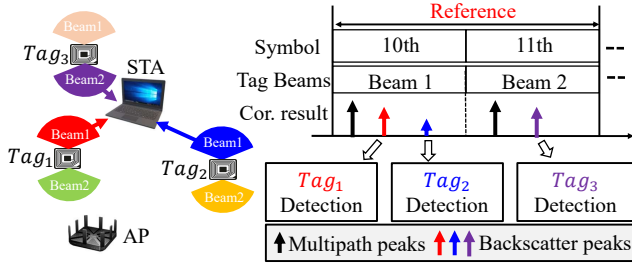
6 Concurrent Multitag Channel Extraction

B³ enables simultaneous detection of multiple tags, significantly reducing the beamforming overhead in the bistatic configuration as the number of tags increases. There are two main reasons why B³ facilitates concurrent multitag operation. First, we note that since different tags may have different propagation delays (i.e., different traveling distances) based on their locations, the timing of the peaks can be used to separate different backscatter paths. This is especially true considering that 802.11ad/ay has a 1.76 GHz sampling rate, which can provide a high resolution of cross-correlation. Second, due to the directionality of each transmission beam, only a small number of tags respond in each BF frame. This means that although there can be many tags, only a few tags within the beam coverage actually backscatter for a given sector.

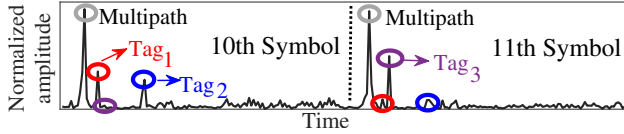
Fig. 10(a) shows an example of multiple tags, and Fig. 10(b) shows the measurement results of a receiver. Since the receiver is reachable through beam 2 of Tag₃, its peak appears in the 11th symbol. On the other hand, responses from Tag₁ and Tag₂ are observed in the same symbol. However, due to the different traveling distances, the peaks appear at different delays, enabling us to distinguish the tags' responses. Furthermore, as depicted in Fig. 10(c), due to the different coverage of each sector, not all tags respond in all sectors as their backscattering depends on how much signal they receive for a given sector. This enables B³ to operate with little to no inter-tag interference, as we show in our evaluation.

7 Bistatic Backscatter Beamforming

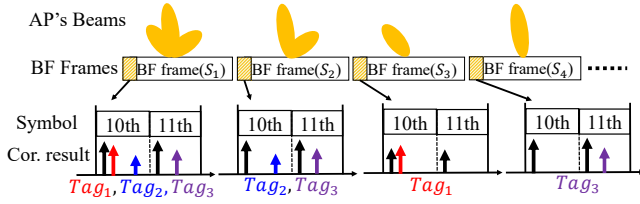
As illustrated in Fig. 3, the STA measures the backscatter channel across multiple beam sectors from the AP to the tag during Phase 1.



(a) Example topology with 3 tags



(b) Peaks in signal of reference symbols measured at receiver

(c) Multitag operation for a given AP sector ($S_1, S_2, \dots$)**Figure 10: Simultaneous multi-tag beamforming in B^3 .**

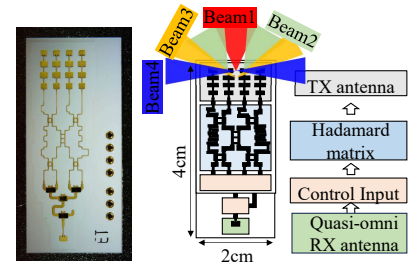
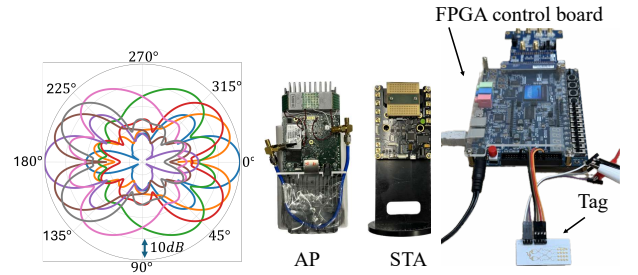
It then compares these measurements to a predefined codebook of transmit beam patterns to infer the AoD from the AP to the tag. The AoD is estimated by solving the following maximization problem:

