MAP-FI: An Ultra-low Power Multiple Access IoT System Based on Commodity Wi-Fi

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Abstract

We present MAP-FI, an ultra-low power multiple access backscatter system that can be deployed by little modified commodity Wi-Fi devices. With MAP-FI, several ultra-low power tag can transmit simultaneously piggybacking on combined 802.11g OFDM signal and continuous wave all synthesized by modified commodity Wi-Fi devices. The backscattered signals can then be decoded as a standard 802.11g packet by commodity Wi-Fi receiver without any change. MAP-FI's key invention is how to implement OFDMA to backscatter system, which can augment the capacity of the system. In turn, this invention can improve the future explosive growing IoT gadgets. The standard 802.11g packet allows the widespread deployment of low-power backscatter system using widely available Wi-Fi devices. The theoretical uplink rate from tags is 250 kbps, which is enough for the sensor network.

1 Introduction

Embedded and connected gadgets - colloquially referred to as the Internet-of-things (IoT) - are increasingly making it possible to continuously monitor our bodies, personal lives and surroundings to improve health, energy usage, security and so on. These gadgets (e.g. wearable, fitness/health trackers, security cameras/microphones, thermostats) integrate with cheaply available sensing technology to continuously measure physical variables such as temperature, heart rate, ambient sounds, etc. and upload them via wireless links to the cloud or to mobile devices. Analytics applications then analyze such data to implement useful functionality such as fitness monitoring, intruder detection, regulating HVAC, etc. The future is likely to bring many more such devices helping us instrument more parts of our lives and surroundings, and enable us to measure and analyze almost every aspect of our lives. We will refer to these IoT gadgets as either IoT sensors, or tags, or simply sensors in the remaining of our paper depending on the context. To widely realize the IoT vision, we believe that the wireless connectivity on these devices needs to satisfy three key requirements:

- **R1: Sufficient throughput and range:** A typical such gadget produces anywhere between a few Kbps (e.g. temperature sensors measuring every 100 ms) to a few Mbps (e.g., security microphones/cameras recording audio/video), and can be placed anywhere in the home or on the body. So the wireless link from the gadget to the wired gateway connected to the Internet or terminals which needs the should provide at least a few Mbps of uplink throughput and a range of dozens of meters.
- **R2: Very low power design:** These gadgets need to be able to operate for a long time without requiring battery replacements, or ideally without batteries at all. Recent work has demonstrated the possibility of powering these devices primarily using power harvesting from ambient RF sources such as TV and cellular signals which can harvest up to 100 microwatts[11, 8, 7], or even by Wi-Fi router[9]. Hence, ideally the gadgets radio should provide the necessary throughput and range using a few tens of microwatts of power to be operable without batteries. If feasible this would eliminate the need for dedicated powering infrastructure such as RFID readers.
- **R3: High capacity of sensors:** The number of IoT sensors and wearable devices will increase rapidly in the future. Meanwhile, the frequency band resource of ISM is really limited. Furthermore, considering the fact that the system shouldn't interfere the existing ISM transmissions such as Wi-Fi, BLE and ZigBee etc., it may needs a few tens of the gadgets to communicate at the same time. Therefore, high capacity of sensors in limited band resource is

one of the key requirements.

- **R4: Commodity based design:** The most infrastructure-assisted backscattered systems need special devices working in full-duplex mode or sending special signal such as continuous wave(CW). These devices are not commodity based devices which makes the system with more cost and difficult to expand to social application. Therefore, ideal design should be based on commodity devices or can be implemented with the hardware of commodity devices.

To the best of our knowledge, no current systems satisfies all three requirements, especially **R3**. Recent work on passive frequency-shifted backscatter [4, 14, 12]is the closest, but it does not satisfy **R3**, it only provides packet mode multiple access methods, which is insufficient for future more tags applications. Other work on backscatter[2, 5] satisfy **R1, R2**, but not **R3** and **R4**. RFID based systems satisfy **R1**[3, 10, 13] and some of them satisfy **R2**, but not **R1**, **R3** and **R4**. They would require the widespread deployment of dedicated RFID reader infrastructure as well as require their own spectrum band of operation in the unlicensed band. Standard communication radios such as Wi-Fi or Blue-tooth Low Power would satisfy **R1** and **R4**, but clearly cannot satisfy **R2**, they require between 30-50 mW (Bluetooth) to several hundred mW (Wi-Fi) of power to operate.

