Implementation of Multi-Access Tag Based on OFDM

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Abstract - Traditional Wi-Fi has been considered power-consuming device thus cannot be used in the field of IOT. We plan to introduce **MAP-Fi**,a low-power, multi-tag system based on orthogonal frequency division multiple access (**OFDMA**) that uses the technology of backscatter to communicate. Ideally speaking, tags are able to transmit backscattered signal while consuming power with magnitude order around μw. The feature of low-power is achieved by separating power hungry RF component and low-power digital components of traditional Wi-Fi transmitter. This semester I built a prototype hardware.
Keywords - Backscatter, Wireless Communication, Multiple Access

1 Background Information

1.1 OFDM

OFDM stands for **Orthogonal Frequency Division Multiplexing**, which is a modulating technique used in Wi-Fi signal transmission. OFDM signal is multi-carrier modulated signal, which means it has multiple subcarriers to transmit the signal. Take Wi-Fi transmission as an example, in each channel of the total three channel of Wi-Fi, there are 52 subcarriers, thus the transmitted signal $x(t)$ can be expressed as follows,

$$x(t) = \sum_{n=-26}^{26} x_k(t) = \sum_{n=-26}^{26} X_k e^{j2\pi(f_c+kf_0)} \tag{1}$$

where X_k is the symbol transmitted on k_{th} subcarrier, $f_c = 2.4GHz$ and $f_0 = 312.5KHz$ in the case of Wi-Fi transmission. Note that $X_0 = 0$ and $x_{-21}(t), x_{-7}(t), x_7(t), x_{21}(t)$ are served as pilot signal used for synchronization and contain no data.

1.2 Backscatter

Unlike traditional Wi-Fi transmitter, instead of generating RF signal directly, tags in our system modulate the radar cross-section of the antenna to change the reflected signal. This is achieved by switching the impedance of the circuits followed by the antenna, when changing such impedance, the reflect coefficient is altered as well. The backscattered signal can be expressed as follows

$$S_{backscatter} = \Gamma \cdot S_{incident} \tag{2}$$

where $\Gamma = (Z_a - Z_c)/(Z_a + Z_c)$, Z_a, Z_c is the impedance of the antenna and the impedance of the circuit followed by the antenna, in most cases, $Z_a = 50\Omega$.
And the power of the backscatter signal can be expressed as follows

$$P_{backscatter} = P_{incident} \cdot \frac{|\Gamma_1^* - \Gamma_2^*|^2}{4} \tag{3}$$

Thus to achieve the maximum backscatter power, we select Γ to be +1 and -1, where the circuit followed by the antenna is in the state of short and open respectively.

1.3 Related Work

Passive Wi-Fi: Bringing Low Power to Wi-Fi Transmission[1] - They demonstrated for the first time that one can generate 802.11b transmissions directly by using a single-tone RF signal to do backscatter communication. In this paper, they built a hardware to serve the function of frequency shift and modulation and used FPGA to process baseband signal. Our basic idea is similar to this paper, however, we use our system in multiple carrier modulation instead of single carrier modulation.
HitchHike: Practical Backscatter Using Commodity WiFi[2] - They came up with an idea to do SSB modulation instead of DSB modulation in the previous paper to in order not to waste spectrum resource. Unlike the previous paper, they generate Wi-Fi packets indirectly by using Wi-Fi signal transmitted by commodity Wi-Fi transmitter to do backscatter transmission. I take the idea of hardware implementation this paper as a reference and did my work.

2 Basic Principle

The process of our system is first to generate a single-tone RF signal in the transmitter side, then shift the frequency to the desired 48 frequencies and modulate data we want to transmit on signals whose frequencies are shifted after that. Therefore, there are two function of tags in our system, **frequency shifting** and **modulating**.
Why do we need frequency shifting and how to do it? - Since the power of single-tone RF signal are usually very large (normally -10 -20 dBm), in order not to corrupt our transmitted signal, we need to shift the frequency to the desired frequencies first. To do this, we use two basic equation, **equation (2)** mentioned in section 1.2 and **trigonometry equation** expressed as follows

$$2sin2\pi ftsin2\pi\Delta ft = cos2\pi(f-\Delta f)t - cos2\pi(f+\Delta f)t \tag{4}$$

Due to some basic knowledge about Fourier series, we can use square wave to approximate sine function

$$Square(\Delta ft) = \frac{4}{\pi}\sum_{n=1,3,5...}^{\infty}\frac{1}{n}sin2\pi n\Delta ft \tag{5}$$

If we replace the reflective coefficient in **equation (2)** with $Square(\Delta ft)$ in **equation (5)**, we can have the frequency shifted, only with some harmonics which can be omitted considering the performance of Wi-Fi receiver in practice.

