Wi-Metal: Detecting Metal by Using Wireless Networks

Kaishun Wu
College of Computer Science and Software Engineering, Shenzhen University
Email: wu@szu.edu.cn

***Abstract*—With an increasing need for worldwide counter-terrorism, security is becoming a top priority on the agenda of local governments. Governments has enforced patrols, security forces, and security equipments such as door frame detectors, screens and hand-held detectors in public places like railway stations and airports . The main purpose of these security equipments is to detect potentially dangerous metal objects. And the way to detect metal is mainly based on electromagnetic induction and X-rays. On the one hand, detectors based on electromagnetic induction needs to be placed close to the examined objects and on the other hand, detectors based on X-rays are usually large, expensive, complex, harmful and the detecting distance is limited on many occasions. For the above reasons, current metal detection equipments cannot be deployed on a large scale with a low cost scheme. But with the popular use of Wi-Fi in public areas, low-cost and large-scale deployment is possible if we could use Wi-Fi to detect metal. Since the dielectric constant and the reflection coefficient of metal are different from those of nonmetal objects, the effect of Wi-Fi signal reflection caused by metal objects is different from nonmetal items as well. Thus we attempt to use this observation to enable metal detection. But using Wi-Fi to detect metal will encounter some challenges. Factors such as the interference caused by multi-path effect and other signal sources, shapes, materials and surface smoothness of the target, as well as the angle of reflection will cause great impact on a detecting result. However, we implement a system by using a series of methods to eliminate most of the interferences and use machine learning algorithm to identify metal. We implement this system in commercial products. We conduct several experiments and their average accuracy and false alarm are respectively more than 90% and less than 10% in 1 meter detecting distance.**

***Index Terms*—Metal Detection, Channel State Information, Wi-Fi.**

I. Introduction

Routine security check in such places as bus stations, train stations and airports have always been one of the important dimensions of living quality for public spaces. Traditionally, metal detectors are used based on electromagnetic induction or X-rays. As to electromagnetic induction, metal detectors consist of an oscillator producing an alternating current that passes through a coil producing an alternating magnetic field. If a piece of electrically conductive metal is close to the coil, eddy currents will be induced in the metal, and then a magnetic field will be produced too. As to metal detectors based on X-rays, images of the measured object can be obtained. X-ray can penetrate the detected object and the transmitted light falls on the receiving panel. It draws the picture of the target according to the intensity of received light. The metal objects can block the majority of x-rays. As a result, the metal produces a shadow with a similar size in the panel which can be identified by a computer.

Such existing metal detectors are widely used but have several limitations. Detectors based on electromagnetic induction must stay close to the target to get more accurate results such as hand-held metal detectors. It needs a very strong power if we operate a relatively long-range detection. X-rays C based metal detectors however, may cause harm to human body because of the radiation that may kill human cells and increase risks of cancer for people with massive exposure. X-rays detectors are always huge, difficult to make and transport. For the above reasons, detectors based on

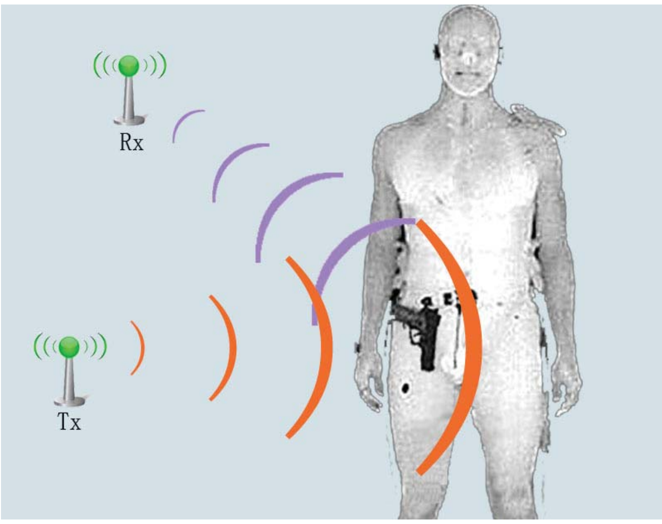

Fig. 1: The Illustration of System

electromagnetic induction and X-rays are very difficult and costly to deploy on a large scale in public places. The application is usually confined to the gates or entrances of a closed building structure, so warning alerts would not cover as far and wide as the whole public zone such as an open-style shopping plaza or a populated pedestrian square.

