Can WiFi Backscatter Achieve the Range of RFID? Nulling to the Rescue

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ABSTRACT

RFID and WiFi backscatter systems use similar techniques to enable battery-free wireless communication. Despite their similarities, existing WiFi backscatter systems achieve a much shorter range than RFID systems. The main reason for this limitation is self-interference. In particular, in any backscatter communication, the reader needs to transmit and receive at the same time. RFID systems do this by using full-duplex hardware. Unfortunately, existing WiFi devices do not have full-duplex capabilities. Therefore, to enable backscatter communication using existing WiFi devices, today's WiFi backscatter systems use two WiFi devices where one transmits and the other one receives. However, since the tag's reflection is very weak compared to the query signal, it is very challenging to detect and extract the tag's reflection from the query signal. This problem is known as self-interference. In this paper, we propose a novel approach for eliminating this problem in WiFi backscatter systems without any hardware modifications on existing WiFi devices. Our empirical evaluations show that our technique improves the range of in-channel WiFi backscatter systems to that of RFID in both line-of-sight and non-line-of-sight scenarios. Moreover, our approach enables WiFi backscatter communication even in scenarios where the tag has no LOS path to any WiFi device. None of existing WiFi backscatter systems work in this scenario.

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1 INTRODUCTION

Backscatter communication is a lucrative technology for many IoT applications since it consumes near-zero power, and enables IoT sensors to be battery free or run on a tiny battery for many years. One example of backscatter technology is Radio-Frequency IDentification (RFID). Although RFID has been around for decades, the need for installing bulky and expensive RFID readers have hindered the use of this technology for many emerging applications such as smart home services [2, 14]. To solve this problem, WiFi backscatter has been proposed which enables backscatter communication between IoT sensors and existing WiFi devices (i.e. without using specialized readers) [3, 7, 9, 13, 16–19]. However, despite numerous studies on WiFi backscatter, no IoT sensor utilizes this technology today. This is mainly due to the limited range of WiFi backscatter, especially in non-line-of-sight scenarios [8].[1] Unfortunately, because of this limitation, WiFi backscatter is not a substitute for RFID. In this paper, we explore how we can significantly increase the range of WiFi backscatter technology.

The main reason for the limited range of WiFi backscatter compared to RFID is *self-interference*. In any backscatter system, there is a query device which sends a query signal to tags. Then each tag sends its data by modulating and reflecting the query signal back to the query device. The query device then receives the tag's signal and separates it from its own transmitted signal. However, as the distance between the query device and the tag increases, the tag's signal becomes orders of magnitude weaker than the query signal, and hence, it becomes very challenging to separate and decode the weak tag's signal. Today's RFID readers solve this challenge by using a special hardware, known as full-duplex radio. This hardware allows RFID readers to simultaneously transmit a query signal and decode the tag's signal even when the tag is far. In contrast to RFID readers, unfortunately, existing WiFi devices do not have full-duplex radios and therefore they cannot simultaneously transmit and decode a tag's signal.

[1] Note, all existing WiFi backscatter systems require two or three WiFi devices in order to communicate with a tag. Past work has defined their range as the distance of the tag to the furthest WiFi device. However, to do a fair comparison, the range should be defined as the distance of the tag to the closest WiFi device.

One possible solution to solve this problem in WiFi backscatter is to modify WiFi devices and equip them with full-duplex hardware, enabling them to transmit and receive simultaneously. However, this solution hinders the widespread deployment of WiFi backscatter systems. Another solution is to use two WiFi devices where one transmits and another one receives [13]. However, since the tag's signal is orders of magnitude weaker than the transmitted signals, the receiving WiFi device still suffers from the interference problem, and hence these systems have limited range. Finally, some studies have proposed to shift the tag's signal to another WiFi channel to avoid interference. In these systems, the frequency of a tag's signal is different from that of the query signal. However this solution creates many limitations such as requiring modification to WiFi devices, creating interference to other WiFi devices, and requiring a power-hungry 20 MHz clock [4].[2] Unfortunately, these limitations make WiFi backscatter far from ideal. To the best of our knowledge, there is no WiFi backscatter system that works with existing WiFi networks, has similar power consumption as RFID and yet achieves long range.