$$S_{backscatter} = \Gamma \cdot S_{incident} = Square(\Delta ft)\cdot sin2\pi ft$$
$$= \underbrace{\frac{\pi}{4}[cos2\pi(f-\Delta f)t - cos2\pi(f+\Delta f)t]}_{desired} + \underbrace{\frac{\pi}{4}[\sum_{n=3,5...}^{\infty}\frac{1}{n}cos2\pi(f-n\Delta f)t - cos2\pi(f+n\Delta f)t]}_{omitted} \tag{6}$$

The period toggle (Δf) between +1 and -1 of reflective coefficient can be realized by a RF switch which toggle between the state of short circuit and open circuit.
How to Modulate? - We only want to implement the simplest case of digital modulation - **BPSK** in our system. The two phases required in BPSK is 0(data 1) and π(data 0), which means the desired signal is $cos2\pi(f-\Delta f)t - cos2\pi(f+\Delta f)t$ and $-cos2\pi(f-\Delta f)t + cos2\pi(f+\Delta f)t$ respectively. Accordingly, the square waves corresponding to the two different phases are $\frac{4}{\pi}\sum_{n=1,3,5...}^{\infty}\frac{1}{n}sin2\pi n\Delta ft$ and $-\frac{4}{\pi}\sum_{n=1,3,5...}^{\infty}\frac{1}{n}sin2\pi n\Delta ft$ respectively. Thus we need to generate two square waves with the same frequency Δf but different phases(0 and π) and choose which wave we need to transmit data.
How to solve the problem of spectrum waste? - As we can see from the **equation (6)**, suppose the desired frequency we need is $f+\Delta f$, the frequency component $f-\Delta f$ becomes a 'mirror' component and thus waste the resource of spectrum. In order to solve the problem, [2] came up with an alternative. The schematic of their hardware is shown as follows.

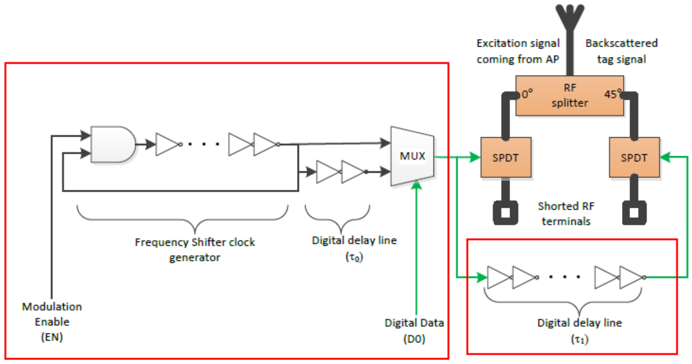

Figure 1: Diagram of SSB Modulation[2]

Where τ_0 is used to create phase π in BPSK modulation and τ_1 is used to change the expression of square wave from $\frac{4}{\pi}\sum_{n=1,3,5...}^{\infty}\frac{1}{n}sin2\pi n\Delta ft$ to $\frac{4}{\pi}\sum_{n=1,3,5...}^{\infty}\frac{1}{n}cos2\pi n\Delta ft$, the change is necessary and will be explained in the following content. The mathematical proof of this approach is given below, note that the incoming signal is expressed as $\sqrt{2}Asin2\pi f_c t$ and $r_1(t) = r_2(t) = Asin2\pi f_c t$ are the output signals of the RF splitter since RF splitter is a power divider.

$$r_1(t)\angle 45^\circ = Asin(2\pi f_c t + \frac{\pi}{4}), r_2(t) = Asin2\pi f_c t$$

$$r_{1backscatter}(t) = r_1(t)\angle 45^\circ \cdot \frac{4}{\pi}\sum_{n=1,3,5...}^{\infty}\frac{1}{n}sin2\pi n\Delta ft \approx -\frac{2A}{\pi}cos[2\pi(f_c+\Delta f)t+\frac{\pi}{4}] + \frac{2A}{\pi}cos[2\pi(f_c-\Delta f)t+\frac{\pi}{4}]$$

$$r_{2backscatter}(t) = r_2(t) \cdot \frac{4}{\pi}\sum_{n=1,3,5...}^{\infty}\frac{1}{n}cos2\pi n\Delta ft \approx \frac{2A}{\pi}sin[2\pi(f_c+\Delta f)t] + \frac{2A}{\pi}sin[2\pi(f_c-\Delta f)t]$$

$$S_{backscatter}(t) = r_{1backscatter}(t)\angle 45^\circ + r_{2backscatter}(t) = \frac{4A}{\pi}sin2\pi(f_c+\Delta f)t$$

As you can see from the final result, there only exists frequency component $f_c + \Delta f$ and the 'mirror' component is eliminated.

3 Hardware Implementation

According to the diagram, the devices we need to build the hardware of the tag are: one RF splitter/combiner, two RF phase shifter(one create 45° and the other create 0°, considering the insertion loss caused by the device, I chose two of such device to make sure the amplitude of output of the two phase shifter are approximately the same), two SPDT/SPST switch and the list of device I choose are shown as follows.