As an emerging and increasingly popular technology for mobile communication, Wi-Fi is used for close-range communication based on radio whose frequency is generally between 2.4GHz and 6G. The radio can be reflected, refracted and diffuse-reflected by other objects. Different shapes, surface smoothness will produce different reflection, refraction and diffuse reflection. Existing Wi-Fi signal receiver and transmitter devices have been reliable and solid. The most popular Wi-Fi technology is MIMO, which can transmit data with multi-antennas. The cost of communication by using Wi-Fi equipment is relatively inexpensive. Today, Wi-Fi has been used around us in railway stations, airports, bus stations and shopping malls. But there are some difficulties by using Wi-Fi for object detection. Wi-Fi signals in indoor environment will be interfered by multi-path effect and other signal sources. Interior walls, furniture and other facilities will have impact on Wi-Fi propagation path and intensity. The signal with the same frequency generated by other sources will produce a synergistic effect which can also interfere with the intensity of the targets signal. Radio propagation will decay over an increasing transmitting distance in the air. It is difficult to distinguish the targets reflected signal and refracted signal with the above interference. We need to eliminate the interference, identify a way to collect and process accurate signals, and establish a reliable model to distinguish target from other different objects.

Therefore, we propose WI-METAL, a technology that leverages wireless signals combined with some other techniques to detect metal and calculate the distance between the detector and metal as shown in Fig.1. We use CSI (Channel State Information) tools

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in commercial NIC to catch OFDM subcarrier and CSI Matrix which are considered more fine-grained than RSSI (Received signal strength indication). We use the amplitude extracted from CSI Matrix to measure the wave reflection caused by metal. We consider the target as a metal item if the reflection is strong due to metals high reflection coefficient [1] [2] [3]. The majority of radio signals transmit through human body with fewer reflection. The phase extracted from CSI Matrix is used to eliminate part of the interference caused by multi-path effect so as to get more accurate result. The phase of radio generated in the two antennas is different due to a different angle and frequency [4]. The radar equation and radar cross-section are used to calculate the distance between the target and the detector [5]. We can identify the moving direction according to the linear change of the amplitude. The amplitude reflected by the target is weaker if the target is moving away from the detector [6] [7] [8]. We can also get the position of the target by calculating the distances from the target to both the transmitter and the receiver. We use the K-Means model to cluster the target into metallic or non-metallic groups based on the received amplitude datasets. To summarize this paper, we have the following conclusions:

- We use commercial AP and NICs to detect metal objects based on CSI. To the best of our knowledge, this is the first work to use CSI in wireless network for detecting metal objects. Our system can easily deploy in public places like airport, train station and shopping mall in a large scale.
- We using phase and multi-antennas technology to cancel part of interference cause by multi-path effect and other signal sources in a adjustable incident angle. We also use machine learning algorithm to distinguish target metal materials from other objects.
- Wi-Metal has a high accuracy to detect metal in our experimental results. It has an average 98% accuracy in distinguish metal from other nonmetallic things within 1 meter, 91% accuracy within 2 meters and 91% accuracy within 3 meters. The detail is described in Table 1.

The rest of this paper is organized as follows. A brief overview on related literature is given in Section. 2. This is followed by Wi-Fi techniques and the preliminary design in Section. 3, which includes CSI and the analysis of signal propagation model. Then in Section. 4, the system details and relative technology are described. Section. 5 shows the experimental results. Finally, we will conclude our our work.

II. Related Work

A. Radar

Radar is important in military actions as it can not only detect moving aircrafts and warships, but also precisely calculate speed and identify position of moving targets by analyzing the signals reflected by the surface of the target [9]. The Doppler effect is used in calculating the speed of the target and the distance between radar and the target. The distance between radar and the target could be any length from 1 kilometer to 100 kilometers). However, there are some shortages that prevent radar from being a civilian equipment. Firstly, radar is expensive for ordinary people to afford. Secondly, radar is huge in size and difficult to operate and control for civilians who have no relative knowledge background. Lastly, radar is limited in military use and in selling by law.