In this paper, we show how we can solve the self-interference problem in WiFi backscatter without using specialized hardware or shifting the signal to another channel. Our solution is to build on the nulling capability of WiFi networks. In modern WiFi networks, beamforming is used to increase the signal strength at a particular station while nulling is used to eliminate a transmitted signal at a particular station. Nulling is achieved by using multiple antennas for transmission and adjusting the phase of signals transmitted from each antenna. The phases are adjusted in a way that transmitted signals are added destructively at a particular location.

At a high level, similar to some past work we use two WiFi devices, one for transmitting and another one for receiving. However, our transmitter device nulls its signal at the receiving device. Therefore, the receiving device does not hear the transmitter signal, eliminating the interference. On the other hand, the tag receives, modulates and reflects the transmitter's signal. The receiving WiFi device can easily decode the tag's signal even when the tag is far away since there is no interference. It is worth mentioning that nulling is widely supported by many WiFi devices including almost all modern WiFi access points [12]. Therefore, our proposed idea can be easily implemented on today's WiFi devices.

In this paper, we make the following contributions:

- We solve the self-interference problem in WiFi backscatter systems by using the nulling capability of WiFi devices.
- We show that our approach can significantly improve the range of WiFi backscatter communication.
- We empirically evaluate the effectiveness of our approach using existing WiFi devices. Our experiments show that our approach improves the range of WiFi backscatter to the same range as RFID. Furthermore, our approach enables WiFi backscatter to work in NLOS scenarios in which past WiFi backscatter systems do not work.

[2]High precision 20 MHz oscillators consume more than 1 mW which is orders of magnitude higher than the power consumption of the reset of their circuit. Therefore they opt for ring oscillators which only work when the temperature does not change (even a few degrees) [3].

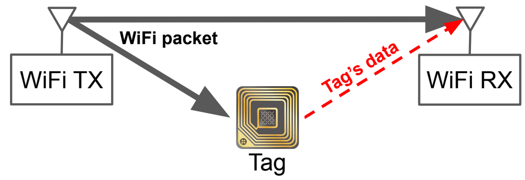


Figure 1: Architecture of WiFi backscatter systems

2 BACKGROUND AND RELATED WORK

In this section, we review existing WiFi backscatter systems and past work on solving the self-interference issue. Figure 1 shows the general architecture of WiFi backscatter systems. This architecture consists of a WiFi transmitter that sends WiFi packets that act as query signals. A backscatter tag receives the query signal and modulates its data by backscattering this signal. Finally, a WiFi receiver receives the combination of query signal and backscatter signal, and tries to extract the tag's data from it. We can generally classify existing WiFi backscatter systems into two categories: *in-channel* and *out-of-channel* WiFi backscatter systems.

In in-channel WiFi backscatter systems such as *WiFi backscatter* [13] and WiTAG [3, 4], the query signal and the backscatter signal are in the same WiFi channel. These systems have very limited range since the backscatter signal is orders of magnitude weaker than the query signal, creating self interference. In particular, in these systems, tags need to be relatively close to a WiFi device in order for their signal to be decodable. For example, in WiTAG, the tag should be within one meter from a WiFi device in non-line-of-sight scenarios. Similarly, the range of *WiFi backscatter* [13] is less than one meter in almost all scenarios.

To solve the range problem, *out-of-channel WiFi backscatter* systems (such as SyncScatter [9], HitchHike [16], FreeRider [17], and MOXcatter [19]) have been proposed. These systems shift a tag's signal to another channel to avoid the self-interference problem. In the absence of a strong query signal, a tag can achieve a longer range compared to in-channel systems [8]. However, this comes at a cost since the tag needs to shift the signal to another channel. First, since backscatter tags are incapable of performing WiFi carrier sensing, these systems create interference for other WiFi traffic on the second channel and vice versa. Second, these systems require a 20 MHz clock to shift the signal which significantly increases their power consumption. Last, these systems require modification to existing WiFi devices. In contrast to existing WiFi backscatter systems, our work shows how we can significantly improve WiFi backscatter range without hardware modification to existing WiFi devices and without using a second channel.

Finally, the most directly related studies to our work are Wi-Vi [5] and LiveTag [11]. These studies focus on using WiFi for sensing applications such as human tracking and human-object interaction. Wi-Vi uses WiFi beamforming and nulling to remove the reflection from static objects when tracking humans behind a wall. LiveTag designs tags for human-object interaction. This system uses beam nulling to reduce the strength of signal in line-of-sight path in order to monitor the signal coming from non-line-of-sight paths. LiveTag achieves less than 1 m operating range. In contrast, our work focuses on improving the range of WiFi backscatter for communication purposes. We show how by completely nulling the WiFi signal at the receiver, we can enable a WiFi backscatter system which works even in non-line-of-sight scenarios.

