Next Generation of Wi-Fi System

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***Abstract*—In this paper, we first introduce the basic idea of how to enable OFDMA in Wi-Fi backscatter for capacity. In our method, the excitation signal is reflected, modulated and shifted in the frequency band of the OFDM subcarriers by the tag; OFDMA is achieved by coordinating the tags to transmit information to the receiver through the orthogonal subcarriers through backscatter. However, OFDMA in Wi-Fi backscatter has its own disadvantages. In our previous work, we have difficulties in increase the range of the system. In order to improve the sensitivity of the receiver and the transmission range of the transmitter, we need of use some radio frequency signal technologies. Using Multiple-Input Multiple-Output(MIMO) and beamforming technology in tags and either receivers or transmitter is a good choice to improve the range and data rate of this system. We increase the numbers of antennas on tags and build a prototype in 802.11g OFDM framework to validate our design. We discuss contributions of our study concerning theoretical and practical audiences, and point out future research directions.**

***Index Terms*—OFDMA, backscatter, receiver, tag, MIMO, beamforming**

I. Background

Recent years have witnessed the rapid development of Internet of Things(IoT), people prefer larger channel capacity than speed. In recent years, OFDM is a multi-carrier modulation mechanism adopted by 802.11a/g/n/ac. In order to have tiny energy budget when providing wireless connection for Internet of Things, researches on Wi-Fi backscatter have been extensive exploration. However, while promising in addressing the power consumption challenge, the existing Wi-Fi backscatter design still maintains low capacity for two reasons: Tags must transmit sequentially cause concurrent transmissions from multiple backscatter devices(tags) may cause conflicts. Another reason is that the spectrum efficiency under the single-carrier modulation scheme is low so that transmitting tags exclusively occupies the spectrum resources.

The advantage of existing design is that the peak speeds of individual connection is high which is up to 11Mbps. However, the requirements of Internet of Things care more about supporting short burst of data in the ad hoc network which will be a large number of data packet. 802.11ax generation of Wi-Fi system confirms this conclusion. Based on this idea, Orthogonal Frequency Division Multiple Access(OFDMA) technology is used in 11ax which rapidly improves the capacity than the data speed. OFDMA is based on Orthogonal Frequency Division Multiplexing (OFDM) as we mentioned before which is a multi-carrier modulation scheme used by 802.11a / g / n / ac. Since OFDMA uses orthogonal multi-carrier modulation, it is allowed that the frequency bands of the subcarriers may partially overlap which causes higher spectral efficiency. Whats more, OFDMA is a multiple access mechanism that allows OFDM subcarriers to be allocated to different devices simultaneously, therefore, OFDMA system allows many devices to transmit data packet simultaneously and the maximum capacity will be higher than that based on single carrier modulation system. Therefore, it is necessary to implement a system using Wi-Fi backscatter to achieve OFDM modulation based on tiny power.

However, only using backscatter and OFDMA in next generation of Wi-Fi system can not fulfill the requirements of capacity and the range of communication. Thus, based on the basic idea of enabling OFDM using backscatter, we use Multiple-Input Multiple-Output (MIMO) to have extended channel capacity.

On the other hand, the power ratings of transmitter and power amplifier will directly decide the range of communication. In other words, the power of the transmitting labels on tags from the reception of the signal will cause smaller scale. Besides, as frequency bands are more crowded, the center frequency of Wi-Fi system may up to higher frequency after several generations. Higher radio frequency will have more available spectrum but smaller scale. Therefore, without higher sensitivity receiver, we need to increase the transmitting power both on tags and transmitters. Beamforming can be used at both the transmitting and receiving ends in order to achieve spatial selectivity. In addressing the challenges above, we implement MIMO on tags and redesigned the hardware of the tags.

II. Previous Work

The OFDMA backscatter system we build uses the excitation signal transmitter to first reserves the Wi-Fi channel by issuing RTS-to-CTS messages. After that the transmitter sends a customized frame as shown in Fig. 1. The first part of the frame contains the 802.11g preamble for tx-rx synchronization and PHY header; The second part is produced by modulating the CW with OOK, which contains necessary preamble allowing the tx-tag symbol clock synchronization, and control information destined to tags such as subcarrier