$$(\hat{\phi}, \hat{\theta}) = \arg \max_{\phi_i \in \Phi, \theta_j \in \Theta} \left\| \frac{\mathbf{r}}{\|\mathbf{r}\|}, \frac{\mathbf{t}_{\phi_i, \theta_j}}{\|\mathbf{t}_{\phi_i, \theta_j}\|} \right\|^2 \quad (1)$$

where $\mathbf{r}$ denotes the received signal strength vector and $\mathbf{t}_{\phi_i, \theta_j}$ is the reference transmit beam pattern corresponding to candidate azimuth (ϕ_i) and elevation (θ_j) angles. Similarly, in Phase 2, the AP estimates the AoD from the STA to the tag using the same procedure. After exchanging AoD estimates along with the tag's best beam direction toward the receiver via feedback (as detailed in Sec. 5.3), both the AP and STA obtain (i) directional information toward the tag and (ii) the tag's best beam toward a receiver as described in Sec. 5.3. For AP and STA beamforming, the AoD information, $(\hat{\phi}, \hat{\theta})$, is then used to steer high-gain beams aimed at the tag. While computing the optimal beamforming vector for a given AoD is straightforward in theory, real-world deployment is constrained by the limited phase resolution of commodity mmWave phased arrays, which typically support only coarse (e.g., 2-bit) phase quantization. This constraint introduces non-convexity into the beamforming problem, rendering the optimization problem more challenging to solve. To address this, we adopt a lightweight, quantization-aware optimization method based on gradient descent with projection [21, 61]. The algorithm iteratively refines a continuous beamforming vector and projects it onto the nearest supported discrete phase values. This approach creates new high-gain transmit and receive beams to maximize

signal gain toward the tag, achieving high performance under practical hardware constraints. To initiate reliable and high-throughput backscatter communication, the transmitter shares the tag's best beam information with the tag using packet-level downlink signaling. Leveraging its knowledge of the tag's AoD, the transmitter embeds beam information by switching among different beam patterns. These changes produce measurable amplitude variations at the tag, which are detected using a simple power detector. Based on this feedback mechanism, the tag selects its best transmit beam and starts backscatter modulation. After completing bistatic beamforming, the tag can employ various modulation schemes for payload data. We note that B^3 mainly focuses on bistatic beamforming and does not explore different modulation schemes. Extending our design, the tag can implement amplitude modulation for payload data by switching beams. In our prototype, the hardware supports a 40 MHz beam-switching rate, enabling 40 Mbps amplitude modulation. Other modulation schemes, such as the phase modulations proposed in prior works [7, 65], can also be supported by B^3 . Furthermore, the achievable SNR gain can help improve the data rates of such modulations during data communication.

8 Implementation

(a) B^3 prototype

(b) Tag beam patterns

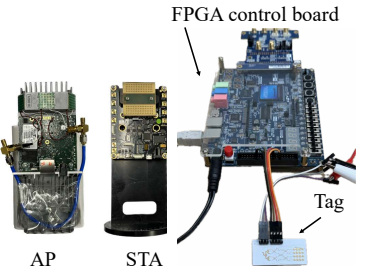
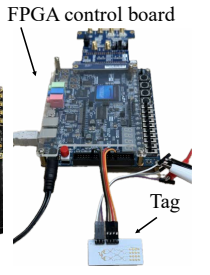
(c) B^3 devices(d) B^3 control

Figure 11: (a) The front side of prototype; (b) Four beams of prototype; (c) Commodity 802.11ad/ay TX AP and mmWave SDR STA; and (d) Control board with a tag prototype.

