Can IoT Devices be Powered up by Future Indoor Wireless Networks?

Tianxiang Li   Mohammad H. Mazaheri   Kalaivani Kamalakannan   Haofan Lu   Omid Abari
UCLA
United States

Abstract

The number of wireless access points (such as WiFi and 5G) is rapidly growing in indoor environments. In this paper, we ask whether these indoor wireless access points can transfer power to IoT devices besides their communication capability. In particular, our vision is that most indoor access points will be underutilized during nights, and hence, why not use them to transfer power to IoT devices during those times. To evaluate this idea, we first perform a comprehensive study on the feasibility of using different frequency bands to transfer power. Our analysis shows that high-frequency signals (such as mmWave) are the best candidates to transfer power, and have the potential to power IoT devices up to 15 meters. However, achieving this requires addressing multiple challenges. In this paper, we review some of these challenges and propose solutions, enabling IoT devices to harvest energy from mmWave signals with spending (almost) zero energy.

CCS Concepts

• **Hardware** → **Wireless devices**; **Power and energy**.

Keywords

millimeter-wave, wireless power transfer, frequency scanning antenna, backscatter

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1 Introduction

The number of worldwide Internet of Things (IoT) devices is expected to grow to more than 29 billion by 2030 [25]. Although this is exciting, there is a major challenge in deploying IoT devices: *their batterylife*. Most today's IoT devices require their battery to be replaced or recharged every couple of months. For example, smart home sensors such as motion, temperature and moisture sensors require their battery to be changed every 6 months. Similarly, WiFi home security cameras require their battery to be recharged every 4 months. Although a batterylife of a few month might seem long enough for a device, unfortunately, this would not be the case in a few years. In particular, considering the fact that the average number of IoT devices in an American house is expected to reach fifty in the next few years [10, 26], we would need to change one to two batteries per week in our homes. Moreover, in many cases, the IoT sensors are not even in reach, so the battery charging or replacement requires lots of effort.

In this paper, we ask whether future indoor access points (such as WiFi or 5G) can transfer power to IoT devices to recharge their battery and/or significantly increase their batterylife. In particular, we are interested to learn which frequency bands are the best for transferring power wirelessly. On one hand, high frequency signals (such as mmWave bands) experiences greater path loss than low frequency RF signals (such as WiFi bands). Therefore, at first glance, mmWave signals may seem unsuitable for transferring power. However, on the other hand, FCC allows much higher transmission power for indoor mmWave networks than traditional indoor wireless networks [9]. Moreover, due to small wavelength of mmWave signals, their antennas are tiny [1, 19], and many of them can be packed into a small area to create high gain antenna to harvest more energy. Therefore, due to these trade-offs, it is not clear whether low frequency signals are more suitable than mmWave signals for transferring power or vice versa.

In this paper, we perform a comprehensive study of these trade-offs, as well as an end-to-end performance evaluation of using 900 MHz (RFID), 2.4 GHz (WiFi), 5.8 GHz (WiFi), and 28 GHz (mmWave 5G) signals for transferring power to IoT devices. We focus our evaluation on the indoor environment such as smart home or smart factory. Our results show that mmWave bands are much better candidates for transferring power to IoT devices than lower frequency wireless signals. However, in order to transfer power to IoT devices using mmWave signals, we first need to address multiple challenges. The main challenge is that indoor mmWave access points and mmWave harvester devices use directional antennas with narrow beams, and hence, the maximum power is transferred when these beams are aligned. Moreover, when a node moves, it needs to search again for the best beam direction. Although past mmWave work has proposed different approaches and schemes for creating a directional beam and searching for the best beam direction [3, 6, 13, 14, 23], they are not practical for our application. This is mainly due to the fact that existing schemes require phased array antennas. Unfortunately, phased arrays are costly and consume a significant amount of power which makes them impractical for energy harvesting IoT devices [2, 20].