3 SELF-INTERFERENCE PROBLEM

Since the query signal is orders of magnitude stronger than a tag's reflected signal, the query signal acts as an interference for the tag's signal. These results in a very low SINR (Signal to Noise and Interference). In fact, as the distance of the tag from WiFi devices increases, the SINR will become too low to successfully decode the tag's data. This problem which is known as self-interference is the main reason that WiFi backscatter systems have very limited range. To solve this problem, past WiFi backscatter work proposes to build a tag which shifts its reflection to another channel. Although this approach solves the self-interference issue, it has created other issues which make them incompatible to existing WiFi networks, as explained in Section 2.

To solve the self-interference problem without shifting the signal to another channel, our approach is to use *nulling*. In the following section, we explain how nulling solves the self-interference problem, significantly improving the range of WiFi backscatter systems.

4 NULLING TO THE RESCUE

To solve the self-interference problem in WiFi backscatter, and significantly improve their range, we propose to use nulling. In particular, we use the same architecture as shown in Figure 1, except that the AP sends a packet while nulling its signal at the client. Therefore, the client does not hear the AP's signal directly anymore. On the other hand, the tag is still receiving the AP's signal and can reflect it to the client.

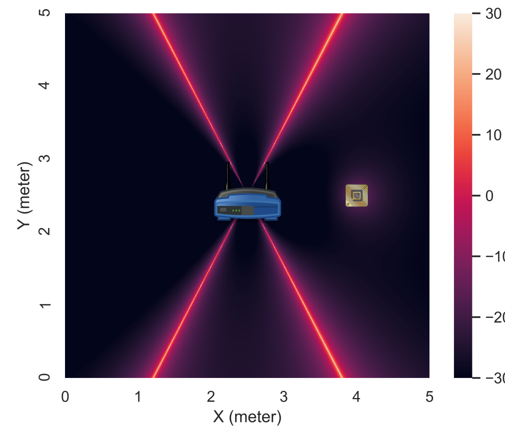


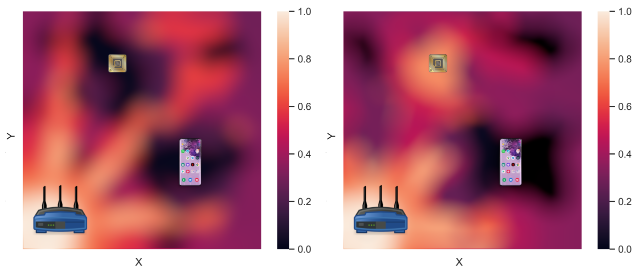
Figure 2: Increasing the SINR (i.e., log scale) of the tag's signal using nulling. In this setup, the AP has two antennas which are spaced by one wavelength. Both antennas transmit the same signal but with some phase difference.

Note, since the client is only receiving the tag's signal, the SINR will be much higher compared to past WiFi backscatter systems, resulting in a much longer range.

To better understand the impact of this approach on eliminating the interference and improving the SINR of the backscatter signal, we designed a simulator. In our simulation, we consider a backscatter tag, a client and an AP with two antennas. The AP transmits a signal while performing nulling at a client (i.e. the antennas transmit the same signal but with different pre-coding values). For simplicity, we assume a free space scenario without multi-path propagation. We then compute the strength of AP's signal and tag's reflection in different locations. Figure 2 plots the SINR of tag's reflection for different locations. In most locations, the SINR is significantly below zero, meaning that the query signal (interference) is much stronger than the tag's signal. Therefore, it is impossible to detect the tag's signal in those locations. Interestingly, in the area around the tag, the SINR is close to zero. In fact, this is exactly why today's WiFi backscatter systems work only when the tag is very close to the client device. Finally, there are four directions that the SINR is significantly above zero. These are directions that the AP is nulling. Note, there are four directions (instead of multiple spots) since we assume a free space scenario where the antennas are omni-directional and one wavelength spaced. This result implies that if the AP nulls its signal at the client location, the client can easily receive and decode the tag's signal even when the tag is far.

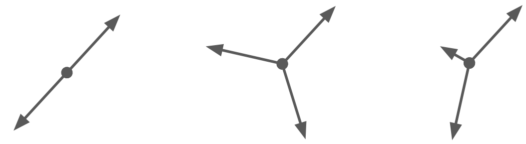
5 WHAT IF THE SIGNAL IS NULLED FOR THE TAG TOO?