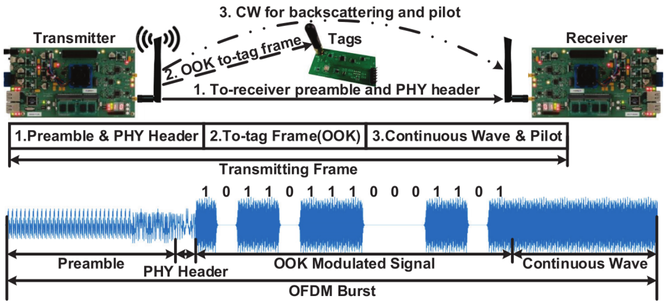

Fig. 1. System overview

allocation command and ACK; In the third part, the CW is to be broadcast and backscattered by tags, and the pilot subcarrier is for the receiver to calibrate phase and residual frequency offset with the transmitter. The backscattered symbols from tags are concatenated with the burst preamble and PHY header from the excitation signal transmitter to form a complete OFDM burst at the receiver.

When the tag detects the correct OOK, it is activated. Before tag starts to backscatter, it inserts a tag-to-rx preamble into the tags local payload, which is a sequence that has strong autocorrelation in order to eliminate static phase offset. The cause of static phase offset is that backscattered signals arrive at the receiver later than the preamble due to circuit delay, tx-to-tag preamble processing delay and the longer propagation delay. So we introduce a tag-to-rx preamble which is inserted to the front of other backscattered signals by which the receiver can recover the static phase offset.

The preamble sent from the transmitter and the backscattered symbols from tags arrive at the receiver in sequence, which form a complete OFDM burst. The synthesized burst is then processed by the receiver as shown in Fig. 2. The I/Q stream from the ADC is processed by regular modules sequentially, including packet detection, LTS correlation, synchronization, frequency correlation, CP removal, FFT and demapping, after which a complex number sequence is obtained. Additional processing is enhanced into the original phase estimation module as shown in Fig. 2, in order to address the phase offset incurred by backscattering. Another streamlining in the receiver is to bypass the bitstream processing module as shown in the right part of Fig. 10. The module includes functionalities of deinterleaving, Viterbi decoding, and descrambling. The Viterbi decoding is a reverse operation corresponding to the convolutional coding process in the transmitter. Note that the input of the bitstream processing module on the transmitter side is the bitstream for producing the excitation signal; however, the input stream on the receiver side is payload data backscattered from tags. The inconsistency makes the Viterbi decoding module believe that the received bitstream is corrupted and perform corrections on the stream, which pollutes the payload data and results in communication failure. Consequently, we need to bypass this module at the receiver.

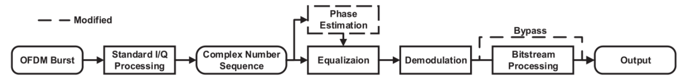

Fig. 2. Processing in the receiver

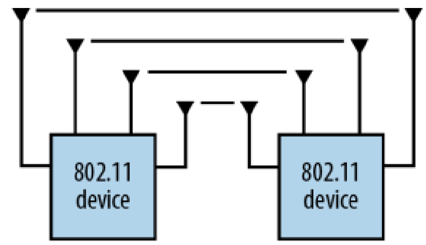

Fig. 3. The structure of MIMO system

III. Related Work

In order to support the requirements of future industries such as IoT, we need to up the rate of data packet. Increasing the speed of a network can be done in two ways. First, protocol designers can try to increase the raw speed as measured by the transmission rate. Second, protocol designers can increase the speed perceived by users by increasing the efficiency of the protocol, to transmit more data with a given period of time which means to transmit data packet in the period channel at the same time. Although the second protocol uses more antennas, it can up the speed of the data rates in a clear channel to 600Mbps in 802.11n.

Before MIMO, 802.11 used a single data stream. A transmitter and a receiver used one antenna, which was also called Single-Input Single-Output(SISO). The data transmitted between the SISO system was called one stream. However, in a SISO system, the upper band of data speed is ensured by Shannons Law. Therefore, to increase the throughout of our channel, we decided to increase the number of channels. Instead of a single lane in each communication, we use more lanes to transmit data packet. That is, the receiver has multiple inputs, and the transmitter uses multiple outputs. Although SISO systems may have multiple antennas, however, only one antenna is active for any given data frame. In the MIMO system, all of the antennas are active simultaneously. Each antenna in the MIMO transmitter sends its own data stream as input into the radio channel, and each antenna in the MIMO receiver collects its own data stream as output from the radio channel. Fig. 3. shows the basic structure of MIMO systems. The figure simplifies the system by showing the simple case of a data stream going between pairs of antennas. In real-world channels, complex matrix math is used to divide the multiple data streams through the radio channel. In the ideal case, each pair of antennas in the MIMO system is capable of transmitting its own independent data stream.