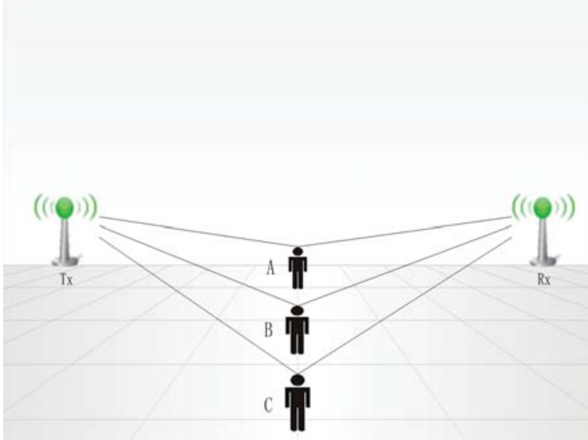

Fig. 2: Different Detect Position in Experiment

B. Wi-Fi based motion detection

Recently, the domain of Wi-Fi localization and Wi-Fi motion detection are getting some progress [10] [11] [12]. Some research teams use Wi-Fi to calculate the position and the speed of human body such as FILA [13]. It calculates the distance between senders and targets based on Wi-Fi attenuation during the transmission, while some other research teams use Wi-Fi to detect motions (e.g. wave hand, walk, falling) of human body. They use interference caused by preventing the transmitting channel of Wi-Fi to identity human motions.

C. Wi-Fi based material detection

In [1], the authors use high frequency (e.g. 60GHz) radio to detect tumor. The permittivity and reflection coefficient of a tumor is different from normal human tissues. Different tissues of the human body have different permittivities. So different tissues will get different reflections of high frequency radio in the same experimental situation. To detect the sort of tissues by wireless technique is possible in theory if support from perfect experimental facilities stands in place. The system in [1] is realized in a simulation software and thus verifies the theory. In [4], the system use commercial 2.4GHz frequency to draw image of the target. The system can draw the targets image according to the different reflection strength in its different part. It uses multi-arrays antennas to receive the reflection of Wi-Fi and calculate the distance. However, the system that implements on USRP is non-commercial and expensive for civilian use.

III. WI-METAL Overview

A. Overview

WI-METAL consists of a sender and a receiver. The sender is used to transmit Wi-Fi signals by using a commercial AP, while the receiver is used to absorb signals transmitted by the sender and reflected by the target with different materials by using a commercial NIC, as shown in Fig.1. WI-METAL uses amplitude and phase extract from a CSI matrix to judge that if the material is metallic. CSI matrix contains the accuracy attributes of a Wi-Fi channel and the subcarriers of an OFDM stream. Because different materials have different reflection coefficients, the receiver will get different amplitude strength reflected by different materials at the same distance, reflection area and angle. We distinguish the material of the target by analyzing the change of reflected amplitude strength. We also calculate the transmitting distance between the sender and the target, and the reflected distance between the receiver and the target by use radar equation. We can locate the position of the target by calculating the transmitting distance and reflected distance with the theory of triangulation. Such factors as distance, reflection area and reflected angle will affect the strength of reflection with the same material. The reflected strength will get stronger if the target is closer or the reflection area getting bigger at the same angle and with the same material. We can determine the moving direction based on it. WI-METAL uses the phase and multi-antennas to eliminate interference caused by multi-path effect so as to obtain higher accuracy. The change of phases between two antennas is not the same for different transmitting angles and transmitting frequencies. We use it to choose the signals with the right frequency and angle in our system.

B. Preliminary

Channel state information represents the channels state of a communication link on OFDM technology. To be more specifically, CSI describes how a link transmits from the transmitter(s) to the receiver(s). It also combines the effect and interference caused by scattering, fading, wrong angle, power decay and so on. In summary, CSI greatly indicates the performance of a link and the interference caused by other factors.

In a flat-fading channel, the OFDM system in the frequency domain can be described as below:

$$y = Hx + n, \tag{1}$$

Where x and y are the received and transmitted vectors while H is the matrix standing for channel and n stands for white Gaussian noise (AWGN) vector. All subcarriers in CSI can be described as

$$\hat{H} = y/x \tag{2}$$

which is the value extract from the PHY layer. CSI of a single subcarrier is represented as

$$h = |h| e_j sin\{\angle h\} \tag{3}$$

where $|h|$ is the amplitude and $\angle h$ is the phase of each subcarrier. We can extract amplitude from CSI matrix easily according to [14] [13].