To solve this challenge, we propose to use Frequency Scanning Antenna (FSA) and backscatter technology [7, 21, 28]. In particular, we develop a directional energy harvesting antenna which is completely passive while enables the access point to steer the harvester device's beam. Furthermore, we propose an efficient and low power

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beam alignment mechanism based on backscatter technology which enables the access point to align its beam and the harvester device beam, even when they move.

The contributions of this paper are as follow:

- We study the feasibility of using different indoor signals to transfer power to IoT devices considering constraints such as FCC regulations, antenna size, etc. Our results show that mmWave signals are much better candidates to transfer power compared to traditional wireless signals such as WiFi and sub-GHz signals.
- We propose a system architecture and link establishment protocol for IoT devices to harvest energy from indoor mmWave access points. Our design is based on passive beamforming and backscatter technology.
- We evaluate our system in terms of power transfer at different distances. Our results show that it is possible to harvest 1 mW and 0.1 mW power at the distances of 7.5 m and 15 m indoors, respectively. This enables the IoT device to significantly increase their batterylife.

2 Background and Related Work

Existing wireless power transfer systems can be divided to two types: near-field magnetic coupling and far-field electromagnetic radiation [5]. Magnetic coupling in wireless power transfer, such as in smartphone wireless chargers, involves the transmission of electrical energy between a transmitting coil and a receiving coil through an oscillating magnetic field. However, despite their high efficiency, these systems have a very short operating range (i.e. less than a foot) since the strength of the field falls off inversely with the cube of the distance from its source. In contrast to the near-field magnetic coupling approach, the far-field electromagnetic radiation approach uses RF signals to transfer power between two devices. In these systems, a charger device transmits a signal using its antenna. Then user devices receive the signal on their antennas and use harvesting circuits to harvest energy. Existing systems mostly operate at ISM bands such as 900 MHz, 2.4 GHz, 5.8 GHz and mmWave bands [5, 18]. Given the inherent trade-offs across various frequency bands in terms of communication distance, antenna size, and power regulations, there lacks a a comprehensive analysis on which frequency band is best for wireless power transfer. Although there are a few survey work which discuss the potential and challenges of higher frequency bands such as mmWave for power transfer [30], none of them provide a conclusive end-to-end comparison with different frequencies. Moreover, they do not take into account various parameters such as the FCC regulations, the antenna aperture, and the power conversion efficiency based on recent hardware advances. In this workshop paper, we perform a comprehensive study and an end-to-end performance evaluation of using different frequency bands for transferring power, while considering practical factors such as FCC, antenna size, path loss, hardware efficiency, etc.

There are some existing work such as GuRu on power transfer using mmWave. However, these systems use a fixed beam antenna on the harvester device [12, 22, 24]. Unfortunately, this approach is significantly limiting power harvesting efficiency across various orientations and during mobility. Moreover, these systems require the harvester device to constantly provide feedback to the access point using a separate communication module such as Bluetooth or WiFi, which significantly increase the complexity and power consumption of the harvesting device. Finally, the authors in [4] proposed a multi-beam mmWave energy harvester using Rotman Lens and patch antennas. However, the Rotman Lens has multiple output ports, and therefore it requires a DC combiner network to combine the power of all ports. This adds complexity and reduces the efficiency of the system. In contrast, our design, based on Frequency Scanning Antenna (FSA), not only creates multiple spatial beams, but also naturally combines all the power harvested from beamforming via a single output port. Moreover, we propose a link establishment protocol based on backscatter communication which enables the access point to steer the harvester's beam, and align it toward itself without any need for a separate module.

3 Which Spectrum Band is the Best for Wireless Power Transfer?

A typical wireless power transfer system consists of a power transmitter which sends power using radio waves signals and a power harvester which collects these waves and convert it to DC power through a rectifier circuit. In this section, we perform an end-to-end performance evaluation of wireless power transfer system operating at four different frequency bands: 900 MHz (RFID), 2.4 GHz (WiFi), 5.8 GHz (WiFi), and 28 GHz (mmWave 5G). Our evaluation is based on commodity devices which are compliant with Federal Communications Commission (FCC) regulations. Our goal is to see whether using mmWave signals have any advantages or disadvantages compared to other signal frequencies.