In the new backscatter system, there are two antennas rather than one on tags. In order to have better performance, we need to redesign tags. The crux of new backscatter system is the strict synchronization and the timing constraints. This section describes how to realize new backscatter system and tags, so that readers could pay special attention to certain sections in later discussions.

A. New Frame Structure of Tags

Before using tags to achieve backscatter and signal modulation, we need to redesign the frame structure. In the previous design, the frame structure is shown in Fig. 4. However, when we add an antenna on tags and the receiver. We have to estimate the channel transfer matrix before transmitting data packet from tags. So we design the new frame structure shown in Fig. 5. There are several definitions explained in the later discussion.

Fig. 4. The previous frame structure

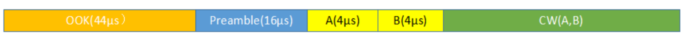

Fig. 5. The new frame structure

- On-off keying (OOK) denotes the simplest form of amplitude-shift keying (ASK) modulation that represents digital data at the presence or absence of a carrier wave. In its simplest form, the presence of a carrier for a specific duration represents a binary one, while its absence for the same duration represents a binary zero.
- Preamble training symbol contains two parts: short training symbol(STS) and long training symbol(LTS). A typical preamble training symbol has ten STS and two LTS. The interval of each STS is a quarter of the normal OFDM symbol interval and the interval of each LTS is the same as a normal OFDM symbol. The preamble training symbol is mainly used for time synchronization, frequency offset estimation and channel estimation.
- When the receiver of tag detects OOK, it enables two streams simultaneously and, if we name them as stream A and stream B, lets stream A backscatter symbol A(HT-LTSA) immediately and later lets only stream B backscatter symbol B(HT-LTSB). Since the length of HT-LTSA and HT-LTSB frames are known, each of which consumes 4μs respectively, the timing is easy to design and control.
- Continuous wave(CW) is the transmitting signal after modulation.

As we mentioned before, we design a new hardware implementation of tags. In the previous system, tags are controlled and signals are modulated by a piece of Field-Programmable Gate Array(FPGA) chip. Similarly, we need to modify the timing relationship and controlling output using Very-High-Speed Integrated Circuit Hardware Description Language(VHDL). Comparing the frame structure in Fig. 4. and Fig. 5, in the previous system, the antenna was ready to send data packet after detecting the OOK signal. However, in the new frame structure, after OOK is the preamble signal lasted for 16μs. Thus, we need to delay the enabling system signal for 16μs.

Besides, symbol A and symbol B have their own timing requirements. As we described before, these two symbols are used to estimate the channel transfer matrix before transmitting data packet. We can simply define the channel transfer matrix as $\mathcal{H}$. Assume that each tag has two antennas X_1, X_2 and each receiver has two antennas Y_1, Y_2. There are four channels for each pair of one tag and one receiver. Thus, we can define $\mathcal{H}$ as:

$$\mathcal{H} = \begin{bmatrix} \mathcal{H}_{11} & \mathcal{H}_{12} \\ \mathcal{H}_{21} & \mathcal{H}_{22} \end{bmatrix}$$

$$X * \mathcal{H} = Y$$

$$\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} * \begin{bmatrix} \mathcal{H}_{11} & \mathcal{H}_{12} \\ \mathcal{H}_{21} & \mathcal{H}_{22} \end{bmatrix} = \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}$$

Using the acknowledge of matrix,we can simply find that X_1 and X_2 have to be active solely when X_1 transmits symbol A and X_2 transmits symbol B. In other words, symbol A is transmitted by antenna X_1 and at the same time, antenna X_2 is inactive. After symbol A is transmitted, symbol B should be transmitted by antenna X_2 and similarly, antenna X_1 is inactive. When transmitting CW, antenna X_1 and antenna X_2 are both active.

B. Hardware Implementation of Tags

In order to augment the communication distance and enhance the capacity to get guaranteed communication, we introduce MIMO in our system. To be specific, we use two antennas on our tags and receiver to implement multi-antenna. The first thing that should be taken into account is that thanks to low capacity our system has low efficiency. To tackle this problem, we need to make use of the two antennas to backscatter and receive the signal. Specifically, we have the two antennas backscattering the same signal using space-time block code. In effect, STBC transmits the same data stream twice across two spatial streams so that a receiver that misses a data block from one spatial stream has a second shot at decoding the data on the second spatial stream. Due to the fact that both streams are transmitted in the same frequency, there is possibility that interference would occur. However, in outdoor environment if the distance between two antennas are big enough, the relativity of two streams can be reduced greatly while in indoor system thanks to multipath effect the distance can be small. Thus, MIMO is feasible in our system.