B^3 prototype. We have developed a PCB prototype of our B^3 tag as shown in Fig. 11(a). The PCB prototype is printed on the Rogers Ro4003C and Rogers RT/Duroid 5880 PCB. We have printed 14 such tags. The tag consists of linear patch array antennas for transmission with 4 beams and a single receive patch antenna, covering the frequency range of 56 to 63.5 GHz. The tag forwards the backscatter signal towards 0° to 180° . The transmission block comprises

a 4×4 patch antenna array, an SP4T switch (ADRF5054BCCZN-R7) [12], and a 4×4 Hadamard beamforming matrix. The switch offers 40 MHz of switching speed, which is higher than the necessary switching speed of 14 MHz (Golay symbol rate) as per B^3 design. Each sub-array of the 4×4 array antenna consists of a linear array of four patch antennas. To maximize the gain using a high permittivity material (Rogers RT/Duroid 5880 PCB), an element spacing of 0.63 wavelength is used. The antenna array is impedance-matched across the 56–71 GHz frequency band, ensuring efficient operation within the 60 GHz range. The 4×4 Hadamard matrix creates a passive beamforming network, which is switched using the SP4T switching block. It generates one central beam (0°) and three split beams with two main lobes (at $\pm 19^\circ$, $\pm 31^\circ$, and $\pm 51^\circ$) offering 3.5 dBi-gain coverage of $\pm 90^\circ$ and the main lobe gain greater than 10.5 dBi combined with the array antenna. Fig. 11(b) shows the coverage of our prototype antenna. The beam pattern is optimized using the FIT (finite integration technique) solver of CST Microwave Studio 2024 [11]. As shown in Fig. 11(c), the AP is a standard 802.11ad Mikrotik [37] device equipped with the Qualcomm QCA6310 chipset and a 6×6 antenna array. The receiver uses a SiversIMA 60 GHz RF front-end with a 4×16 element phased array. Channel extraction is performed via cross-correlation on I/Q samples collected from a Keysight MSOS404A oscilloscope connected to the SiversIMA. Modern wireless networks—sub-6GHz WiFi, mmWave WiFi, and 5G NR—already apply cross-correlation in their signal processing pipelines [18], allowing integration without hardware modification. Lastly, as shown in Fig. 11(d), we use a TeraSIC Cyclone V GX Starter Kit FPGA board with a microcontroller (SAM4SD32C) to control our B^3 tag.

9 Evaluation

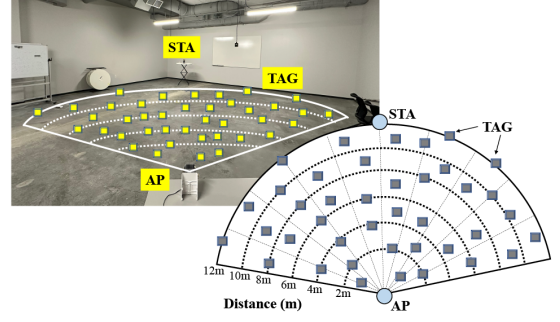
We evaluate B^3 under various scenarios to understand (i) the read range and angle for bistatic backscatter, (ii) performance under tag blockages, (iii) multi-tag beamforming and scalability, (iv) the impact on preamble functionality, and (v) the need for backscatter path extraction.

9.1 B^3 read range and angle

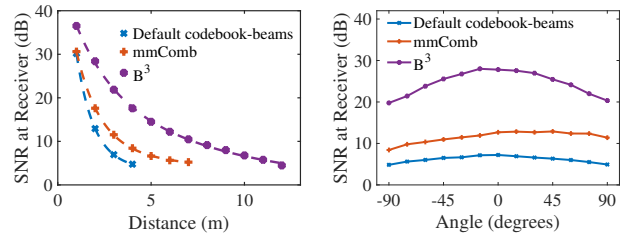
We evaluate the performance of the B^3 tag across various distances and angles within an 18 m $\times$ 15 m indoor space, as shown in Fig. 12(a). We conduct an experiment by varying the incident angle of the backscattered signal at the tag side. Over 400 measurements are collected across 40 different locations, which are randomly selected to introduce variations in both incident angle and distance. The positions of the AP and STA devices are kept fixed as they find their beams towards the tag using B^3 procedure. The signal incident angle for the tag varied from -90° to $+90^\circ$.

