Millimeter Wave Backscatter: Toward Batteryless Wireless Networking at Gigabit Speeds

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ABSTRACT

Backscatter networks (such as RFID, and WiFi backscatter) are very attractive for IoT applications due to their ultra-low energy consumption. In fact, their required energy to operate is low enough that it can be harvested from the environment without having a battery. However, existing backscatter networks offer very limited data-rates (i.e. at most one Mbps). Hence, despite their energy benefit, their applications are very limited. This paper presents the design of mmTag, a backscatter network which can achieve Gbps data-rates. mmTag achieves this by developing a backscatter technology operating in the mmWave spectrum band. mmWave promises to enable high throughput wireless links by offering massive chunks of high-frequency spectrum. However, to use mmWave frequencies in backscatter networks, we need to address a fundamental challenge: beam alignment. mmWave devices require highly directional antennas with very narrow beams, and communication is possible only when the transmitter's beam is aligned with the receiver's beam. However, existing beam searching techniques require power hungry components, and most importantly require the node to transmit a signal which is not possible for a backscatter device. mmTag solves this problem by building a mmWave backscatter tag which performs beam alignment without using any active component. Finally, we implement mmTag and empirically demonstrate some results.

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1 INTRODUCTION

Backscatter technology offers very low-power wireless communication, and hence it is very attractive for IoT devices with limited energy resources. This technology enables IoT devices to piggyback their data on the radio frequency (RF) signals of other devices, instead of generating and transmitting their own signals. Eliminating the need for an active transmitter and power hungry RF components has enabled backscatter devices to communicate on a very low energy budget. For example, existing backscatter devices such as RFID and WiFi backscatter tags have shown that backscatter technology can reduce the power consumption of IoT devices by orders of magnitude [3, 16, 35]. This reduction enables IoT devices to run on a tiny battery for decades or even be batteryless, where energy is harvested from the surrounding environment through light, motion, etc. However, despite the energy benefit, current backscatter networks have a major limitation: they provide very limited throughput. Even at short ranges, their rate is at most one Mbps. Although an Mbps link might be enough for many today's IoT applications, such as monitoring temperature, occupancy, etc., it will not be enough for future applications such as augmented reality (AR) lenses, brain implants with thousands of probes, and many other emerging applications with limited energy resources. In this paper, we explore how we can develop a backscatter network which enables orders of magnitude higher throughput than existing backscatter networks.

The low data-rate of existing backscatter networks (such as WiFi backscatter [16] and RFIDs [31]) is the result of two facts. First, to achieve ultra-low-power communication, backscatter systems have to use simple data modulation schemes such as on-off keying (OOK) or binary phase-shift keying (BPSK). Unfortunately, these schemes have very low spectral efficiencies. Second, existing backscatter systems operate in spectrum bands with limited bandwidth. For example, most RFIDs operate at 915 MHz spectrum band, with 500 kHz channel bandwidth [6]. Hence, the combination of limited available bandwidth and low spectral efficiency have resulted in a very limited data-rate in today's backscatter networks.

To benefit from the energy advantage of backscatter technology while solving their throughput problem, we ask whether it is possible to build a *millimeter wave (mmWave)* backscatter network. mmWave frequency bands (i.e. above 24 GHz) offer multi-GHz of unlicensed bandwidth, 200x more than the bandwidth allocated to today's WiFi and RFID [11, 14]. The availability of such a spectrum promises to enable orders of magnitude higher throughput. However, building a backscatter system which operates in mmWave frequency bands is very challenging. The main challenge to achieve this goal is the *beam alignment* requirement.