So far, we explained how nulling can be used to significantly improve the SINR of backscatter tags and hence increasing their operation range. However, since the location of the tag



(a) Configuration 1 (b) Configuration 2

Figure 3: If the signal is nulled at the tag too, the access point can try another configuration for nulling the signal at the WiFi device.



(a) (b) (c)

Figure 4: The effect of number of antennas on nulling.

is random with respect to the AP and client, there is a chance that the tag is also placed in a location where the signal is nulled. Figure 3(a) shows an artistic illustration of this scenario. Darker colors represent lower received signal power at a given location. In this scenario, the AP tries to null the signal at the client, however, the tag is also coincidentally placed in a null location. Hence, the tag does not hear nor reflect the AP's signal. Although it is very unlikely this scenario happens, when it happens the tag can not communicate anymore.

To solve this problem, and make sure that the tag can work in all locations, we propose to perform nulling using different pre-coding values. As explained in Section 4, WiFi APs pre-code their transmissions such that the signal received at a particular destination is cancelled. Therefore, if the AP's signal is nulled at both client and the tag, we use different pre-coding values such that the signal is nulled only at the client side. However, the issue is that if the AP has only two antennas, the received signals at the destination must have the same amplitude but 180 degree phase differences to cancel each other, as shown in Figure 4(a). Therefore, if the two signals cancel each other in both the client's and tag's location, using a different pre-coding will not help remove the nulling from the tag. To solve this issue, our idea is to use an AP with three antennas to null the signal. As as shown in Figure 4(b and c), when we use three antennas, there are multiple different solutions to send signals that they cancel each other at the destination, For example, in Figure 4(b), the three signals cancel out each other while having the same amplitude with 120 degree phase differences. In Figure 4(c), the three received signals cancel out each other while having different amplitudes. The ability to have different solutions to perform nulling, enables the AP to perform nulling at the client location while the tag's location is not nulled. Figure 3(b) shows an example in which a different transmission configuration changes the location of nulls. In particular, by just changing the pre-coding values, the AP can still null at the client while making sure the tag is not in a null location. Our system uses this approach and tries different pre-coding values until the signal is not nulled at the tag while it is nulled at the client. This idea can be implemented by cycling through these pre-coding values and monitoring for the tag's signal. If the tag is not detected for a while, the transmitter can switch to another configuration.

6 EVALUATION

In this section, we empirically evaluate the effectiveness of our technique in improving the range of WiFi backscatter systems.

6.1 Testbed

We use a USB WiFi card with RTL8812AU chipset [1] as the AP to transmit WiFi packets. This card is connected to a laptop that runs Ubuntu 20.04. We use an ESP32 [10] WiFi module as the receiver. Both the AP and client are off-the-shelf devices and we don't make any hardware modifications to them. We connect the AP to two antennas where they transmit the same signal but with different phases. This enables the AP to perform nulling at the client. For the tag, we use a typical WiFi antenna connected to an HMC536 RF switch [6] which is controlled by a Microcontroller. The tag continuously switches between reflective and non-reflective modes. We run our experiments in a typical home environment in both line-of-sight and non-line-of-sight scenarios.

6.2 Backscatter signal strength

Line-of-sight scenario: In this experiment, we place both the AP (TX) and the client (RX) in the same room, as shown in Figure 5. The AP transmits WiFi packets while its signal is nulled at the client. We also place the tag in the same room while it is switching between reflective and non-reflective modes. We measure the SNR of the tag's signal at the client side using Channel State Information (CSI) reported by the ESP32 module. We place the tag at 20 locations as marked on the figure. In every location we run an experiment for 60 seconds. The reported values (inside the circles) are the average SNR over the duration of the experiment.

The figure shows that the SNR of the tag's signal at the receiver side is more than 7 dB for almost all locations. Note, for a WiFi backscatter system which uses On-Off Keying (OOK) modulation, SNR of 7dB results in the Bit Error Rate(BER)

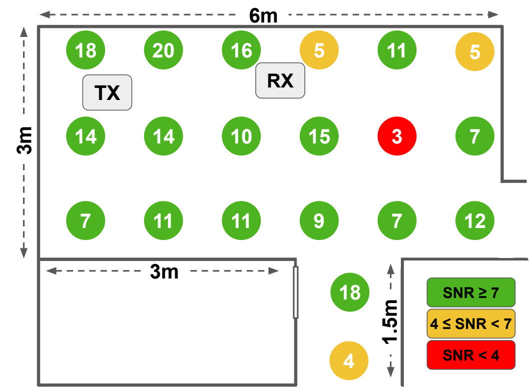


Figure 5: Line of sight SNR measurement for different tag's location. Each circle shows the SNR of the tag's signal at the receiver (RX) side for that location.