To understand the impact of different beam patterns, we consider three transmitter-receiver configurations:

- (1) Default codebook beams: In this setting, the transmitter employs the default codebook provided by the MikroTik WiFi device, while the receiver uses a quasi-omnidirectional beam pattern. This configuration is the typical configuration used in 802.11ad/ay WiFi. The transmit beam chosen by the AP in this setting is likely to be suboptimal for the tag.

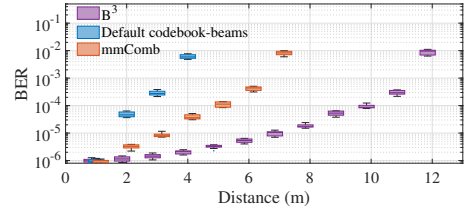


(a) Illustration of the tag deployment at a 18m $\times$ 15m indoor lab



(b) SNR results for distance

(c) SNR results for angle



(d) BER results at different distances

Figure 12: Experiment setup and results for 40 different tag positions with random distance and angle

- (2) mmComb [7]: This configuration uses a transmitter beam from the codebook similar to the default codebook case, but calculates a narrow beam from the receiver towards the tag. However, mmComb does not support tag-side beams and multibeam operation, requiring the receiver to be at a fixed, pre-known location.
- (3) B^3 : In comparison to the above two schemes, B^3 configuration creates bistatic high-gain beams towards the tag using the AoD estimation and backscatter channel extraction, enhancing backscatter communication reliability.

Figure 12(b) presents SNR as a function of distance under the three configurations. The default codebook beams result in a steep SNR drop as the distance increases, limiting the effective backscatter communication range to just 3 meters ($\leq 10^{-3}$ BER) due to low antenna gain. mmComb improves the SNR performance and read range compared to the default case with the addition of receiver side beam, but the range is limited to 6 meters. On the other hand, due to B^3 ability to estimate the correct AoD and corresponding weight vectors, the read range increases to 11 meters, essentially resulting in a 3x improvement over the default configuration with 13 dB SNR gain. The increase can be attributed to the proper extraction of the

backscatter channel at both ends in the bistatic communication and the corresponding AoD estimation for beamforming. Compared to mmComb, which aims to reduce the multipath effect caused by wider, codebook-based transmit beams, the use of a transmit side narrow beam in B^3 reduces this multipath automatically and improves the backscatter SNR.

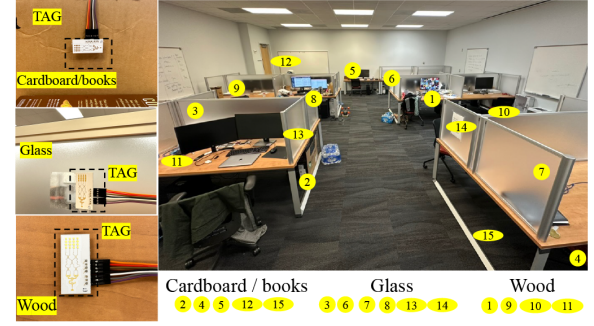
We also evaluate the impact of angular variation by changing the orientation of the tag while keeping the AP and STA in a fixed position and orientation. In this experiment, the distance between the AP/STA and the tag is fixed at 3 meters, while the relative angle between the tag and STA (Rx) is changed from -90° to $+90^\circ$. We note that our tag uses a quasi-omni Rx antenna; hence, rotation relative to the AP (Tx) is of less significance compared to the rotation relative to the STA (Rx). As shown in Fig. 12(c), a peak SNR of 28 dB is observed when the tag directly faces the STA. This corresponds to our tag's beam pattern gains as shown in Fig. 11(b). In our experiments, mmComb performs much worse compared to B^3 , likely due to mmComb's use of the default codebook beam from AP and its inability to adapt for changing receiver location without multibeam operation.

Figure 12(d) shows the bit error rate (BER) across varying distances for the same three configurations while demodulating the tag ID bits. As expected, higher SNR leads to better BER in B^3 with $\text{BER} \leq 10^{-3}$ up to 11 meters compared to the same for up to 7 meters in mmComb. This performance is also comparable to that of existing RFID tags, which operate effectively up to approximately 9 m [54]. This low BER can guarantee reliable long-range mmWave backscatter communication due to B^3 's bistatic beamforming, and further range extension is possible through improved tag antenna design.