Beam Alignment Challenge: Due to the high frequency nature of mmWave signals, these signals experience greater attenuation than low frequency signals. Therefore, mmWave radios cannot employ omni-directional antennas. Instead, they have to use directional antennas to focus their transmitted and received power into narrow beams [14]. Hence, communication between two mmWave nodes is only possible when their beams are well-aligned as shown in Figure 1. Moreover, when a node moves or its surrounding changes, it needs to search again for the best beam

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direction. Although past mmWave work has proposed different approaches and schemes for creating a directional beam and searching for the best beam direction, they are not practical for backscatter devices for two reasons [9, 14, 17, 25]. First, in order to steer a beam, most existing schemes require phased array antennas. Unfortunately, phased arrays are costly and consume a significant amount of power which makes them impractical for backscatter devices [2, 22]. Second, most importantly, all existing schemes require both nodes to transmit and/or measure the received signals. Backscatter devices can neither transmit nor measure the received signals, it can only reflect signals. Therefore, to build a mmWave backscatter device, we need to design a beam searching scheme which does not require the device to have any transmitter nor receiver. Moreover, we need to avoid using power hungry mmWave blocks (such as phased arrays) in our design.

This paper introduces mmTag, a wireless system that enables mmWave backscatter networks.[1] mmTag addresses the main challenge in using mmWave spectrum for backscatter networks. In particular, mmTag overcomes the beam alignment problem by developing a directional backscatter tag which reflects the received energy back in the direction of arrival, regardless of the incidence angle. This enables the tag to have its beam always aligned toward the reader even if they move. mmTag achieves this without using any costly or power hungry mmWave components such as amplifiers and phase shifters. In particular, mmTag uses only an array of passive patch antennas connected together by novel design of transmission lines.

This paper makes the following contributions:

- We introduce mmTag, a mmWave backscatter network which solves the data-rate limitations of today's backscatter networks.
- We design a novel backscatter tag using a passive beamforming technique. Our tag modulates and reflects the received signal back to the direction of arrival, regardless of the incidence angle. This solves the beam alignment requirement of mmWave communication without using any costly or power-hungry components.
- We built a prototype of mmTag and evaluated its performance empirically. Our results show that it is possible to achieve robust communication rates of 1 Gbps at a range of 4 ft and 10 Mbps at a range of 10 ft.

2 BACKGROUND

2.1 Backscatter Communication

Backscatter technology is the most energy-efficient wireless communication link [5, 15, 35–37]. A typical backscatter system consists of two parts: a reader and one or multiple backscatter tags. The tag communicates to the reader by backscattering instead of generating and transmitting its own signal. In particular, the reader transmits an RF signal to the tag. Then, the tag replies to the reader by reflecting the signal using simple modulation schemes. For example in RFID, the tag uses on-off keying (OOK) modulation where reflecting the reader's signal represents a '1' bit, and absorbing the signal represents a '0' bit. Due to its low-power consumption, this communication technology is well-suited for applications where battery replacement is challenging or the battery life is expected to be long.

[1]Note that the term "mmWave backscatter" is often used in the mmWave literature to refer to mmWave-based imaging of objects by reflection (such airport scanners) rather than for communication or networking which is the goal of this paper.

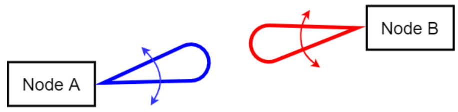


Figure 1: mmWave devices need to focus their energy into beams, and align them to establish a communication link.

2.2 mmWave Communication

mmWave refers to high frequency RF signals in the range of 24 to 100 GHz. At this frequency range, there is multi-GHz of unlicensed bandwidth available. The availability of this large bandwidth promises to enable wireless networks with orders of magnitude higher throughput than today's wireless networks [26]. However, a major challenge in using mmWave signal in a wireless network is that these signals decay very quickly with distance, requiring mmWave radios to focus their power into very narrow beams to compensate for propagation loss [26]. The beam can be created by using an array of antennas [20]. Luckily, since the antenna size is proportional to the wavelength, and the wavelength of mmWave signal is within millimeters, one can pack many mmWave antennas into a small area, creating a narrow beam. Although mmWave radios can compensate for the propagation loss using directional beams, this creates a new challenge since communication is only possible when the transmitter's and receiver's beams are aligned [14]. Hence, mmWave devices need to continuously search the space for the best beam direction before establishing a communication link.