To satisfy the requirements above, typically **R3**, here are three main challenges:

(a) How to implement multiple access method to Wi-Fi device? The multiple access methods can be divided into two types: 'packet mode method' and 'circuit mode and channelization method'. Wi-Fi use CSMA/CA, a kind of packet mode method to avoid collisions of coexisting Wi-Fi devices. To implement CSMA/CA, the devices need to sense the carrier continuously, which consumes lots of power. Setting the transmitter as the host and the tags as the clients, we can solve the power consuming question by implementing CSMA/CA by transmitter. Then the transmitter send control message to activate the tags activated. The specific network stack design will be introduced in section 4.

Circuit mode and channelization method typically contains TDMA, FDMA, CDMA, SDMA, etc. Since 802.11g and more advance technology use OFDM to transmit signal, we intuitively tend to implement OFDMA to multiple access system by setting the tags to OFDM subcarriers.

(b) How to fulfil synchronization among transmitter, tags and receiver? The most critical problem OFDM system has is synchronization. In our system, the receiver and the transmitter are first synchronized by preamble, then the tags is synchronized to the transmitter by downlink synchronization signal. Furthermore, in indoor scenario, considering that the propagation delay is quite low compare to 0.8 μs cyclic prefix(CP), the spatial distribution of tags won't affect the synchronize proceeding.

(c) How does MAP-FI share the Wi-Fi network? Traditional Wi-Fi shares the network using carrier sense. However, this requires a Wi-Fi receiver that is ON before every transmission. Since Wi-Fi receivers require power-consuming RF components such as ADCs and frequency synthesizers, this would eliminate the power savings from our design. Instead, we delegate the power consuming task of carrier sense to the plugged-in device. At a high level, the plugged-in device performs carrier sense and signals the passive Wi-Fi device to transmit. 3 describes how such a signaling mechanism can also be used to arbitrate the channel between multiple passive Wi-Fi devices and address other link-layer issues including ACKs and retransmissions.

Our system is illustrated in fig.1. It contains a transmitter, several tags and a commodity receiver such as laptop or smartphone. The theoretical uplink rate for each tag is 250 kbps. The theoretical downlink rate is also 250 kbps.

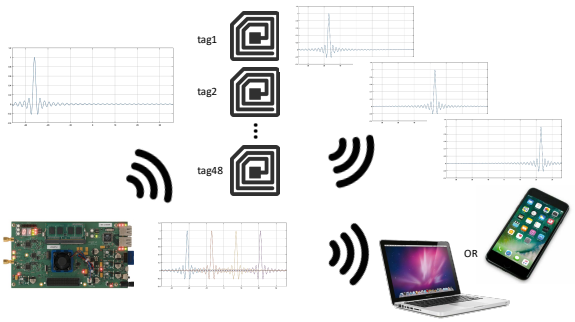


Figure 1: The architecture of the 802.11g transmitter FPGA core

To show the feasibility of our design, we build prototype backscatter hardware and implement the system in different scenario. gonna replenished after evaluation

Contributions. We make the following contributions:

- We demonstrate for the first time an Orthogonal Frequency Division Multiple Access backscatter system based on 802.11g. We present backscatter techniques that synthesize 20MHz OFDM transmissions that can be decoded on existing Wi-Fi devices.

- We designed the system with only a few changes on the firmware design of commercial Wi-Fi router for the transmitter and no changes on the receiver. Meanwhile, we combine several techniques such as

single-sideband(SSB), bi-direction communication, frequency shifting to our system.

- We design a network stack for the multiple access Wi-Fi system in other to guarantee the coexistence with other Wi-Fi devices and other devices using ISM transmission.

- We build a hardware prototype on an FPGA platform and evaluate it in several scenarios. IC design?

2 802.11g Primer

MAP-FI backscatters 802.11g packets from commodity Wi-Fi with little modification. Here we give a brief description of the 802.11g PHY encoding and decoding procedure. The block diagram for the 802.11g OFDM PHY is shown in fig.2. Following will introduce the main encoding part of the PHY. The decoding part is just in the opposite way. maybe introduce the receiving procedure is better?