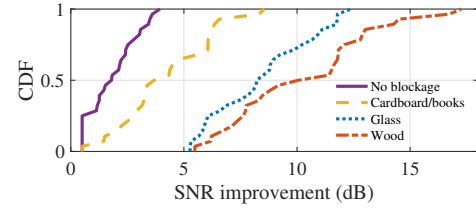
9.2 Blockage

We conduct experiments to evaluate B^3 for indoor blockage scenarios as shown in Fig. 13(a). The objective is to understand how our bistatic beamforming enables or enhances the backscatter communication in the presence of blockages and NLoS links. We vary the AP and STA locations while placing the tag in such a way that their communication is blocked by different materials/objects in a $12\text{ m} \times 8\text{ m}$ university lab room. Here, the signal transmitted by the AP is either received by the tag after penetrating these objects or through reflection (NLoS) paths from nearby reflectors. We verify this behavior by analyzing the estimated AoD from AP and STA to the tag and manually validating if the chosen beam penetrates or reflects from the objects.

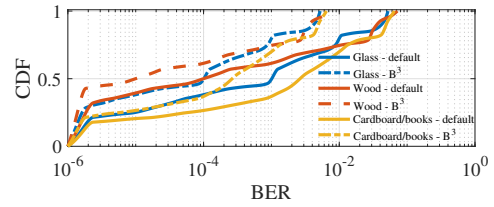
Fig. 13(b) shows the SNR improvement compared to the default codebook beamforming achieved under different blockage conditions. We observe that when the signal penetrates materials such as wood or glass, the received backscatter SNR is notably weaker, leading to more frequent misidentification of the tag's direction. In contrast, objects like cardboard boxes or books introduce less attenuation, enabling more accurate estimation of the optimal beam sector. On average, B^3 's beamforming provides an SNR improvement of approximately 8 dB across all blockage scenarios compared to the default codebook beam configuration. Fig. 13(c) shows that B^3 's bistatic beamforming significantly reduces the BER across all three types of blockage, including glass, wood, and cardboard/books.



(a) Experiment setup for blockage and NLoS evaluation



(b) SNR improvement by B^3 for various blockage cases



(c) BER for various blockage cases compared to default codebook beamforming

Figure 13: Experiment setup and results for blockage scenario

These results demonstrate that our bistatic beamforming makes mmWave backscatter communication possible even in scenarios with high attenuation, including blockages and NLoS conditions.

9.3 Multi-tag support and scalability

Multi-tag microbenchmarking. We first randomly deploy four tags in a room and measure their concurrent response on STA to understand how well our technique of embedding tag IDs in the preamble works in practice. Fig. 14(a) shows the cross-correlation result for the received signal at the receiver. The peaks for different tags have separate delays due to different traveling distances corresponding to tag locations. As we can see, the tag ID for each tag can be determined by the STA by simply comparing its corresponding peaks with the reference slot. Fig. 14(b) shows the cross-correlation difference between the current slot and the reference slot. The process is also able to successfully filter out the multi-path peaks and isolate the tag peaks for ID and channel calculations. Since the LoS path and all multipath remain unchanged, they are canceled out through the cross-correlation difference. On the other hand, the tag ID can be extracted by PPM demodulation as shown in the figure.

Scalability of B^3 . We now deploy five tags at different locations in a $12\text{ m} \times 8\text{ m}$ university lab room. The positions are randomly chosen with different relative orientations compared to the AP and