3 RELATED WORKS

The related work can be categorized into three main areas:

1) mmwave Communications: Past work on mmWave communication mostly focuses on applications that require very high-data rate link, while having substantial energy and computing power. For example, [7] presented a system that enables high throughput links between server racks by using mmWave technology in data centers. There are also 5G applications using mmWave [10, 27, 28]. mmWave has also been used for Virtual Reality to stream high data-rate video from PC to the VR headset [1, 8]. In contrast, this paper focuses on designing a mmWave backscatter network which enables low-power mmWave communication. This is required for low-power applications which cannot benefit from existing mmWave radios and protocols, due to their complexity and power consumption. Some prior work has designed a backscatter mmWave tag [18]. This work is limited by its fixed beam and does not solve the beam searching problem. Hence it does not support mobility or different angles of the tag with respect to the reader. It only works when the tag is exactly in front of the reader. In contrast, our work focuses on designing a mmWave backscatter network which supports mobility and enables communication link, regardless of the angle of the tag with respect to the reader.

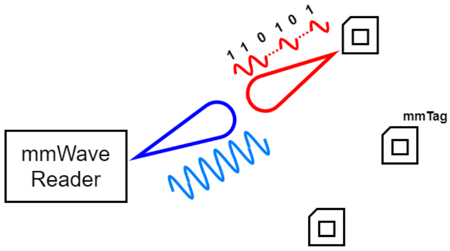


Figure 2: mmTag reader scans the space by steering its beam. When the reader beam is toward a tag, the tag modulates and reflects the reader's signal back in the direction of arrival.

2) mmWave Beam Searching: There is a significant amount of work in the area of mmwave beam alignment [1, 14, 19, 30, 33]. They propose different techniques to speed up the beam searching process, enabling mmWave link for mobile applications. However, these techniques require phased arrays to steer the beam electronically and search for the best beam alignment. Unfortunately, phased arrays are expensive to build and have high power consumption [2, 21, 22, 34]. Recent work has proposed a beam searching process without the use of phased array by exploiting channel blockage [22]. However, this work and other existing beam searching techniques require the node to have an active radio where it can transmit a signal or measure the received signal. Unfortunately, active radios significantly increase the power consumption of a wireless node and are therefore not suitable for a backscatter design. In contrast, this paper introduces mmTag which performs beamsearching without requiring any phased array, transmitter or receiver. In particular, mmTag achieves this by building a directional tag which reflects the signal back to the direction it was arrived, regardless of the angle of incident. This enables the backscatter tag to automatically align its beam toward the reader without exhaustively searching for the best direction to focus its beam.

3)Backscatter Networks: In the past few years, many RFID sensing systems have been designed in the research community, targeting a variety of applications ranging from food monitoring and smart homes to touch sensing and localization [13, 23, 24, 32]. There is also a significant amount of work focused on designing wireless networks for RFID tags [31]. However, existing RFID tags enable throughput of less than a Mbps. Recent work have proposed designing WiFi-based backscatter tags [4, 16, 37]. Their goal is to design backscatter tags which can communicate to WiFi devices. Although these backscatter systems enable much higher throughput than traditional RFID tags, their throughput is still very limited. For example, HichHike can only support 0.3 Mbps in the best scenario [35]. BackFi tries to solve the throughput problem of WiFi backscatter systems by using customized full-duplex radios. However, it can only support up to 5 Mbps at a short range of 3 ft [4]. In contrast, mmTag tries to solve the throughput problem of backscatter networks and achieves Gbps data rates using mmWave technology.

4 mmTAG OVERVIEW

mmTag is a backscatter communication system, operating at mmWave frequency bands. It enables high-throughput wireless links while benefiting from the low-power nature of backscatter technology. As shown in Figure 2, mmTag consists of two parts: a reader, and one or more tags. The reader uses directional antennas to create transmitting and receiving beams. Then, it steers these beams together while transmitting a query signal. When the beams are facing toward a tag, the tag receives the query signal then modulates and reflects the signal back to the direction of arrival (i.e. direction of the reader). The reader receives the backscattered signal and decodes the tag's message. Note, the best communication path between the reader and the tag might be a line-of-sight (LOS) path or a non-line-of-sight (NLOS) path. In particular, when the line-of-sight (LOS) path is blocked, the tag and the reader chooses an NLOS path to communicate.