C. Challenges

Using Wi-Fi to detect metal could face many challenges. Multi-Path effect could interfere the strength of the received signal. The waves reflected by metal may be weak due to remote distance, wrong angle and small volume. As a result, the specific wave may not be known due to strong interference generated by other factors such as wall and furniture. Even there is no wall or furniture in the experimental environment, the signal from the transmitter direct to the receiver is strong enough in preventing reflected waves to be extracted. However, calculating the distance between the detector and the target metal will face even worse situation. The attenuation of the right wave is difficult to calculate for the reason that the effective area of the targets surface and the effective area of the receiving antennas are difficult to measure. Moreover, the smoothness of the reflection surface can also affect the reflections strength. The smoother the surface is, the stronger reflection will be caused in the situation where other conditions remain unchanged. In addition, volume is an important factor that should be take into consideration. The bigger the target is, the stronger reflection will be produced if other conditions remain unchanged. The target will be invisible for our system if the width of the effective reflection area is much smaller than the wave length (eg.120mm).

IV. System Design

A. System Structure

WI-METAL consists of a transmitter such as an AP and a receiver such as a network card. The computer installed with network card can obtain CSI (channel state information) of the communication link. A CSI consists of a matrix which contains 30 subcarriers information based on OFDM. CSI can be used to calculate the amplitude and phase of subcarriers. The transmitter and receiver lie in X-axis, and the target lies between the transmitter and receiver and above X-axis. The angle to the transmitter and receiver is about 0-150 degrees as shown in Fig.2. The radio spreads to the surrounding space. The target will reflect the radio at a specific angle. The amplitude of the signal will attenuate during transmission and reflection. The receiver will take in part of the reflected signal at the right angle, and in real-time in our system. The received signal contains radio transmitted directly from the transmitter and reflected by the target or other objects in a room. The signal will not be changed when the target is replaced with different materials, while the radio reflected by the target will be different with other material. The combined signal caused by direct transmission and reflected by other object may cover the weak amplitude change of the targets reflection variety. Therefore, we propose a method to eliminate such interference by using phase difference in antenna arrays for radio with different frequency and transmitting angle. The detail is shown in the next paragraph. The CSI matrix obtained from the NICs is the key data to measure the difference in amplitude and phase. The amplitude of signal reflected by metallic material is much stronger than nonmetallic material. As a result, the received CSI matrix will be different for targets with different materials. K-Means clustering algorithm is used in this system to distinguish the metallic from nonmetallic. More accurate results will be produced by processing multi-times clustering. A metallic signal will be transmitted to the alarm system if the target was clustered to metallic category. Then the alarm system will alert people by displaying words, audio, light and images. Distinguishing moving direction is also integrated to our system. We can calculate the change of the distance between the transmitter and the target or the distance between the receiver and the target by using radar equation. The received amplitude will change as distance and the reflected angle vary. By using this system, we can distinguish the targets material and moving direction.

B. The Measurement of Amplitude

In WI-METAL, we collect the data of the signal by using CSI tools [14] which can be integrated into the Linux kernel. The CSI tools can obtain the channel state information of Wi-Fi signal from network module of Linux kernel. And the origin data of CSI contains a multidimensional matrix that describes the state of communication link from transmitters to receivers. The detail CSI information was explained in section4.2. We can easily extract the amplitude and phase from CSI matrix according to the formula (1), (2) and (3).

C. Elimination of Multipath Reflection Interference

There are three antennas in our NIC. The phase of the received signals in different antennas may be different. The radio needs more time to reach further antenna as shown in Fig.3. In this figure, the radio needs to travel more d1 distance to reach Antenna B or more

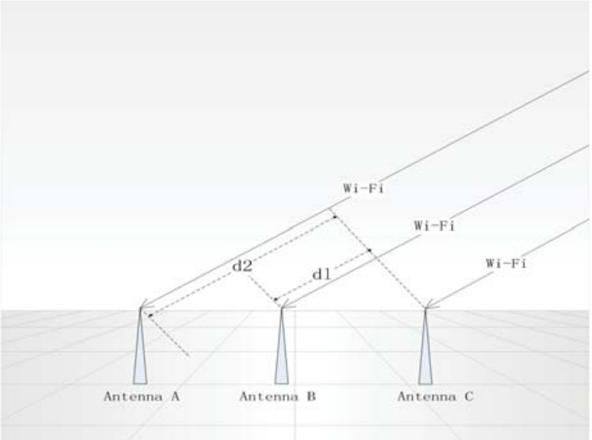

Fig. 3: Interference Cancellation by Using Multi-Antennas

d2 distance to reach Antenna A from Antenna C. The distance between the two antennas can be coded as d .The phase of the radio will be changed after more d distance is covered. So the same radio signal must travel more d distance if it wants to reach the second antenna from the first antenna. So the phase calculated in the first antenna is different from that in the second antenna according to the formula (3). The change of phase between two antennas can be coded as $\Delta \oint(n)$ and calculated as below.