3.1 Link Budget Parameters

Here, we explain different parameters we consider in our link budget analysis.

FCC regulation and Transmit Power: We first investigate how much power a power transmitter can radiate to the air based on FCC regulation. The total output power radiated in a transmitting direction is known as the Effective Isotropic Radiated Power (EIRP), which consists of the transmitter output power and the transmitter's antenna gain. The max EIRP at each frequency band is regulated by the FCC. The max EIRP permitted for 900 MHZ band and indoor WiFi access points at 2.4 GHz and 5.8 GHz is 36 dBm [9]. At mmWave frequency of 28 GHz, the max EIRP for indoor access points is 55 dBm [8], the max EIRP for outdoor access point can reach up to 75 dBm [8]. Hence, a transmitter operating at 5G mmWave bands can radiate almost 20 dB higher power than a transmitter operating at other frequency bands for indoor scenarios and this number further increases for outdoor scenarios.

Propagation Path Loss: Next, we compare the propagation path loss for signals at different frequencies. The equation for calculating the received power (P_r) is shown in Eq.(1), where P_t is the transmitter output power, G_t is the gain of the transmitting antenna, G_r is the gain of the receiving antenna, d is the distance between the transmitter and the receiver, f is the signal frequency, and c is the speed of light in vacuum.

$$P_{\mathrm{r}}(dB) = P_{\mathrm{t}}(dB) + G_{\mathrm{t}}(dB) + G_{\mathrm{r}}(dB) + 20log\frac{c}{4\pi fd} \quad (1)$$

Frequency	Input power to rectifier (dBm)				
	-20	-10	0	10	20
900 MHz	16%	26-60%	60-69%	N/A	N/A
2.4 GHz	20%	45%	57-72%	53-73%	84%
5.8 GHz	N/A	23%	18-34%	50%	60-82%
24-35 GHz	N/A	N/A	10-12%	15-35%	37-62%

Table 1: Power Conversion Efficiency. This table shows the PCE of rectifiers used in existing literature at different frequencies and different input powers [27, 29, 30].

Based on Eq.(1), the path loss of the signal is determined by the transmission distance (d) and the frequency of the signal (f). This means that given the same transmission distance, the higher the signal frequency, the higher the propagation path loss.

Antenna Size: The relationship between the antenna gain (G) and the effective antenna aperture (A_e) is shown in Eq.(2).

$$G = \frac{4A_e\pi f^2}{c^2},\ G(dB) = 10log(\frac{4A_e\pi f^2}{c^2}) \quad (2)$$

When the antenna aperture size is the same, the higher the transmission frequency, the higher the gain of the antenna. This means that for the same antenna area, the gain of the receiving antenna will be much higher for mmWave compared to lower frequencies. Note, higher antenna gain means that the receiver can collect more power to harvest energy. For example, for the same aperture size, an antenna operating at 28 GHz has almost 100, and 1000 times higher gain compared to an antenna operating at 2.4 GHz and 900 MHz, respectively.

Energy Harvester Efficiency: Once the RF signal is received at the output of the receiving antenna, it has to be converted to DC power for usage. This conversion is done using a circuit called rectifier. In a rectifier, the ratio of output DC power to input RF power is quantified as the Power Conversion Efficiency (PCE). This conversion efficiency is impacted by the quality of RF to DC converter components and various losses due to mismatch in the circuits. Unfortunately, the losses worsen at higher frequencies. Table 1 shows PCE of existing circuits operating at different frequencies for different range of input powers. As the table shows, the higher the signal frequency, the lower the PCE.