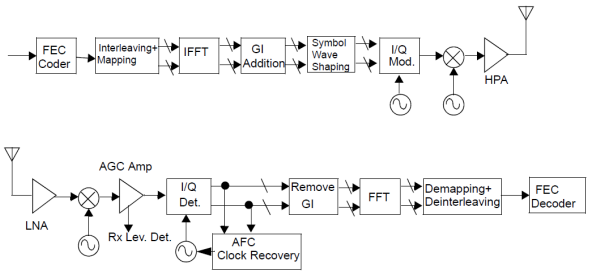


Figure 2: Transmitter and receiver block diagram for the OFDM PHY

Scrambler. 802.11g data scrambling is performed by XORing the incoming data bits with the output of a 7-bit linear feedback shift register using the same polynomial shown in Fig.3. Given the scrambling seed, the output sequence of the circuit is deterministic. According to the Wi-Fi standard, the scrambling seed is set to a pseudo-random non-zero value. In principle, this information should be available on the Wi-Fi hardware. A number of commercial Wi-Fi chipsets use a predictable sequence of scrambling seeds. Further, certain Atheros chipsets also allow us to set the scrambling seed to a fixed value in the driver. Using this, we reverse the effect of the scrambler.

Convolutional Encoder. 802.11g uses convolutional encoding on the scrambled bits to be resilient to noise and interference. It uses a 1/2 rate convolutional encoder where two coded bits are output for each incoming scrambled bit. The higher 2/3 and 3/4 coding rates are obtained by dropping some of the 1/2 rate encoded

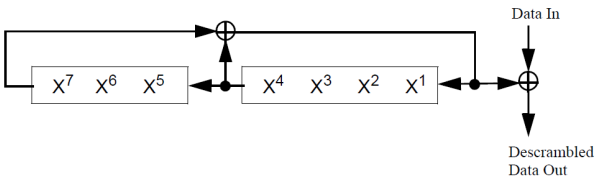


Figure 3: Data scrambler

bits. Specifically, given the scrambled bits, $b[k]$, the two encoded bits are,

$$C1[k] = b[k] \oplus b[k-2] \oplus b[k-3] \oplus b[k-5] \oplus b[k-6]$$
$$C2[k] = b[k] \oplus b[k-1] \oplus b[k-2] \oplus b[k-3] \oplus b[k-6]$$

Interleaver. The encoded bits are interleaved across different OFDM frequency bins to make adjacent encoded bits more robust to frequency selective channel fading. We note however that when using a sequence of all ones or zeros as our encoded bits, interleaving again results in a sequence of all ones or zeros and does not require us to perform any special operation.

IFFT data mapping. Fig.4 illustrates the correspondence of subcarriers and IFFT input.(The subcarrier ID is the same as those in fig. 5)

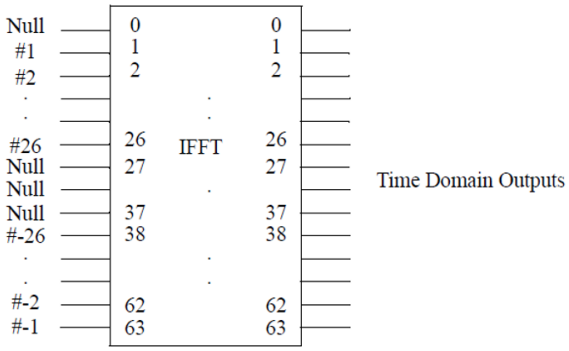


Figure 4: The subcarrier mapping strategy shown by IFFT module

3 System Design

We use backscatter to transform 802.11g transmissions from tags to commercial Wi-Fi devices simultaneously with the help of AP to implement the goal of multiple access. In this section, we first introduce the overall communicating procedure, then discuss the multiple access implementation. In the rest of this section, we illustrate the three main actors of our system: transmitter, tags and receiver.

3.1 Communicating procedure

We illustrate a requesting data procedure, which describe the collaboration among transmitter, tags and receiver and occupying only one channel. Say a MAP-FI receiver wants to get information from tags. Before any of the above transmissions happen, the receiver first sense the medium to ensure that there are no ongoing transmissions in associated channel.