The circuit of the tag modified is easy to implement. Because we just need to backscatter two streams of signal, it is obvious that we simply replicate the backscatter part of the circuit and then it is modified to adapt to MIMO system. The modified circuit of tag is shown as Fig. 6.

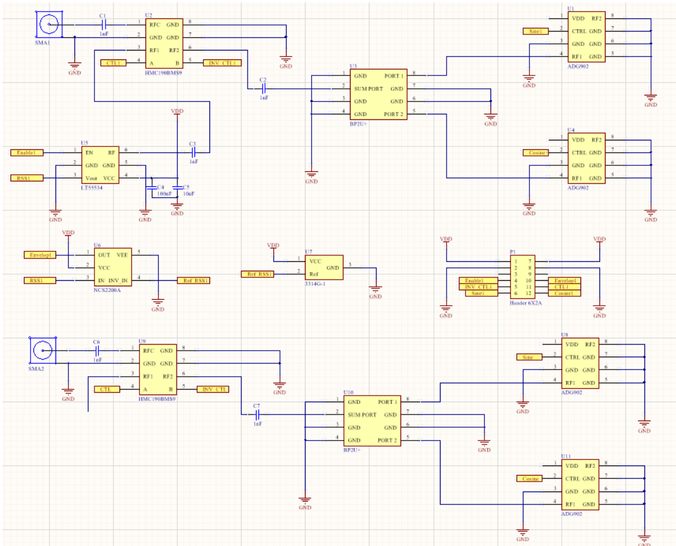

Fig. 6. Circuit of tag for MIMO

C. Signal Modulation Using FPGA

In the previous system, all devices are selected following the guidelines for low power consumption. In order to maintain the consistency of the system design, new system should apply low-power design. The power of the backscatter part is the sum of tag's power and FPGA power. Since the hardware implementation of tags are ensured, we need to simplify the design of FPGA program and circumvent the hardware circuit maps that can increase their power consumption significantly. For example, using IP cores usually can reduce power while achieving the same circuit function that achieved by us. However, the resources of IP cores are not unlimited. Excessive use of FPGA resources can lead to a dramatic increase in power consumption. Therefore, we must balance this design with the need to balance power consumption with chip resources as much as possible.

Before we program it in the FPGA chip, we have to run behavior simulation to check the right logic and post-layout simulation to check the right timing constraints. Fig. 7., Fig. 8. and Fig. 9. are the results after simulation. Fig. 7. shows that the enabling system signal delays 16 periods after detecting the OOK signal. Fig. 8. shows that the status of active antenna for antenna X_1 and antenna X_2. Fig. 9. shows the data packet transmitted by the antenna X_1 and antenna X_2. From these figures, we can confirm that our design meets the requirements of controlling tags.

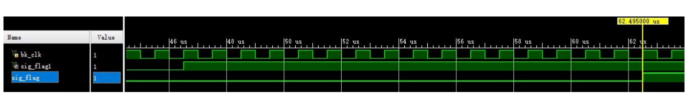

Fig. 7. Delay of enabling system signal

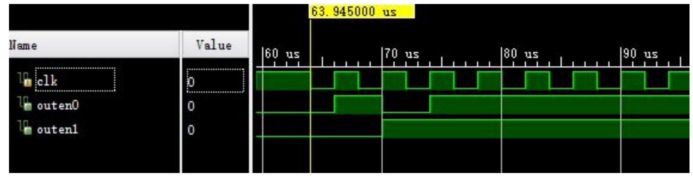

Fig. 8. Status of antennas

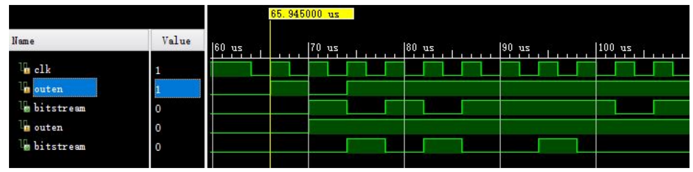

Fig. 9. Data packet transmitted by antennas

D. Beamforming

Beamforming is a signal processing technique used in antenna arrays for directional signal transmission or reception. This is achieved by combining elements in an antenna array in such a way that signals at particular angles experience constructive interference while others experience destructive interference. Beamforming can be used at both the transmitting and receiving ends in order to achieve spatial selectivity and increase signal power. The implementation of beamforming can be divided into digital and analog beamforming. For example, if there are n elements, the digital beamforming is that each of the n signals passes through an analog-to-digital converter(ADC) to create n digital data streams. Then these data streams are added up digitally with appropriate scale-factors, to get the composite signals. By contrast, the analog beamforming approaches entails taking the n analog signals, scaling or phase-shifting them using analog methods. And then it digitalizes the sum of these analog signals to have a single output data stream.