Over the next few sections, we will discuss how mmTag performs the beam alignment without using active mmWave components and phased arrays. In particular, we explain how we can build a tag which reflects the signal to the direction of arrival, regardless of the angle of incidence. Finally, we show how mmTag performs data modulation.

5 BEAM ALIGNMENT CHALLENGE

As mentioned earlier, mmWave signal decays very quickly with distance. Therefore, in a typical mmWave communication, mmWave radios need to use very directional antennas with narrow beams to compensate for the signal loss and achieve an acceptable range. Moreover, since communication between two nodes is only possible when the transmitter and receiver beams are aligned, mmWave radios must be able to steer their beams to align them. A steerable directional antenna is typically implemented using a phased array. A phased array is an array of antennas, where each antenna connected to a phase shifter. The phase shifter controls the phase of the signal on each antenna which enables creating and steering a beam electronically. Finally, in order to find the correct direction for beam alignment, recent work has proposed different search techniques [9, 14, 19, 30, 33].

Similar to a typical mmWave communication, mmWave basckcatter communication also requires both the reader and tags to use steerable directional beams and search for their correct direction. However, existing beam alignment approaches are not suitable for backscatter tags due to two reasons. First, all of these schemes require nodes to transmit and/or measure the received signals. However, a backscatter tag does not have any transmitter or receiver chain; it can only reflect signals. Second, existing schemes require phased arrays which have high power consumption (a few watts) and are costly (hundreds of dollars) [2, 22]. In the following, we explain how we solve the beam alignment problem of backscatter tags without using any active block (such as phased arrays, transmitter or receiver) in our tag design.

5.1 Principles of Antenna Array

Before explaining our solution, we first provide some principles about antenna arrays. An antenna array is an array of N antennas, spatially separated by d. In an antenna array, the signal received by the n^{th} antenna element can be written as:

$$x_n = x_0.e^{-jK_0.n.d.sin(\theta)}; \ n \in [0 : N-1], \qquad (1)$$

where K_0 is the free space wave number, d is the spacing between the elements, and θ is the angle of signal arrival. In a typical antenna array, $d = \frac{\lambda}{2}$ and $K_0 = \frac{2\pi}{\lambda}$, where λ is the wavelength of the signal. We can simplify Eq. (2) to:

$$x_n = x_0.e^{-j\pi.n.sin(\theta)};\ n \in [0 : N-1] \tag{2}$$

This equation shows that if we want to receive a signal only from direction θ, we can multiply the received signal at each antenna with $e^{j\pi.n.sin(\theta)}$ and then combine the signals of all antennas. Similarly, this equation shows that if we want to use an antenna array to transmit a signal only to direction θ, we need to feed the following signal to each antenna:

$$y_n = y_0.e^{+j\pi.n.sin(\theta)};\ n \in [0 : N-1] \tag{3}$$

where n is the antenna number, and y_0 is the signal fed to the first antenna. It is interesting to note that the only difference between Eq. (2) (i.e. equation for receiving from direction θ) and Eq. (3) (i.e. equation for transmitting to direction θ) is the inverted signal phases.

5.2 Passive Beam Searching

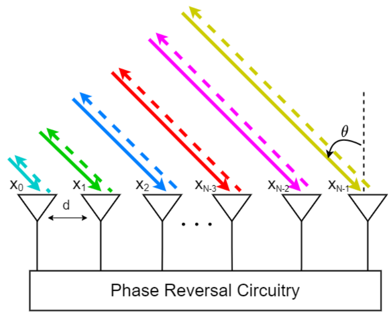
Now, we explain how we solve the beam alignment problem in backscatter systems. The backscatter tag requires to have two beams. One for receiving the signal from the reader and the other one for reflecting the signal back to the reader. Our observation is that, due to the symmetry of forward and backward channels in backscatter communication, the best direction for these two beams are the same. Said differently, the tag needs to reflect the signal back to the direction of arrival. Now, the question here is how we can build a passive reflector which reflects the received signal back in the direction of arrival, regardless of the arrival (incidence) angle. Note, this is different from a typical reflector (such as mirror) which does this only when the angle of incidence is 0 degree.