Once the channel is found free, the receiver sends a request packet contains IDs of specific tag from which the receiver willing to achieve information. Then transmitter send PPDU as section 3.3.1 depicts. This signal is sent and decoded using the ultra-low power receiver described in section 3.4.4. The packet starts with an ID unique to each MAP-FI tag(see fig.10). When the tag detects its ID, it will change the shifting frequency Δf_i corresponding to the control state bits assigned. After broadcast starting send frame, the tags modulate there information to the pre-allocated subcarriers and format a 802.11g signal. The receiver decodes the signal as the typical 802.11g signal. Then send ACK packets to transmitter to implement ACK mechanism as section 4.3 describes.

3.2 Multiple access

The method of multiple access can be divided into packet mode methods and circuit mode and channelization methods[6].

3.2.1 Packet mode method

Generally, different transmitters share the transmission medium by following contention based random multiple access methods, such as Aloha, CSMA/CD for wired networks, CSMA/CA for wireless networks. By designing the system under the structure of Wi-Fi, we can easily implement CSMA/CA to our system. This however requires the sensing device is ON before every transmission. Since sensing devices require power consuming RF components like low noise amplifier, frequency synthesizers, mixers and ADCs, this would eliminate the power savings from our design. Instead, we delegate the task of carrier sense to the transmitter or the receiver. The example is contained in section 3.1

3.2.2 Circuit mode and channelization methods

While Wi-Fi follows a suite of standards, we focus on 802.11g for our system because 802.11g use OFDM signal to create transmission which provides subcarriers for us. Therefore, among the common methods: TDMA, FDMA, CDMA and SDMA, we intuitively find that we can implement OFDMA method to our system which following 802.11g standard by mapping the tags signals to those subcarriers.

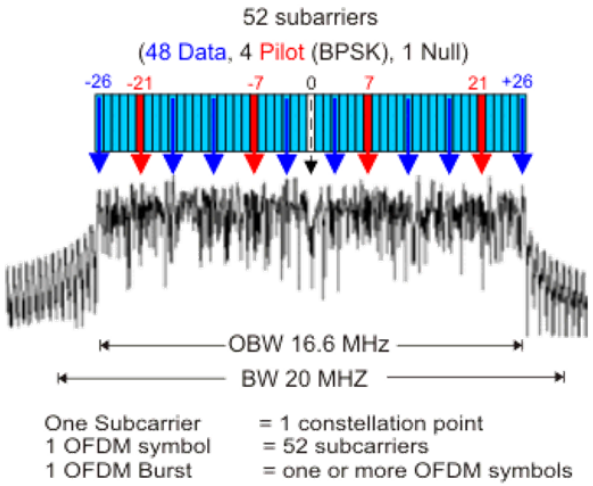


Figure 5: The subcarrier mapping strategy shown by IFFT module

Generally, OFDM system has four imperfections: time offset, carrier frequency offset(CFO), sampling frequency offset(SFC), phase offset. The CFO between the transmitter and receiver is first adjusted by preamble. As to the subcarrier frequency offset, since the shifted frequency is tens of megahertz, the subcarrier frequency offset is relatively small.

3.3 Transmitter

Considering that the frequency shifting method needs CW to achieve subcarrier narrow band signals, furthermore, we want to make the transmitter more commercial, we should better make few changes to the Wi-Fi routers TX logic. Since commercial routers realize hardware logic by FPGA, SoC, etc., we can reach the goal. In our system, we use WARP v3 board and the 802.11 reference design v1.6.2 to build our system. [1]

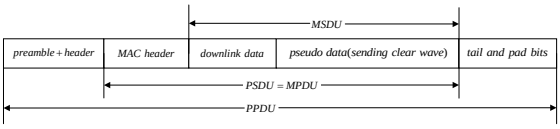


Figure 6: The format for the PPDU

3.3.1 PPDU format

Fig.6 illustrates the format for the PPDU of our system working transmission, including typical OFDM com-

ponents: OFDM PHY preamble, OFDM PHY header, PSDU, tail and pad bits. PSDU includes MAC header and MSDU. The PPDU is transmitted by transmitter. The components will be introduced in following parts.

3.3.2 Preamble

The preamble contains ten short training symbol(STS) and two long training symbol(LTS). The STS is used for signal detect, AGC, diversity selection, coarse frequency offset estimation timing synchronize. The LTS is used for channel and fine frequency estimation. Although we can also generate the preamble following the frequency shifting and modulate strategy and can get a much more accurate channel estimation. Since channel estimation is only used to reduce the deviation of modulated signal. The tolerance of the EVM [should tested by experiment], the use of more accurate estimation to equalize the received signal does not deserve to solve the challenges of 48 tags allocation and implementing the 802.11 MAC protocol. Therefore, we choose to transmit preamble at the transmitter.