3.2 Link Budget Analysis

So far, we have explained the trade-offs between mmWave and lower frequency signals in terms of FCC EIRP limit, path loss, antenna size, and energy conversion efficiency. Next, we will combine all the above factors and provide an end-to-end link budget calculation. By substituting Eq.(2) in Eq.(1), and considering the circuits efficiency, the harvested DC power at the IoT device can be calculated using the following equation.

$$P_{DC} = EIRP + 10log(A_e) - 20log(d) - 10log(4\pi) + 10log(\eta) \quad (3)$$

Note, in our calculation, we replaced P_t+G_t with $EIRP$, as defined by FCC regulations. Furthermore, we assume that the IoT node dimensions are constant regardless of the operating frequency, meaning that the allowable antenna aperture size will be the same regardless of the operating frequencies. Finally, we convert the received power to DC power by considering the RF to DC PCE (η).

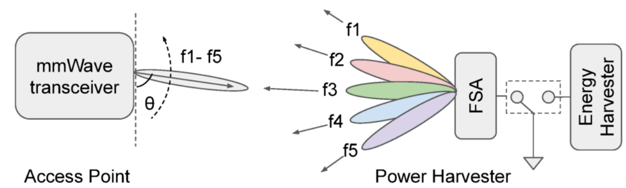

Figure 1: mmCharge Beam Alignment. During beam alignment, the access point steers the beam of various frequencies in different directions. The power harvester reflects the received signal back to the access point. The access point builds up a profile based on the reflected signal power to determine the best frequency and direction for efficient signal transmission.

As Eq.(3) shows, the harvested power at the IoT is a function of $EIRP$, IoT antenna aperture size (A_e), distance (d), and RF to DC conversion efficiency (η). Interestingly, the harvested power is not dependent on the operating frequency. This is due to the fact that although higher frequency signals suffer from higher path loss but their antennas have much higher gain (for the same aperture size). Therefore, these two factors counterbalance each other's effects. Finally, it is worth mentioning that although η is lower for mmWave, mmWave has much higher EIRP which compensates for its lower circuit efficiency. In particular, mmWave EIRP is 100 times (20 dB) higher than EIRP of lower frequency signals, while its efficiency is just 20-30% lower as shown in Table 1. In Figure 3, we calculate the harvested DC power for different distances and different operating frequencies, from 900 MHz up to 28 GHz. Our results shows that mmWave is a much better candidate than other frequencies to transfer power.

4 Challenges of mmWave Power Transfer

In this section we illustrate the challenges of mmWave power transfer and introduce mmCharge, a mmWave power transfer system for indoor low-power IoT devices. To build mmCharge we need to address three challenges: achieving low-power beamforming at the IoT node to harvest power from multiple directions; integrating a low-power protocol for beam alignment; and addressing the self-interference issue. For illustration, we use a typical indoor scenario with multiple IoT nodes that harvests power from a mmWave access point (AP).

Beamforming Challenge: Due to the property of mmWave signals, both the AP and the IoT node need to first create beams and then align them before transferring power. We assume the AP is equipped with a phased array and hence can electronically create and steer its beam toward the node. However, for the IoT node, we cannot use phased array due to complexity and power consumption. Existing mmWave power harvesters generally use an array or grid of antenna elements, forming a fixed beam to receive power [11, 22]. This limits the power harvesting efficiency at different orientations and during mobility. To achieve low-complexity and low-power beamforming on the IoT node, enabling it to harvest power across multiple directions, we design a passive antenna system based on Frequency Scanning Antenna (FSA). FSA is a passive structure which transmits or receives signals from a specific direction such that the angle of the direction is a function of the signal frequency [15–17],, as shown in Figure 2(b). Compared to traditional beamforming techniques such as phased arrays that utilize power-hungry phase shifters to form beams in different directions, FSA forms beams based on the natural effect of phase shift caused by the difference in signal wavelength when the signal travels through the structure of the FSA [16]. Hence, FSA can form beams in multiple directions, while being simple, passive, with no power consumption.