Using principles of an antenna array described in Section 5.1, we can show that one approach to build such tag is to design an antenna array where each antenna element reverses the phase of the received signal, and then reflects it back. This would give us a tag which reflects the signal back to the same direction as incidence angle, for any incidence angle. Now, the question is how we can reverse a phase of a signal.

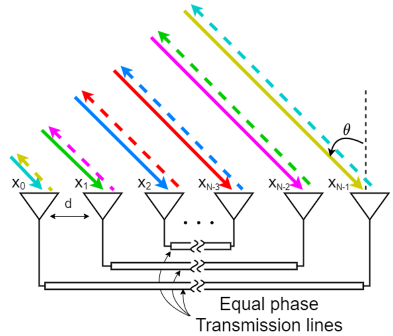
A common way to reverse the phase of a signal is to use the phase reversal circuits, as shown in Figure 3(a). However, these circuits are complex and power hungry and hence they are not suitable for a passive backscatter tag. To solve this problem and build a mmWave backscatter tag which reflects to the same direction as arrival direction, we design an antenna array using Van Atta technique [29]. As shown in Figure 3 (b), we use an array of antennas where each antenna is connected to its mirrored antenna using a transmission line.[2] Therefore, each antenna receives a signal and passes it to its mirrored antenna to reflect it. Now, if we carefully design the transmission lines to have the same phase shifts between antenna pairs, the reflected signal from n_{th} antenna element will be:

$$y'_n = e^{j\phi}x_{N-n-1};\ n \in [0 : N-1] \tag{4}$$

[2]transmission lines can be simply implemented by Copper strips on a PCB board.



(a) Active Approach



(b) Passive Approach (mmTag)

Figure 3: Directional reflectors using two different approaches. The solid arrows show the received signal and the dashed arrows show the reflected signal of each antenna element. In (a) each antenna reflects its own received signal, while in (b) each antenna reflects the signal received by its mirrored antenna.

where x_{N-n-1} is the signal received by the $(N-n-1)^{th}$ antenna element, and ϕ is the phase shift caused by the transmission lines. Then using Eq.2, we can write:

$$\begin{aligned} y'_n &= e^{j\phi}x_0e^{-j\pi(N-n-1)sin(\theta)} \\ &= e^{j\phi}e^{-j.\pi.(N-1)sin(\theta)}x_0.e^{+j\pi.n.sin(\theta)} \\ &= y'_0e^{+j\pi.n.sin(\theta)};\ n \in [0 : N-1] \end{aligned} \tag{5}$$

By comparing Eq.5 with Eq.3, we can see that the mmTag design creates a directional reflector which reflects the signal back to the direction of arrival regardless of incidence angle. Hence, our design solves the beam alignment problem of backscatter tags by enabling passive beam forming which does not need any active components.

6 DATA MODULATION

So far we have explained how mmTag is able to reflect the incoming signal back to the same direction, solving the beam alignment problem in mmwave backscatter systems. However, to enable the tag to send data, it must modulate the reader signal with the data before reflecting it back to the reader. However, we need to do this in a low-cost and low-power manner. Hence, to modulate the data, we use RF switches between each antenna element and the ground port, as shown in Figure 4. When the switches are off, the antennas

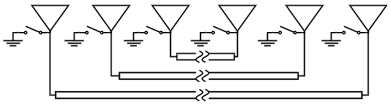


Figure 4: Data Modulation. In order to modulate the signal, mmTag uses simple RF switched to turn on and off each antenna by connecting it to its ground.

work normally. Thus, in this mode, the tag receives the mmWave signal from the reader and reflects it back to the same direction. When the switches are on, the antennas are short circuited to the ground and do not resonate as normal antenna anymore. In this mode, the tag does not receive nor reflect the reader's signal back to the reader. Therefore, by connecting the data stream to the control line of switches, we can control the amplitude of the reflected signal back to the reader. For example, when the data bit is '0', the switches are off and the amplitude of the reflected power is high at the reader. When the data bit is '1', the switches are on and the reader receives no reflected signal from the tag. Therefore, the reader can simply decode the tags data using on-off keying (OOK) demodulation.