Devices	Model
RF splitter/combiner	BP2U+
RF phase shifter	JSPHS2484+
SPST switch	ADG902

Table 1: Bill of Material

The red circled parts of the diagram are written in VHDL and are implemented on NEXYS 3 FPGA board.
I have made a prototype board myself and also have run some test to find out whether it would work. The prototype is shown as follows.

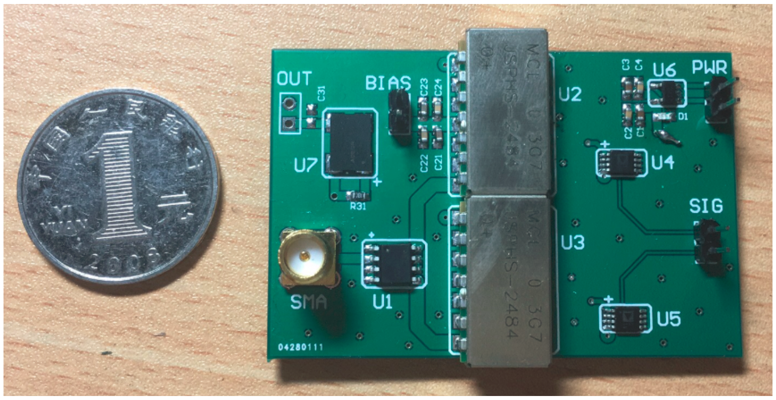

Figure 2: Hardware Prototype

4 Test Result

Test Environment - Lab 4-103, SEIEE Building
Test Instrument - Spectrum analyzer and RF signal generator
Test Date - May 11, 2017
Test Parameters - $f_c = 2.4GHz, \Delta f = 20.3125MHz$ and transmitted power $P_{transmit} = 20dBm$
Test Distance - Very close(less than 10cm)
Test Results - frequency of received signal $f_r = 2.42GHz$, received power $P_{receive} = -8dBm$ and received backscatter power $P_{backscatter} = -44dBm$
The phenomenon of the test is shown as follows

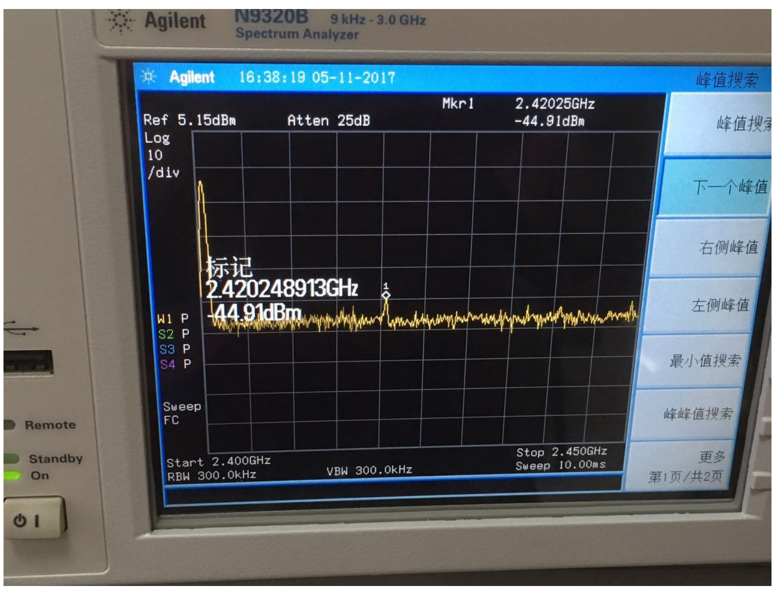

Figure 3: The preliminary Test Result of Frequency Shift

From the phenomenon, we can find that the tag can serve the function of frequency shifting and the attenuation caused by tag is around 30dB. Normally speaking, -44dBm is sufficient for reliable wireless communication, however, considering the distance, there is still a lot of work to do.

5 Follow-up Work

- Increase the power of the backscattered signal and SNR
- Further test the function of modulation
- Combined test with other parts of our system

6 Conclusion

I implement a prototype of low-power, multi-access tag based on OFDM. The feature of low-power is achieved since we have removed the power hungry RF component. The tag can serve the function of frequency shifting and modulating. We take the hardware diagram of [2] as a reference and design our own tag. We solved the problem of spectrum waste caused by 'mirror' component generated in the process of frequency shifting. We also run some test on our tag and find some problems.

7 Acknowledgement

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Reference

[1] Bryce Kellogg, Vamsi Talla, Shyamnath Gollakota, and Joshua R Smith. Passive wi-fi: Bringing low power to wi-fi transmissions. 2016.

[2] Pengyu Zhang, Dinesh Bharadia, Kiran Joshi, and Sachin Katti. Hitchhike: Practical backscatter using commodity wifi. In *ACM SENSYS*, 2016.