$$\Delta \oint(n) = \frac{2\pi(n-1)dcos(\psi)}{\lambda} \tag{4}$$

Where d is the distance between different antennas and ψ is the angle of incidence for antennas. The n indicates that there are more than two antennas .The $\Delta \oint(n)$ corresponds to a particular frequency in the proximate antennas if given the wavelength λ. $\Delta \oint(n)$is corresponds to a particular frequency. Radio with another frequency will get a different $\Delta \oint(n)$ for the reason that the λ is different. And the radio with the same frequency will also get different $\Delta \oint(n)$ if it has a different incident angle for the reason that the ψ is different. So the $\Delta \oint(n)$ is certain if the frequency of radio is specific such as 2.4GHz and the reflect angle is constant. We can adjust the $\Delta \oint(n)$ to a specific value to eliminate other signals which do not have the right reflected angle and frequency. We consider the angle as the right one if the signals reflected by the target and direct to the receiver without second-reflecting caused by others. We can adjust the place of the transmitter to acquire the right angle. The amplitude of the received signal at the right angle will be stronger than that received at the wrong angle. The signal reflected at the right angle could cause an obvious effect in the receiver after eliminating multi-path reflection interference. As a result, we can focus on the key signal we need.

D. Distinguishing Metal from Other Material

Since different materials have different reflection coefficient, the strength of reflection caused by different materials will be different. The metallic materials will produce strong reflections while nonmetallic ones will produce little reflection. For human body that only a little reflection will be produced and most of the radio will be absorbed or passing through. Based on this observation, we can distinguish metal from human body by signal amplitude. As shown in Fig.4, Fig.5, Fig.7 that human body, book and empty box have low reflection strength while cup, Iphone, Metal Gun and USRP Board produce strong reflection. In Fig.4, the average amplitude intention with no metal gun is close to 2.0. While the average amplitude intention by taking a gun reached 9.0. In Fig.5,the average amplitude intention with no cup is close to 1.9, while the average amplitude intention by taking a gun reached 5.5. The metal gun has a bigger volumn and reflection area than cup. So the radio signal intensity reflected by metal gun is stronger than cup. The difference between metal and nonmetallic object is obvious. More objects amplitude intension are show in Fig.8.

Our goal is to distinguish metal and nonmetal items. Therefore, we divided the data into two categories. Using K-Means algorithm to realize it is an appropriate choice. K-Means algorithm is one of the most widely used algorithms in clustering analysis, which divides the n objects into K classes according to their attributes. The K classes meet the following principle: The similarity among the objects in the same clustering is higher; the similarity among the objects in the different clustering is lower. We use the Euclidean metric formula (Euclidean distance) as the similarity measure formula and use the sum of squared error formula (SSE) as a measure of clustering quality formula.

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Euclidean distance Formula:

$$L_2[(x_1,...,x_n),(y_1,...,y_n)] = \sqrt{\sum_{i=1}^{n} |x_i - y_i|^2} \tag{5}$$

Sum of the Squared Error Formula:

$$SSE = \sum_{i=1}^{k} (x_i - \hat{x_i})^2 \tag{6}$$

The advantages of the K-means algorithm are simple and can be used for all kinds of common data types. Some improved K- means algorithm is even more effective, which is less affected by the data initialization problem, such as the Binary K-means. Here, we set $K = 2$, it means that our data will be divided into two categories in the end. We conduct random initialization for the data, and choose two initial points as the clustering center point from these data randomly. Then we calculate the distance from all the data to the cluster center by Euclidean distance formula. And then we calculate the sum of the squared error (SSE). After several iterations, we choose the minimum of SSE as the final result. Now, the data we collected are divided into two categories, as an important basis for the distinction between metal and nonmetal items.

We set $K = 2$ to distinguish metal items and nonmetal items for the above part. From our intuitive judgment, the difference between metal items and nonmetal items should be considerable while the difference between the metal items is not. In our real life, not all metal items are harmful, it is necessary to distinguish the type of metal items. Therefore, we propose a novel method to identify the category of metal items by using the collected data.