3.3.3 PHY and MAC header

PHY header and MAC header are also sent by transmitter and set the demodulation mode, transmitting rate and MAC frame control of the receiver. In our system, to pledge the magnitude, phase offsets tolerance of receiving signal, we set PHY parameter as (BPSK, 1/2). The MAC frame is configured as data frame to let the tags can piggyback the information to the MSDU frame body.

3.3.4 Downlink synthesis

Tags receive the information by envelope detector, introduced in section 3.4.4. The architecture of the 802.11g transmitter FPGA core is illustrated in Fig. 7. The most important component is the IFFT which let the implementation of OFDM easier.

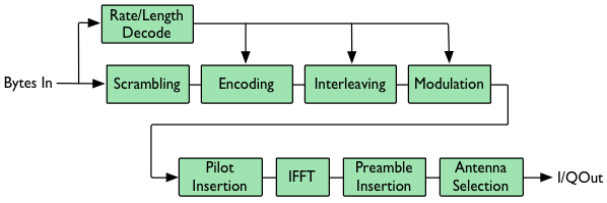


Figure 7: The architecture of the 802.11g transmitter FPGA core

Before IFFT the signals are serial complex signal which will mapping to different subcarrier to achieve the parallel input of IFFT model. 802.11g OFDM transmission uses subcarrier[-26:-22 -20:-8 -6:-1 1:6 8:20 22:26] as data subcarrier, use [-21 -7 7 21] as pilot subcarrier. 802.11n use [-28:-22 -20:-8 -6:-1 1:6 8:20 22:28] as data subcarrier, also use [-21 -7 7 21] as pilot subcarrier. nesseceray? how to express? To send all 802.11g or 802.11n or more advanced OFDM transmision, the routers often use different mapping strategy, mapping data to data subcarrier.

Iyer et al, provides a strategy to transform the payload of 802.11g packets into AM modulated signals. However, this strategy introduce the problems of false peaks by the constant OFDM symbols and glitch by the cyclic prefix. We avoid those problems by modifying the mapping logic to achieve AM modulated signals.

3.3.5 Continuous wave(single tone RF) synthesis

In order to emit single tone RF carrier with the Wi-Fi router, we regulate the transmitting digital logic of 802.11g transmission. As former part described, if we modify the mapping rule to map all the data subcarrier to zero and a value to one subcarrier. Especially, we map to the very border subcarrier -31. After that the result of the IFFT will be time domain single tone. As section 3.3.2 shown, the reflected signal has $\frac{pi}{2}$ phase shift relative to CW. In order to ensure the phase of reflected signal equal to the pre-set phase, the complex value should be set to $model \times (-i)$.

3.3.6 Pilot subcarrier

The pilot signals is used to apply signal synchronization and is an indispensable part of OFDM signal. Adding tags to generate pilot signal will bring in cooperation problem among 4 tags and the transmitter and introduces more cost. Therefore, we choose to send pilot signal at the transmitter successively after sending synchronization and control signal and when generating continuous wave. To reduce the interference of the frequency shifting of pilot signal, we set the value of pilot subcarrier to 1 and the model of border subcarrier to 100 to guarantee the SNR to 20dB.

3.3.7 Working as AP

Our system is working in 'infrastructure mode' which has several benefits: more accessible to the AP, more compatible for more devices and coexisting of other ISM equipment. To let smart phones or other devices get the tags information, the transmitter is working as AP.

3.4 Tag

We combined several techniques to guarantee the tags to consuming ultra-low power, occupying low frequency

band, and be able to communicate with transmitter and receiver in bi-direction.