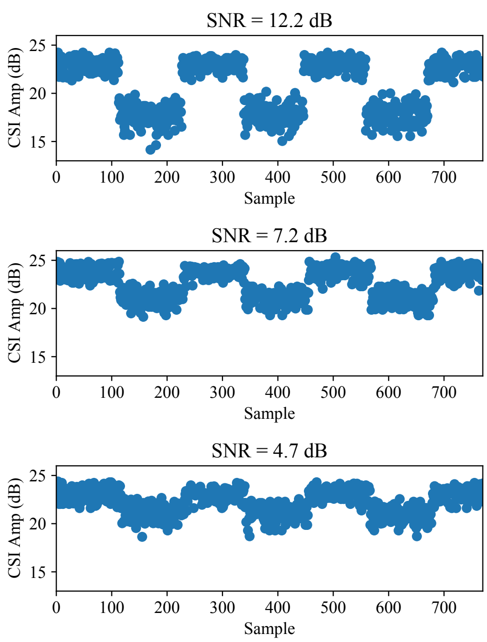
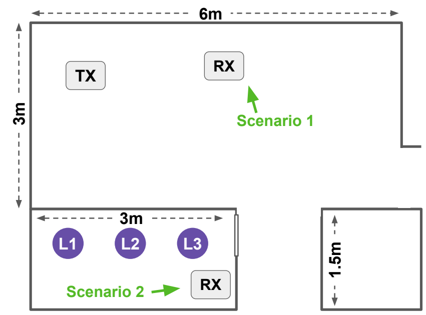
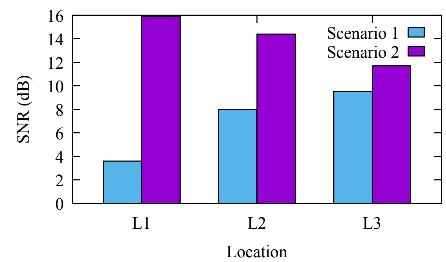


Figure 6: CSI measured at the receiver side for different SNRs. The tag switches between reflecting and not reflecting states about every 100 samples.

of 10^{-3}. Figure 6 shows sample raw CSI measurements for SNRs of 4.7, 7.2, and 12.2 dB. This plot shows how the CSI amplitude changes at the client device over time as the tag changes its state from reflective to non reflective. As can be seen in the figure at lower SNRs such as 4.7 dB the tag's effect is still visible but it will cause a higher bit error rate for communication. When the SNR is more than 7 dB, the distinction between the two states becomes very clear. These results are a significant improvement since past WiFi backscatter systems which do not require any hardware modifications can only achieve this performance when the tag is placed between the two devices or very close to one of the WiFi devices.



(a) NLOS Setup



(b) NLOS Measurements

Figure 7: NLOS experiment setup and results. In scenario 1, neither TX nor RX has LOS path to the tag. In scenario 2, TX has no LOS path while RX has LOS path to the tag.

Non-line-of-sight scenario 1: In this experiment, we place both the AP (TX) and the client (RX) in one room and the tag in another room, as shown in Figure 7(a). Note, none of the existing WiFi backscatter systems work in this scenario since the signal of tag will be significantly attenuated by the wall. Similar to the previous experiment, the tag is switching between reflective and non-reflective modes, and we measure the tag's signal power at the client side using CSI changes reported by the client device. Figure 7(b) shows the result of this experiment. These results show that in non-line-of-sight scenarios where there is a wall between the tag and WiFi devices, we can still achieve good SNR.

Non-line-of-sight scenario 2: In this experiment, we place the AP (TX) in one room, and the client (RX) and the tag in another room, as shown in Figure 7(a). Figure 7(b) shows the results of this experiment. The figure shows that in non-line-of sight scenarios where there is a wall between a tag and the transmitter device, we can still achieve an SNR of more than 10 dB.