In order to further identify the category of the metal items, we use the K-Means clustering algorithm again on the data which is clustered to metal category. We used four different metals which are name as Cup, Iphone 4s, MetalGun and USRP Board. We set $K = 4$, then we use K-Means clustering algorithm to test the data collected.

In the same way, we conduct random initialization for the data, and choose four initial points as the clustering center point from these data randomly. Then we calculate the distance from all the

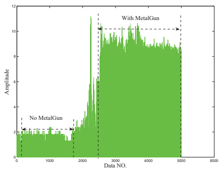

Fig. 4: The difference of amplitude when the people carry metal gun or not

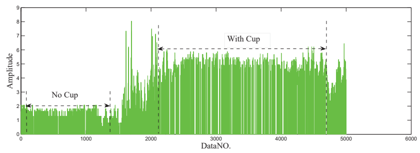

Fig. 5: The difference of amplitude when the people carry cup or not

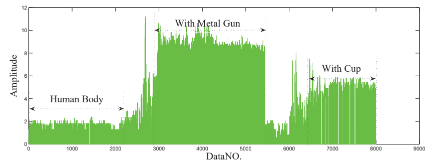

Fig. 6: The difference of amplitude between carrying a cup and carrying a metal gun

data to the cluster center by Euclidean distance formula. And then we calculate the sum of the squared error (SSE). After several iterations, we choose the minimum of SSE as the final result. Now, the data we collected are divided into four categories, as an important basis for distinguishing the different kinds of metals.

V. Performance Evaluation

A. Implementaion

We choose 2.4G Hz Wi-Fi as our experimental frequency for the reason that 2.4GHz is widely used in commercial products such as mobile phones and laptops. We choose commercial 5300NIC and three antenna3 with 5dBi gain as the receiver in our system. We choose Tenda AP which is able to emit 2.4GHz Wi-Fi with 7dBi gain the transmitter. We install the CSI tools in our Lenovo desktop computer which is running with Linux. We use Matlab installed in the computer to extract CSI data. The data on the part of the target will be sent to our K-Means cluster system. We will send alarm messages to a Android client by using TCP/IP communication protocol if the K-Means cluster system determines that the sent data belongs to the metallic cluster. The system will count the alarm so as to calculate the accuracy of detection. The cost of whole system is cost-effective. The receiver and transmitter are located in the same line which is named x-line and the target is in front of them as shown in Fig.2. The whole system operates in a real-time manner.

In the experiments, we use a variety of metal and nonmetal items for testing and collect a large amount of data. In order to test whether we can distinguish metal and nonmetal objects from these data, we make a clustering analysis on the data. Clustering analysis can group objects with the same features into one category. In our experiment, the data obtained by metal-item reflection is divided into a group and the data obtained by nonmetal-item reflection is the other group. Therefore, we can distinguish metal and nonmetal items accurately from the WiFi reflection data.

We have tested our system for hundreds of times and have recorded the results. In our experiment, we set 3 experiment positions to distinguish metal from non-metallic objects: A point (1 meter far away from the line connecting the transmitter and the receiver), B point (2 meters far away) and C point (3 meters far away) as demonstrated in Fig.2. We have also tested eight material objects (USRP Board, Iphone 4s, metal gun, cup, book, big empty box, small empty box and human body) in our experiment. An Iphone 4s contains many metallic circuits and many metallic components (CPU, Memory, Chips). We consider the Iphone 4s as metallic. We classify the USRP Board, Iphone 4s, metal gun and cup as metal while the other objects are sorted as nonmetallic. We put the objects near the waist and stand in front of the receiver and the transmitter as shown in Fig.8. We have done tests 10 times for each item at different distances. In Fig.8, the radio transmits from