With an antenna array, it is possible to arrange transmissions such that the energy is focused or directed towards a particular physical location. By concentrating energy in one direction, it is possible to improve the signal-to-noise ratio and the transmit speed. As is shown in Fig. 6, the distance between two antennas are set to 62.5mm, which is a half of the wavelength λ under 2.4GHz. The merit to set the distance as mentioned is that when the phase offset of two streams is respectively $0,\pi/2,\pi,3\pi/2$, the antenna pattern is pretty regular. When the phase offset is 0, the antenna pattern is shown as Fig. 10. And it rotates 45 degrees each time when the offset is changed to $\pi/2,\pi,3\pi/2$ respectively. Since the strength of signal that tags receive and backscatter is small, we apply beamforming to the two parts. The implement details are discussed below.

First, we modify the circuit of the tags in order to implement beamforming. Because the receiving and backscattering of tag have to use different beamforming methods, we use two ways. For the receiving part, we give respectively two paths for one antenna. For antenna A, we give path of 0 and $\pi/2$ phase offset, while for antenna B, we give path of 0 and π phase offset.

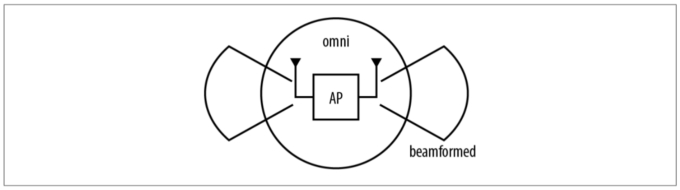

Fig. 10. Antenna pattern of beamforming

Preamble & PHY Headers	To-tag preamble (OOK)	Symbol	Symbol	......	Symbol	Symbol-end	HT-LTSA	HT-LTSB	DATA

Fig. 11. Frame sequence after beamforming enabled

And the selection of the two paths are done by RF switch which is controlled by FPGA. With the selection of different paths, we are able to set the phase offset between two streams to $-\pi$,$-\pi/2$,0,$\pi/2$, which correspond to 4 antenna patterns. For the backscattering part, we add some delay to one stream of the backscattered signal by FPGA, so that the two streams of backscattered signal have similar antenna patterns.

Second, we redefine the frame that transmitter sends as shown in Fig. 11. After the tag is activated by OOK, it receives every symbol with different paths controlled by FPGA and sends the strength to FPGA. If the strength of one symbol goes beyond the threshold, FPGA would fix the current path and use it as the following phase offset. When tag starts to backscatter the continuous wave, it also change phase offset after a fixed period which is synchronized with the receiver. After several period, the receiver knows the best phase offset after measuring all the signal strength the tag backscatters, and it gives a feedback to the transmitter, and transmitter tells the tag to backscatter signal with the optimal phase offset.

With these two beamforming enabled, the system obtains much gain and the signal strength is improved greatly. It is estimated that each beamforming could provide 3dB gain to our system, which would be a fabulous enhancement to our current system.

IV. Conclusion

We have demonstrated that how to enable MIMO in the previous backscatter system. With our approach, tags are redesigned to reflect, modulate the excitation signal and shift it to lie in the frequency band of the OFDM subcarrier. Then the modulated signals are transmitted by multiple antennas to increase the data speed. The crux of the design are to achieve the hardware implementation of tags and timing control by FPGA. We have built a prototype in 802.11g OFDM framework to validate our design. However, as the entire project is still in progress, we lack complete designs of receivers and transmitters. So we don't have the overall system experimental results. Nevertheless, through simulation and testing, we conclude that the existing hardware design and timing control of tags are in line with expectations.

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V. Member Contribution

A. *In this project*

Yixuan Song: FPGA Programming
Siyuan Peng: Hareware implementation

B. *In this paper*

Yixuan Song: Abstract, Background, Related Work(MIMO, New frame structure, FPGA, Beamforming), Conclusion, Reference

Siyuan Peng: Previous Work, Related Work(MIMO, New frame structure, Hareware implementation, Beamforming), Reference