6.3 Range

Finally, we evaluate how much our nulling approach improves the range of WiFi backscatter systems (i.e., the distance to nearest WiFi device). To do so, we evaluate the range of the first in-channel WiFi backscatter system (WB) with and without our approach. We then compare these ranges with that

Category	RFID	Out of channel	In channel		
System		SyncScatter	WiTAG	WB	WB (with our approach)
Scenario 1 (NLOS to both TX and RX)	2-3 m	N/C	N/C	N/C	3 m
Scenario 2 (NLOS to one device)	N/A	8 m	1m	N/C	3 m
Scenario 3 (LOS to both TX and RX)	2-10 m	13 m	4 m	1 m	5 m

Table 1: The range of different backscatter systems in different scenarios. N/A is not applicable, and N/C is not capable.

of the state-of-the-art WiFi backscatter systems. For state-of-the-art WiFi backscatter systems, we consider SyncScatter [9] and WiTAG [3] which have reported the best range for out-of-channel and in-channel backscatter systems, respectively. We compare these systems in three different scenarios: (1) there is no LOS between tag and any WiFi device. (2) there is no LOS between the WiFi devices, but the tag has LOS with one WiFi device. (3) there is LOS between the tag and WiFi devices. Note, the first scenario is the most challenging one since the tag's query signal as well as its reflection must go through a wall.

Table 1 shows the results of this comparison. The figure also presents the range performance for typical RFID systems. We make the following observations:

- Our approach significantly improves the range of the first WiFi backscatter system (denoted as WB) [13]. In particular, we can achieve 5 m and 3 m in LOS and NLOS, respectively, while the first WiFi backscatter system range was 1 m in LOS and not able to communicate in NLOS scenarios. We believe the similar gain can be achieved if one combines our nulling technique with state-of-the-art WiFi backscatter systems.
- Out-of-channel WiFi backscatter systems (such as SyncScatter) achieve better range than on-channel backscatter systems (such as WiTAG). This is expected since they solve the interference problem by moving the backscatter signal to another channel. However, as mentioned in 2, unfortunately, out-of-channel systems create other problems (such as interference to other users, requiring power hungry high frequency oscillators). Hence these systems are not ideal for IoT applications.
- None of existing WiFi backscatter systems work in a scenario where the tag has no LOS to any WiFi device (i.e. scenario 1). In contrast, with our approach WiFi backscatter achieves a 3 m range in this scenario.
- RFID range is 2-10 m in LOS and 2-3 m in NLOS scenarios [15]. However, RFID systems use directional antennas which improves their range but at the cost of limiting the field of view of these systems.

7 DISCUSSION

In this paper, we have shown how we can significantly improve the range of WiFi backscatter systems by using nulling capability available in modern WiFi devices. However, in order to enable a full communication system the following topics require further study:

Real-time Nulling. Our approach requires the AP to null at the client. In this paper, we evaluated the effectiveness of our approach when the location of the AP and Client is fixed (i.e once the AP nulls at the client, the nulling will not change). However, in reality these devices may move and therefore the AP needs to null at the client in real-time. We believe this would be possible since modern WiFi devices already use nulling to achieve multi-user MIMO (MU-MIMO), even in dynamic environments. However, implementing this requires further study and may require modification to the firmware.

Modulation and Coding. The focus of this paper is to show how nulling can solve the self-interference problem in WiFi backscatter systems. We believe that our approach can be combined with most existing WiFi backscatter systems to improve their range. Although our evaluation supports this belief, since different WiFi backscatter systems use different modulation and coding techniques, implementing an end-to-end system where nulling is combined with these systems requires further research.

Failure Detection. In this paper, we show that if the query signal is nulled at both the client's and the tag's location, the communication will fail. However, the AP can resolve this by using different pre-coding values. Designing an approach which can automatically detect this failure and change the pre-coding values requires further research.

8 CONCLUSIONS

WiFi backscatter is a new communication technology which enables battery-free sensors to transmit their data to a WiFi device. Although this technology is very attractive for IoT applications, unfortunately, existing WiFi backscatter systems work robustly only over a short range. Specifically, their tags require to be placed between two WiFi devices in line-of-sight scenarios, or very close to a WiFi device in non-line-of-sight scenarios. In this paper, we propose a new approach which uses the nulling capability of modern WiFi devices to significantly improve the range of WiFi backscatter communication. Our results show that our approach enables robust communication between a tag and WiFi devices even when line-of-sight paths between them are blocked with a wall.

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