Beam Alignment Challenge: Secondly, we need a low-power solution to align the beams of the AP and the IoT node. Most existing mmWave power transfer systems require the power harvester to constantly monitor the received power level and provide feedback to the power transmitter through either Bluetooth or WiFi [12, 24], while the transmitter adjusts its beam direction. However, this significantly increases the power consumption on the harvester, rendering it impractical for low-power IoT devices. We propose a system that combines frequency scanning technique with backscatter technique to address this challenge. Due to the special nature of FSA, to align the AP's and node's beams, the AP needs to determine two parameters: (1) the optimal direction to transmit the signal; (2) the optimal frequency of the signal. Note, the signal frequency is important since only a specific frequency results in the FSA beam to become aligned toward the AP. In particular, the AP must sweep these two parameters to find the combination which results in the highest received power at the IoT node. To enable the IoT node to provide feedback to the AP about its received power without consuming energy, we propose a solution similar to RFID and backscatter technology. In particular, instead of directly connecting the FSA to the energy harvesting circuit, we connect it to a switch which connects the FSA to either a ground or the harvesting circuit, as shown in Figure 1. During the beam alignment process, the node connects the FSA to the ground. In this mode, the FSA works as a reflector and reflects the received signal back. The strength of the reflected signal is determined by the direction of the FSA beam for that frequency in relation to the direction of the AP's beam. The AP then measures the power of the reflection for all combination of the frequency and transmitting beam angle and pick the combination which results in the highest reflection power. However, one issue with this solution is that it takes a long time to find the best beam alignment. For example, if the AP has to try N different directions for its beam, and there are M different signal frequencies to try, it would take $N \times M$ measurements. To speed up this process, instead of sweeping both frequency and direction, the AP transmits at all frequency choices simultaneously, and only sweeps its beam direction. For each beam direction, the AP receives the reflected signal and creates a profile of received signal strength across frequency. Finally, the AP compares all the measured profiles and picks the direction and frequency that provide the highest reflection power. Once the optimal frequency and transmitter beam direction is discovered, the node moves to the harvesting mode.

Self-Interference Challenge: The third challenge is that the reflected signal from the FSA is much weaker than the AP's transmitted signal. In particular, the AP needs to extract the weak reflected signal from its own transmitted signal which creates a strong self-interference. To solve this self-interference problem, one solution is to use full-duplex radio at the AP. However, full duplex radios are very complex and are not available in today's mmWave access points.

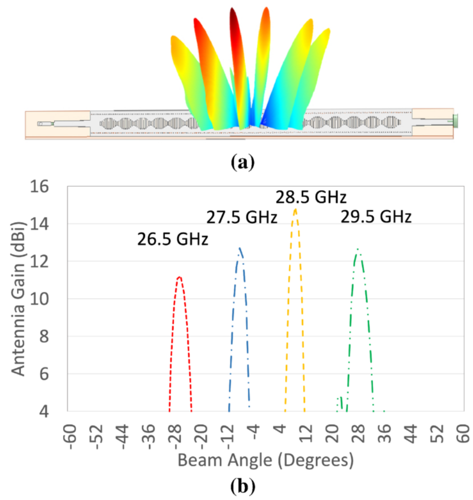

Figure 2: Our Designed FSA and its receiving pattern. (a) The structure of our designed FSA (110×7×0.5 mm). (b) The radiation pattern of the FSA at four sample frequencies. The beam angle increases with the signal frequency.

To overcome this problem, the FSA switches between reflection and absorption modes to modulate the the reflected signal to a different frequency. For example, if the AP transmits at frequencies f_1, f_2 and f_3 the IoT node modulates this signal by turning the FSA on and off at the rate of f_s. Hence, the frequency of the reflected signal will be $f_1 + f_s$, $f_2 + f_s$ and $f_3 + f_s$. Thus this makes it much easier for the AP to measure the reflected signal from its own transmitted signal. Finally, it worth mentioning that the backscatter modulation can be easily implemented by switching the FSA switch (as shown in Figure 1) between the ground and harvester circuit.