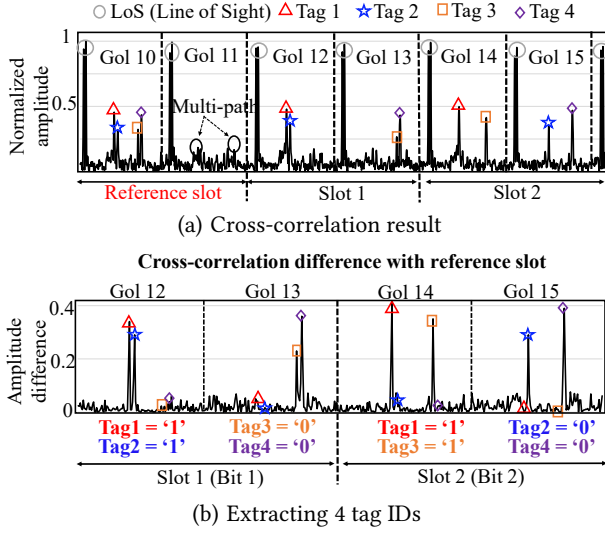
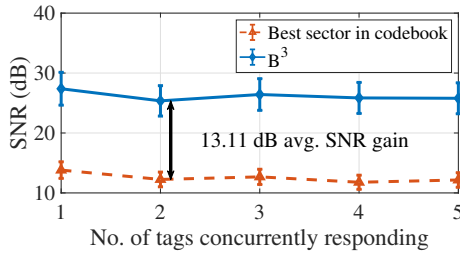


Figure 14: (a) Cross-correlation result at STA (receiver). (b) Cross-correlation difference with reference slot for 4 tags with IDs tag1=11, tag2=10, tag3=01, tag4=00.

	Tags responding concurrently in each AP Sector #									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Tag 1	★		✓		★			✓		✓
Tag 2		★		✓	✓	★	✓	✓		✓
Tag 3			★	✓						✓
Tag 4		✓	★			✓			✓	

(a) Tags' response in different AP sectors



(b) B^3 multitag performance

Figure 15: Multi-tag concurrent operation evaluation.

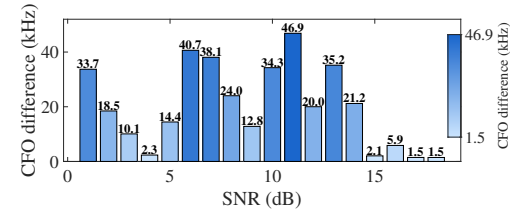
STA. We operate the tags simultaneously, representing a practical scenario where many tags are in a room together.

Fig. 15(a) shows 10 AP codebook sectors and the corresponding tags that respond in each sector. As expected, not all tags respond in each sector due to the directionality of the sectors. To evaluate the effect of concurrent transmissions, we vary the number and combination of simultaneously active tags and measure the SNR of created B^3 backscatter beams. Fig. 15(b) illustrates the SNR performance when up to five tags operate concurrently. Even with five simultaneously responding tags, the average SNR gain achieved by

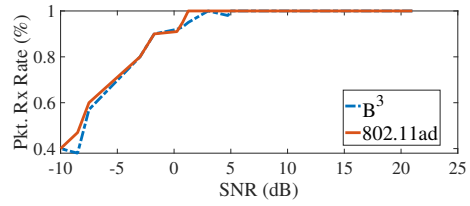
B^3 compared to the default codebook sectors is approximately 13 dB. This improvement stems from B^3 's multibeam operation, which enables effective separation of tag responses based on their respective reference slots. Although tags positioned at similar distances from the AP may cause constructive or destructive interference in cross-correlation, their unique identifiers allow their responses to remain distinguishable and correctly identified. These results demonstrate B^3 's robustness in mitigating clutter and interference, enabling reliable multi-tag operation with consistently high SNR gains.

9.4 Impact on preamble functionality

Since our tag embeds its ID in the preamble of the BF frame, we evaluate its effect on CFO estimation and packet reception at the receiver (STA). We adopt the CFO estimation method from existing works [31]. We analyze 4000 packets to compare the CFO of B^3 (preamble manipulation) and the default 802.11ad protocol (without preamble manipulation) and calculate the difference. As shown in Fig. 16(a), in high SNR cases (>12 dB), we observe less than 6 kHz of CFO difference, which is less than an additional 2% variation in CFO. Moreover, even in scenarios with low SNR, their CFO difference remains below 46 kHz, which is less than a 15.8% deviation in the worst-case scenario. Such a small CFO variation does not degrade the original preamble functionality, as evident from the packet reception ratio results. We evaluate the packet reception