7 IMPLEMENTATION

In this section, we describe the implementation of mmTag's tag and the mmWave reader's setup.

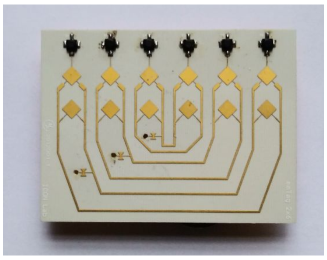


Figure 5: Our mmTag's tag fabricated on PCB. The dimension of the tag is 60 × 45 mm^2

We design and analyze mmTag using ANSYS HFSS software. The tag is then fabricated on PCB using standard Rogers 4835 material with 0.18 mm thickness, as shown in Figure 5. We use simple FET transistors (CEL CE3520K3) as RF switches which costs only 60 cents. This is the only mmWave component used in our tag, making the design low-cost. Our design is tuned to cover the whole 24 GHz mmWave ISM band. The current prototype of the tag is small (2.3 × 1.8 in), including 6 antenna elements which creates a directional reflector with 20 degree beam width. Note, our design can be easily tuned to higher frequency bands (such as 60 GHz) which results in even smaller antennas.[3] For the mmWave reader, we use a signal generator and a spectrum analyzer, and connect them to directional antennas to transmit and receive 24 GHz signal. The reader's peak transmission power is set to 20 milliwatt (mW). Note, the average transmission power will be much lower depending on the duty cycle of the reader.

[3]The higher the frequency, the shorter the wavelength, and therefore the smaller the antennas.

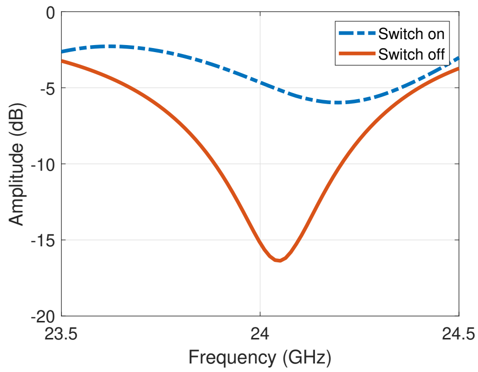


Figure 6: S11 coefficient of a tag's antenna element. When the switch is off, antenna has low S11 at the carrier frequency of 24 Ghz and hence it works properly. When the switch is off, the antenna's S11 is high and hence it does not reflect.

8 EVALUATION

In this section, we evaluate mmTag using both HFSS software and empirical measurements.

Simulation (HFSS) Results: We first evaluate our tag's ability in modulating and reflecting a signal. As described in section 6, we use RF switches to switch the tag between two modes: reflective and non-reflective. Figure 6 shows the result of our evaluation. The figure shows the S11 of a single element of the tag when its switch is off and on. When the switch is off, S11 is -15 dB at the 24 GHZ carrier frequency. This implies that antenna is tuned. Therefore, in this mode, the antenna works properly, and the tag receives the mmWave signal from the reader and reflects it back to the same direction. On the other hand, when the switch turns on, the figure shows the S11 is as high as -5 dB at the carrier frequency. Such a high S11 means that the antenna is not tuned. Therefore, in this mode, the antenna does not work, and the tag does not receive nor reflect the reader's signal. This evaluation confirms that our tag is able to modulate and reflect the mmWave signal.

Empirical Results: Next, we evaluate the performance of mmTag empirically. In this experiment, the mmWave reader transmits a query signal to the tag and measures the power of the signal reflected back from the tag. Figure 7 shows the result of this experiment for different distances between the tag and reader. The figure also shows the noise floor of the reader for different bandwidths as well as the tag's maximum data-rate for some ranges.[4] The received powers are measured empirically and the corresponding data rates are computed by substituting the power measurements into standard data rate tables based on the ASK modulation and BER of 10^{-3}. Note, ASK modulation requires SNR of 7 dB to achieve BER of 10^{-3} [12]. The result shows that increasing the distance reduces the tag's signal power. However, mmTag can still provide 1 Gbps data rate at 4 ft and 10 Mbps at 10 ft, which is significantly higher data rate than what existing backscatter networks achieve at similar ranges.