3.4.1 Ultra low power consumption

To make the tags consume ultra-low power, we need to following

Remove high frequency carrier RF components. RF components include digital to analog converter and RF transceiver ICs, all are high power-consuming. The RF components typically needs several hundred milliwatts. To move the RF components, we choose to modulate the ambient CW at frequency f_{CW} with on-off keying modulation at frequency Δf. Considering the signal is square wave during one OFDM signal, the modulated signal is

$$r(t) = \sigma sin(f_{CW}t)Square(\Delta ft) \tag{1}$$

where Δ is the RCS of the device. From Fourier analysis, the square wave can be written as,

$$Square(\Delta ft) = \frac{4}{\pi}\sum_{n=1,3,5,...}^{\infty}\frac{1}{n}sin(2\pi n\Delta ft) \tag{2}$$

$$\begin{aligned} r(t) = \sigma\frac{2}{\pi}\sum_{n=1,3,5,...}^{\infty}\frac{1}{n}[cos(2\pi(f_{CW}-n\Delta ft)) \\ -\cos(2\pi(f_{CW}+n\Delta ft))] \end{aligned} \tag{3}$$

Low power-consuming clock. Conventional clock source such as crystal oscillator, XTAL consumes several milliwatts, however the ring oscillator consumes only tens of microwatts.

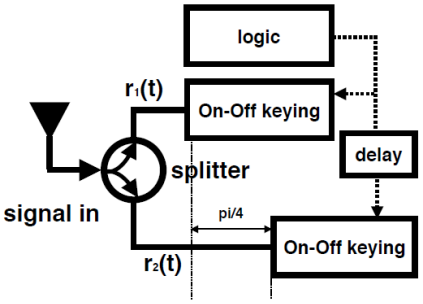
Furthermore, ring oscillator has high flexibility of the frequency, easy to achieve high frequency clock since the frequency is determined by the NOT gate delay and RC.

3.4.2 Low frequency band occupation

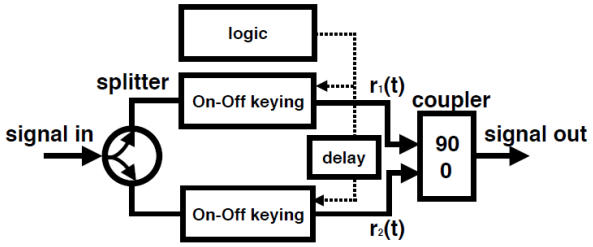
2.4GHz ISM frequency band only has 3 non-overlapping 802.11g channels, meanwhile, the transmitting range of 5GHz is limited. Therefore, reducing the frequency band occupation is essential. Besides the in band CW transmitted by transmitter, the mirror copy of the shifted CW should be removed. The problem can be solved by single side band modulation.

Single Side Band. To eliminate the mirror side band, we apply a phase shifting method, which is shown in fig.8. The second path has a $\frac{\pi}{4}$ phase delay in one direction, equivalent to $\frac{\pi}{2}$ phase shift in total. Therefore the second path signal,

$$\begin{aligned} r_2(t) = \sigma\frac{2}{\pi}\sum_{n=1,3,5,...}^{\infty}\frac{1}{n}[cos(2\pi(f_{CW}-n\Delta ft)+\frac{n\pi}{2}) \\ -\cos(2\pi(f_{CW}+n\Delta ft)-\frac{n\pi}{2})] \end{aligned} \tag{4}$$



(a) Single side-band backscatter with a single antenna



(b) Equivalent conceptual design

Figure 8: Subfigure(a) presents the backscatter design with an antenna for single side-band design. Subfigure(b) shows the equivalent design via unfolding the backscatter design for ease of analysis.

The reflected signal is

$$\begin{aligned} r(t) &= r_1(t) + r_2(t)\angle\frac{\pi}{2} \\ &= \sigma\frac{4}{\pi}\sum_{n=1,3,5,...}^{\infty}\frac{1}{n}[-cos(2\pi(f_{CW}+n\Delta ft)) \end{aligned} \tag{5}$$

3.4.3 Flexibility of changing subcarrier

With fixed frequency shifting the tags should be allocated into 48 groups for 48 data subcarriers, meantime the needs to set tag to several subcarriers to make the system to be a cognitive radio.

3.4.4 Downlink design

Despite the uplink transmission decoded by receiver, the downlink transmission is also critical to our system to carry out the control and synchronization. Thus, we utilize a specially designed RF energy detector based on peak detection to decode information from the Wi-Fi Backscatter reader. As shown in Fig.9, our receiver circuit has four main components: an envelope detector, a peak finder, a set-threshold circuit and a comparator. The role of the envelope detector circuit is to remove the carrier frequency (2.4 GHz) of the Wi-Fi transmissions.