(a) CFO estimation difference



(b) Packet reception ratio

Figure 16: Impact of B^3 on preamble functionality.

ratio (PRR) with and without tag operation by varying the SNR, which is controlled by adjusting the tag's distance from the AP. Since our mmWave SDR platform does not directly support PRR measurement, we utilize a commercial 802.11ad device as the receiver. To obtain SNR values, we extract reports embedded in the beamforming feedback packets, which contain the SNR measured for the selected best transmission sector. We then compare scenarios with and without tag operation in the preamble by measuring the PRR under equivalent SNR conditions. As shown in Fig. 16(b), introducing the tag operation has no noticeable impact on PRR. This is because our design carefully modifies only the redundant symbols in the preamble, preserving overall packet integrity and ensuring compatibility with standard receivers.

9.5 Need for backscatter path extraction

To understand the importance of extracting the backscatter path in multi-path rich indoor environments, we compare B^3 's beam selection with its alternative that does not perform backscatter path extraction (i.e., uses the combined signal of multipath and backscatter together for SNR estimation).

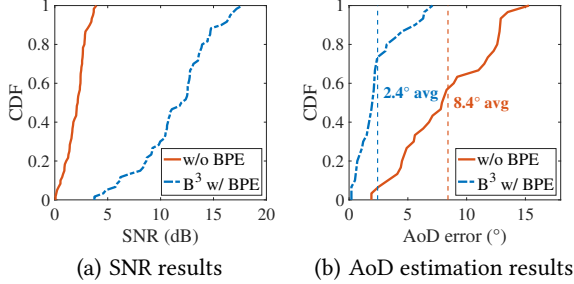


Figure 17: (a) SNR results and (b) AoD estimation results without and with backscatter path extraction (BPE) in B^3 .

Fig. 17(a) shows the SNR results achieved by B^3 with and without backscatter path extraction. The results indicate that without explicitly isolating the backscatter signal, the beamforming process often selects suboptimal beams, leading to limited SNR gains. In contrast, B^3 with backscatter path extraction achieves significantly higher SNR improvements, with an average gain of around 12 dB and consistent performance across different scenarios. We find that when the backscatter path is not isolated and the combined signal (backscatter plus multipath) is used for AoD estimation in Equ. 1, the resultant AoD estimation shows much higher error compared to the case where the backscatter signal is isolated. Fig. 17(b) shows the AoD estimation error from the AP to the tag. By isolating the backscatter signal from surrounding multipath noise, the average estimation error is reduced significantly from 8.4° to 2.4° . This justifies the need for backscatter path extraction in B^3 design and its impact on the resultant beam calculations.

9.6 Tag power consumption

Our tag is made up of four power-consuming components: a clock module, a switch component, a data modulator, and a control module. We simulate the power consumption of the tag IC chip using Libero SoC Smart-Power [36]. The symbol rate of Golay symbols in STF is 14 MHz (length of each symbol $73 \mu\text{s}$). Hence, it requires a 14 MHz clock speed as input for switch control on the tag and consumes only $3 \mu\text{W}$ of power. The RF CMOS SP4T switches consume 2.2 mW. The switch control of the data modulator for embedding the tag ID consumes as low as $2 \mu\text{W}$. Lastly, the control module to determine if the incoming frame is a BF frame or not consumes $76.8 \mu\text{W}$ analyzed by Libero SoC SmartPower [28]. Therefore, the total power consumption of our tag is 2.5 mW, which is lower than typical IoT power consumption and other recent mmWave backscatter systems [32, 35, 39]. We also note that the total power consumption can be as low as $88.8 \mu\text{W}$ if we use the GotMIC gSSD0011 switch [14] (a non-CMOS switch, a series of transistors that do not

require a drain voltage), which consumes only $7 \mu\text{W}$ but requires expensive and complex wire-bonding assembly.