5 Evaluation

Below, we evaluate the performance of mmCharge using both simulation and real-world experiments. We designed and simulated a mmWave FSA similar to the technique presented in [16]. First, we present the performance results of the FSA design. Then we present the performance of mmCharge in receiving and converting the mmWave signal into DC power.

FSA Results: Figure 2(a) shows the structure of our designed FSA. It is very compact in size, with dimensions of $110 \times 7 \times 0.5$ mm. Figure 2(b) shows the radiation (or receiving) pattern of the FSA at different frequencies simulated by CST Microwave Studio. These results show that the FSA is able to effectively create a beam and steer it by changing the signal frequency. In particular, the design achieves a beam steering angle of approximately 56 degrees (-28^o to 28^o) across the mmWave 5G band of 26.5 to 29.5 GHz [1].

End-to-End Performance: Next, we evaluate the performance of mmCharge in transferring power from an AP to IoT devices in an indoor environment. We use our analysis presented in Section 3.2, and perform an end-to-end simulation to estimate the amount of power an IoT device can harvest. To evaluate the correctness of

[1]The bandwidth of cellular or WiFi mmWave bands ranges between 1 to 8.64 GHz, which provides large angle of coverage for the FSA.

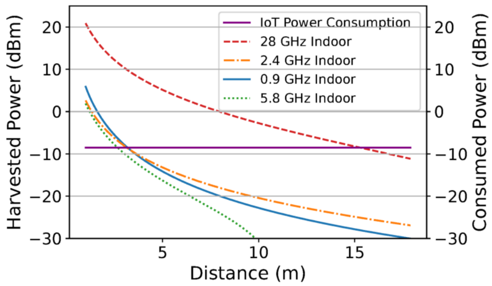

Figure 3: Harvested Power vs Distance ($100cm^2$ **Aperture), based on our link budget analysis.** mmWave signal can transfer much higher power compared to lower frequencies at the same distance. mmCharge's nodes can harvest 1 mW and 0.1 mW power from an indoor mmWave AP at 7.5 m and 15 m away. An mmWave AP can sustainably power up a standard IoT sensor from 15 m away.

our simulations, we also run some real-world measurements in an indoor environment. Note, the PCE in our calculation is based on the received power and signal frequency shown in Table 1. Figure 3 shows the result of our simulation. The figure shows the amount of power an IoT can harvest across different distances between an indoor AP and an IoT node for different operating frequencies. As the figure shows, mmWave signals can transfer much higher power compared to other frequencies. As mentioned earlier, this is due to the fact that mmWave AP can transmit much higher power (EIRP) based on FCC regulations. Moreover, for the same antenna aperture, mmWave antennas have much higher gain and hence they collect higher power. Note, in our evaluation, we assume an EIRP of 55 dBm for the mmWave AP (which is based on FCC). We also assume that the aperture size of the IoT device is $100cm^2$ which is equivalent to the size of two credit cards. Our results show that mmCharge's nodes can harvest 1mW and 0.1mW power when they are 7.5 m and 15 m away from an indoor mmWave AP, respectively. The figure also plots the average power consumption of a typical IoT device using a solid purple line [2]. Interestingly, mmCharge provides more power than the device average power consumption even when they are 15 meters spaced, which is more than enough for most indoor scenarios. In an outdoor scenario, due to much higher FCC EIRP limit [8], this power transmission distance can reach to 150 meters based on our link budget analysis. It is worth mentioning that the distance can be further improved by using larger antenna aperture for the IoT node. One of the main limiting factors of mmWave wireless power transfer is the PCE of the rectifiers [30]. Figure 3 is based on the performance data of mmWave rectifiers shown in recent literature (Table 1). With the development of semiconductors, the PCE of rectifiers at mmWave frequency is expected to improve further, thus the harvested power at mmWave frequency would continue to increase in the future. This results show that mmCharge has the potential to transfer power from an AP to IoT devices and significantly improve their batterylife.