This is a standard circuit design similar to that used in RFID systems. We however tune the circuit elements to be optimal over the whole 2.4 GHz Wi-Fi frequency ranges.

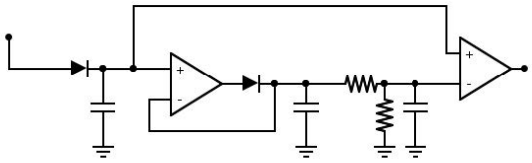


Figure 9: Receiver circuit at the tag to decode the transmissions

3.5 Receiver

The receiver should achieve the modulated OFDM signal. For our design, the structure of the receiver doesnt́ need to be modified. Therefore, a commodity Wi-Fi receiver can be used in our system. However, the frame check sequence(FCS) comes to a question.

The transmitter organized the PHY and MAC layer structure. A MAP-Fi tag converts an incoming single tone radio and assembled with other components transmitted by the transmitter (which introduced in section 3.3) to a backscattered packet. Since the transmitter does not know the content of the tags, although the backscattered packet is a valid OFDM packet on the physical layer, its FCS could be wrong. Can we receive a packet when its checksum is wrong? The answer depends on the Wi-Fi receiver hardware. On some receivers, such as MacBook Pro, we are able to receive and decode packets with bad checksum as long as we configure these receivers into monitor mode. However, some Wi-Fi receivers do not provide this capability and they drop packets with bad checksum in hardware. For those radios, they cannot be used to decode the backscatter packets generated by a MAP-FI tag. [further: application]

4 Network Stack Design

In this section, we introduce a simple network stack and discuss several impact to make the system operational. We first describe the structure of downlink control frame which transmitted after synchronization preamble. Then, we describe the structure of uplink data frame. Finally, we illustrate the overall communication procedure.

4.1 Downlink frame structure

The downlink frame structure is illustrated in fig.10. Tag ID bits are the tag addresses, which are the destination of the frame. ACK bits is used to implement ACK mechanism. Control state is used to allocate the subcarrier of the tags. The all ones tag ID is the multicast address, which means all tags should follow the control state. All ones control state means allocated tags start transmitting as allocated, all zeros control state means not transmitting. Since there are multicast frame, forward error correction(FEC) is better error correcting code for the downlink frame.

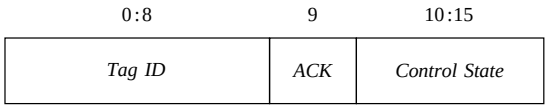


Figure 10: Structure of the downlink frame

4.2 Uplink frame structure

The uplink frame structure is illustrated in fig.11. Tag ID bits are the tag addresses, which are the source of the frame. Length is the data numbers transmitted by tags in bytes.

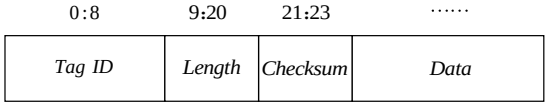


Figure 11: Structure of the uplink frame

4.3 ACKs and retransmissions

The transmitter device listens to the ACKs and conveys this information back to the tags. Specifically, if the ACK is successfully decoded at the transmitter device, it sets the ACK bit in the downlink frame shown in fig. 10 to 1 and sends it to the tags, by piggybacking it during the next period when the sensor is scheduled to transmit. If the ACK is not received at the transmitter before ACK timeout, it immediately performs carrier sense and sends a signaling packet with the ACK bit set to 0. When the tag receives this, it retransmits its sensor value.

5 Evaluation

In this section, we will describe experimental evaluation of our system to understand how our system performs in diverse deployments. Our experiments show the following: [Following part is the tentative content. $\sim$ 5 pages]

5.1 MAP-FI's Performance

5.1.1 Line-of-sight performance

5.1.2 NON-Line-of-sight performance

5.1.3 Impact of WiFi Transmitter Power

5.1.4 Impact of the Value of CW Subcarrier

5.1.5 Impact of Transmitter-Tag Distance

5.2 Tag Power Consumption

5.3 Co-existence with WiFi Networks

5.3.1 How does backscatter impact Wi-Fi?

5.3.2 How does Wi-Fi impact backscatter?

6 Related Work

7 Conclusion

MAP-FI is the first multiple access backscatter communication system that can be augment the capacity of backscatter system...

8 Acknowledgments

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