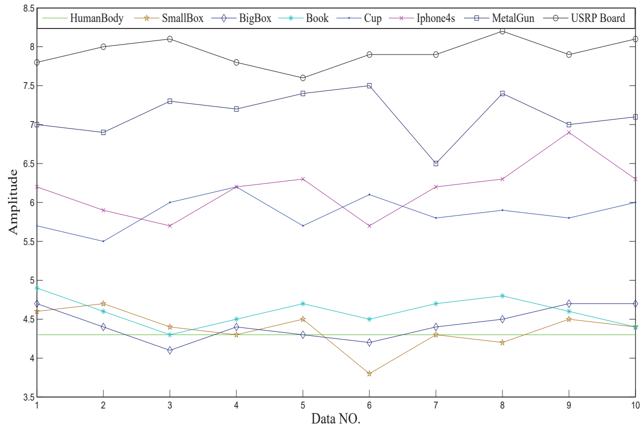

Fig. 7: The difference of reflected amplitude caused by different material

the AP and reaches the metal gun and the human body. Part of the radio transmits through the human body and diffracts from its side. However, only part of the radio is reflected by the metal gun. But not all the reflected radio signal will be received by the antennas connected to the NICs. Part of the reflected signal transmits to other space due to wrong angles. Only the signal reflected at the right angle will be received by antennas and cause effect on the received signals amplitude. The USRP board and the cup as shown in Fig. 9 and Fig. 10 will lead to the same effect for the same reason. But the effective reflection areas for the metal gun, the cup and the USRP board are different. The USRP board has the biggest effective reflection area while the cup has a smallest one. The difference of effects can be found from Fig.7. The average intensity index of the USRP board in Fig.7 is 8.0 and the average intensity index of metal gun is 7.0 . And the average intensity index of cup is 6.0 which is similar to that of Iphone 4s.

Our experiments prove that the metallic materials reflect more radio signal than non-metallic materials according to Fig.4, Fig.5 and Fig.7. The figures show in detail the amplitude reflected by different materials displayed in the experiment.

B. System Performance

In WI-METAL, we have achieved an average 98% accuracy in distinguishing metal from other nonmetallic materials within 1 meter, 91% accuracy within 2 meters, and 91% accuracy within 3 meters. The detail is described in Table 1.

VI. Conclusion

In this paper, we propose WI-METAL, a technology that leverages wireless signals combined with some other techniques to

Fig. 8: Experiment Scene in detecting Metal Gun

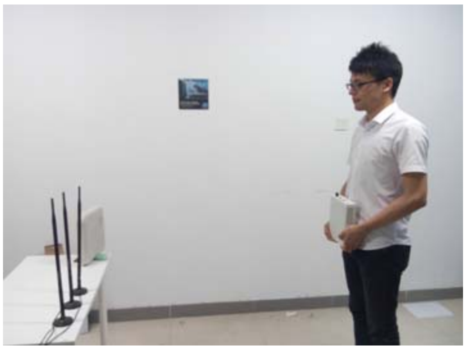

Fig. 9: Experiment Scene in detecting USRP Board

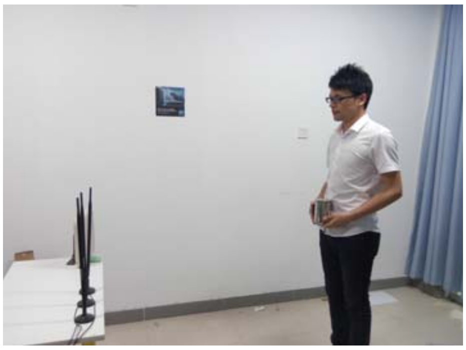

Fig. 10: Experiment Scene in detecting Cup

TABLE I: Metal Distinguish Experiment Results.

Material	Test Position	Precision	False Positive
USRP Board	A(1m)	99%	1%
USRP Board	B(2m)	95%	5%
USRP Board	C(3m)	90%	10%
MetalGun	A(1m)	99%	1%
MetalGun	B(2m)	93%	7%
MetalGun	C(3m)	89%	11%
Iphone4s	A(1m)	96%	0%
Iphone4s	B(2m)	91%	9%
Iphone4s	C(3m)	85%	15%
Cup	A(1m)	95%	5%
Cup	B(2m)	90%	10%
Cup	C(3m)	83%	17%
Book	A(1m)	98%	2%
Book	B(2m)	90%	10%
Book	C(3m)	86%	14%
BigBox	A(1m)	99%	1%
BigBox	B(2m)	93%	7%
BigBox	C(3m)	84%	16%
SmallBox	A(1m)	98%	0%
SmallBox	B(2m)	89%	11%
SmallBox	C(3m)	81%	19%

detect metal. Our future work is to combine multiple systems to improve accuracy of measurements. We need to find new methods to avoid more interference caused by other unrelated factors. We will also do comparison for more kinds of materials to improve accuracy. At present, our system is applicable only to one person under the circumstance that the person stays in a place without strenuous exercise. We attempt to extend our system to a multi-person scenario.

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