Finally, we perform some real-world experiments to validate our simulation results. We used a signal generator (HP 83650B) as a mmWave AP and we used a spectrum analyzer (Agilent 8565EC).

[2]We use the Google Nest Temperature Sensor as an example. It can run on a single CR2 3V lithium battery of 800 mAh capacity for two years. Considering 2400 mWh capacity and two years lifetime, the average power consumption of the device is around 0.14 mW.

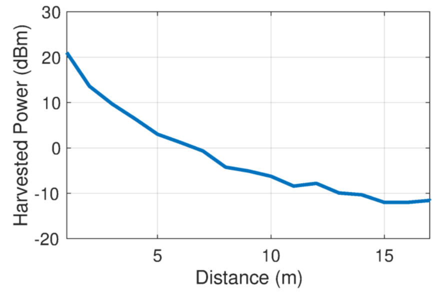

Figure 4: Measured Harvested Power vs Distance. The harvested power from an indoor mmWave AP based on real-world measurements at varying distances.

We connect them to to horn antennas and measure the received power at different distances. Note, although the EIRP can be as high as 55 dBm, the EIRP of the equipment was limited to 20 dBm. Hence, we performed the experiments at 20 dBm and then added 30 dB to it in post-processing. Finally, we also considered the efficiency of converters in our measurement presentation. Figure 4 shows the result of this experiment. The results are very much aligned with our simulation results.

6 Discussion

Below we discuss some challenges that need further research.

Synchronization As mentioned in this paper, the node needs to switch between the beam searching and harvesting mode. This requires the node to know when beam searching is done by the AP and when it is time to switch back to the harvesting mode. One potential solution is to use a power divider instead of a switch. In this case the node is always reflecting while it is also harvesting some power. However, this solution reduces the efficiency of the system since some of the received power is always reflected. Another solution is to design a switch which is triggered by the fluctuation in received power. In particular, when the beam searching is done and the received power remains stable, the switch will be triggered and switch the node to the harvesting mode. Exploring the effectiveness of these solutions is an interesting research direction.

Receiver Sensitivity mmCharge solves the self-interference problem by modulating the reflected signal. However, this requires the receiver to have high sensitivity to detect the reflected signal. In particular, the backscattered signal should be at least 5dB higher than the AP's noise floor to be detectable. Considering an AP with a typical noise floor of -86 dBm, the backscattered signal should be stronger than -81 dBm. Our preliminary results shows that this is achievable for the ranges which our system targets. However, a comprehensive study and experimental evaluation is required to confirm this.

Multi-Device Coordination In the case of multiple IoT nodes harvesting power, the AP needs to align its beam to the nodes at different locations. To distinguish between the signals from different nodes, mmCharge could adopt a solution similar to RFIDs, where each node modulates its unique device identifier in the reflected signal. This enables the AP to build a beam alignment profile for each node to select the best signal frequency and beam direction. For advanced APs with Multiple input multiple output (MIMO) capabilities, it can generate beams toward multiple nodes simultaneously.

Alternatively, the AP could adopt a time sharing solution to power each node at a designated time interval.

7 Conclusions

In this paper, we provide a comprehensive feasibility study to show that future indoor mmWave access points can power up IoT devices. In fact, our results show that mmWave systems are a better candidate for wireless power transfer compared to the systems which use lower frequency RF signal. However, to enable this vision we need to address multiple challenges. The most important challenge is to enable very low power beam alignment architecture and link establishment for mmWave power transfer. We present mmCharge which introduces a new system based on frequency scanning technique and combined it with a backscatter technique to enable IoT devices to harvest energy from mmWave access point while consuming a minimum amount of energy. We believe this paper provides the first step toward enabling future mmWave access points (such as 6G and 802.11ay) to transfer power to IoT devices besides enabling connectivity.

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