[4]The receiver noise floor is computed based on typical Noise Figure (i.e. NF=5) of mmWave receivers, bandwidth, and thermal noise at the room temperature (i.e. 300 K).

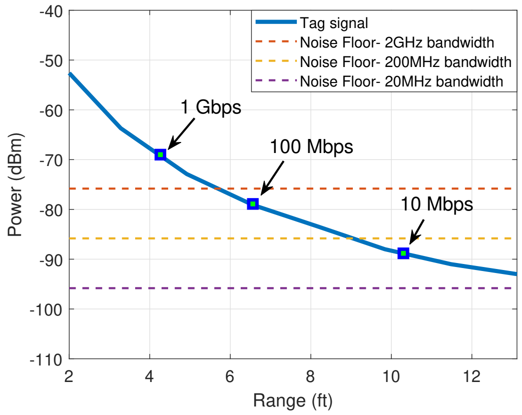


Figure 7: The power of tag's signal measured at the reader side versus distance between the tag and the reader. The figure also shows the noise floor for different reader bandwidth as well as corresponding data rates for some signal powers.

Note, the range and data-rate of mmTag can be further increased by using more antenna elements at the tags.

9 DISCUSSION

In this paper, we have investigated the possibility of enabling high data-rate, low-power wireless links by building backscatter networks which operate at mmWave bands. Our results show that this is a promising direction to enable high data rate connectivity for emerging IoT applications. Nevertheless, since mmWave communication have different requirements than traditional wireless communications, in order to enable a full backscatter mmWave networking system, the following topics require further study:

Self Interference: Similar to any other backscatter systems, the mmTag's reader needs to extract the reflected signal from its own transmitted signal. This is challenging since the reader needs to transmit and receive at the same time. One way to solve this problem is to use full-duplex radios at the reader. In fact, this is how existing backscatter networks (such as RFIDs) separate the tags signal from their own signal. However, this approach is very complex and costly to be implemented at mmWave. Therefore, exploring other approaches such as exploiting the directionality property of mmWave to solve the self interference problem is an interesting research direction.

Supporting Multiple Tags: We implement and evaluate mmTag for a single tag. Extending this work to a network of tags is the subject of future work. However, a simple technique to support multiple tags is to use Spatial Division Multiplexing (SDM). In this technique, the reader steer its beam and scan the environment. Hence, it can read the tags one by one. To support multiple tags simultaneously, one can employ MIMO beamforming which enables the reader to create multiple independent beams simultaneously and direct them toward different tags.

MAC Protocol: Although the reader can separate the signal of different tags by using narrow beams, there is a chance that multiple tags are placed in the same direction and thus they respond together. Hence, designing a MAC protocol for mmWave backscatter network is an interesting problem. One possible solution is to use similar MAC protocol as RFIDs such as Aloha protocol. However, the directionality property of mmWave communication may provide opportunities for more efficient protocols.

10 CONCLUSION

In this paper, we present mmTag, a backscatter communication system which enables orders of magnitude higher throughput than traditional backscatter networks. Traditional backscatter networks (such as RFID and WiFi baskcatter) enable low-power wireless communication which is very attractive for battery powered devices. However, they provide very limited data rates which are not suitable for many emerging applications. In contrast, mmTag is a backscatter network which enables Gbps data rate. It achieves this by building backscatter devices which operate in mmWave spectrum. Hence, it benefits from both low power consumption of backscatter networks and large bandwidth available at mmwave frequencies. We have designed, built and evaluated mmTag. Our result shows that mmTag provides significantly higher data rate than what existing backscatter networks achieve at similar ranges. We believe mmTag enables wireless links for many emerging applications which deliver reach content in real-time.

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