10 RELATED WORK

mmWave backscatter. Backscatter communication enables ultra-low-power devices to communicate by reflecting existing RF signals rather than generating their own. While early efforts focused on sub-6GHz systems such as WiFi backscatter [55, 56, 65, 66], which showed promise in integrating passive tags into commodity WiFi networks, they primarily aimed to extend communication range, enhance link reliability, and increase data throughput. More recently, researchers have begun exploring mmWave backscatter systems [3, 6, 7, 22, 32, 34, 35, 47], motivated by the much higher bandwidths available in the 60 GHz band and the directional nature of mmWave propagation. These mmWave backscatter systems push the boundaries of data rate and device miniaturization. Many of these mmWave backscatter systems such as [3, 32, 47] use mmWave FMCW radars as the readers for the tags and cannot be readily integrated into mmWave WiFi networks. These radars offer precise distance and Doppler measurements, which facilitate localization and sensing in addition to communication. However, such systems often require specialized and expensive hardware, limiting their deployability in commercial mmWave WiFi networks that adhere to standards like IEEE 802.11ad/ay. Other systems, such as [7, 35], focus on increasing the data rates. These efforts mark important progress toward realizing high-throughput backscatter communication, but they primarily suffer from range and low SNR issues. Compared to these, our work focuses on fundamentally redefining the role of mmWave backscatter—not as an endpoint communication mechanism—but as a control-plane tool to reduce overhead and improve scalability in dense or mobile environments.

mmWave beamforming. Beamforming is essential in mmWave communication systems to overcome high path loss and support directional transmission and reception. Traditional exhaustive beam training, as standardized in IEEE 802.11ad/ay, incurs significant overhead because it requires sweeping across all possible beam directions at both the transmitter and receiver ends. To reduce this overhead, various alternative beam training mechanisms have been proposed [24]. Compressive searching [33, 41–44, 49] has been shown to achieve lower beamforming overhead with carefully chosen sectors to probe for each path. Hierarchical beamforming [1, 19, 53] iteratively probes sectors while reducing the beamwidth but requires feedback at every level. Multi-armed beams [16] and multi-lobe beams [20] are also used for reducing search time and increasing reliability, respectively. Authors in [52] proposed a new solution based on power delay profile that can also reduce the beamforming overhead. Similarly, hybrid beamforming [1, 2, 9, 50] has been investigated in the context of mmWave MIMO. Some of the recent works such as [62] aims at profiling the indoor environment with out-of-band modality such as LiDAR and machine learning [23, 59] before performing low-overhead beamforming. However, these solutions do not scale well with high mobility and in cases with dynamic environment changes that require frequent retraining or profiling. In contrast, B^3 introduces a fundamentally different approach by adopting a bistatic configuration: it leverages

the multi-beam operation of passive tags to offload the beamforming task entirely from the tags to high-power mmWave devices such as APs/STAs or BSs/UEs. By embedding distinguishable features into the backscattered beamforming frames, the tags enable these devices to infer optimal beam directions for multiple tags through just a single beamforming scan.

11 Conclusion and Discussion

In this paper, we presented B³, a bistatic backscatter beamforming framework that yields high-gain beams from AP and STA towards the tag in commodity mmWave backscatter networks. At the core of B³ is a multibeam technique that enables the tag to convey its channel and ID using a combination of PPM and OOK modulation. B³ scales to concurrent beamforming for multiple tags within a single beamforming training process and does not require any protocol changes. We evaluated B³ using a custom-developed PCB prototype, 802.11ad/ay WiFi devices, and software radios. The results show that B³ enables robust communication at distances up to 11 m, achieves 13 dB SNR gain, and maintains BER 10⁻⁵ at 5 m. We note that while B³ was developed for 802.11ad/ay WiFi, the design can be extended to other mmWave networks such as 5G NR FR2 with relative ease. Lastly, our tag prototype utilizes a quasi-omni receive beam antenna to facilitate improved reachability. This can be replaced with a passive beamforming network in the future to further improve the gain and backscatter SNR. Additionally, since beamforming frames are periodically transmitted, B³ updates the beampattern every 100 ms for 802.11ad/ay BF frames and every 20 ms for 5G NR SSB frames. Given that the typical walking speed is about 1.1 m/s, our design can support such mobility.

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