The Use of Wireless Signals for Sensing and Interaction

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ABSTRACT

Gestures are a natural form of human interaction. As such there has been much research in using gesture recognition as a way of interacting with electronic devices. In this essay we discuss the possibilities and limitations of using radio-frequency signals to track and classify human motion. For this we present four projects from recent research that leverage wireless signals such as Wi-Fi or ambient TV broadcastings to detect and recognize gestures, both with and without having direct line-of-sight and without instrumenting the human body.

INTRODUCTION

If we think of computers, we traditionally imagine large machines, typically a desktop environment equipped with a display, a keyboard and a mouse. However, nowadays there is a growing trend of moving away from and going beyond the classical desktop. As new technologies emerge and devices are becoming smaller and smarter, we are approaching the vision of the *Internet of Things* (*IoT*) [1]. In this vision, everyday objects are augmented through embedded sensors and potentially invisible computational logic to become smart objects. For example, a flower pot could be equipped with sensors to monitor the moisture of the soil, the temperature, the light intensity as well as the time the plant was last watered [2]. It could use this information to communicate directly with the watering system or send messages to a special watering robot, or the plant's owner to inform her in case the plant needs special care.

It is clear that, in order for us to interact with these devices, they require some kind of interface. However, since the devices are now hidden from sight and embedded into many different objects it is not practical or in many cases not even possible to use traditional interfaces such as keyboards or buttons. In the flower pot example it is easy to see that adding a set of buttons or a display to the pot would be feasible but not a desireable solution. We therefore require new ways of controlling and interacting with these smart objects in seamless way.

One possibility for such a new interface is gesture recognition. The motivation for making use of gestures comes from the fact that they are natural to humans since a large part of the way humans interact with each other consists of gestures. As such it might be possible to use gestures as an intuitive way of interacting with a smart environment. In this essay we give an overview of different techniques used to detect and classify gestures. We then focus on the use of radio-frequency-based (RF) approaches and introduce four projects from recent research.

GESTURE RECOGNITION FOR HUMAN COMPUTER INTERACTION

Spurred by the commercial success of systems such as Xbox Kinect [3] and Leap Motion [4] there has been much research in gesture recognition in recent years. The different approaches can be primarily categorized into five groups.

Vision-based approaches rely on the use of one or more cameras and various image-processing algorithms to extract rich gesture and pose information. An example for such a system would be the previously mentioned Kinect, which consists of an RGB camera as well as an IR camera to measure depth.

Ultrasonic systems use high frequency sound waves to detect motion by measuring Doppler shifts within these frequencies [5].

Electric-field sensing systems detect human motion or proximity by measuring changes in an electric field, either by equipping the environment such as a floor [6], by instrumenting the human body [8] or by building special sensors into hand-held devices [7].

Wearable systems rely on instrumenting the human body with a set of sensors such as gyroscopes and accelerometers to measure the body's movements and extract gesture information from it. One example would be Myo [9], which consists of a band worn around the user's forearm.

RF signals can be leveraged to detect and measure human motion in a similar way to ultrasonic systems where the shift in frequency is observed [13]. There also exist systems that measure the time-of-flight that it takes a signal to reflect off a moving or static object and travel back to a dedicated receiver [12].

In the following section we focus on RF signals and highlight some of their advantages in comparison to other approaches, especially in the context of the Internet of Things.

Using RF for gesture recognition

From the wireless telegraph to modern day Wi-Fi and cellular networks, RF signals have mainly been used for the purpose of transmitting information and played a significant role in the area of communication. However, apart from their potential to encode data, these signals have a variety of properties that make them interesting for human-computer-interaction (HCI).

On the lower end of the radio spectrum (up to 2 GHz) the RF signals have wavelengths that are long enough for them to penetrate dense objects such as doors or walls. As we move upwards on the spectrum into the microwave spectrum this property begins to change. At these higher frequencies the RF signals no longer fully pass through objects but are partly reflected and partly absorbed. It is the combination of penetration and reflection that provides the foundation for sensing without the requirement for line-of-sight. This means that, in contrast to vision- and ultrasonic-based systems, using RF signals makes it possible to recognize gestures even when they are performed behind an obstacle or in a different room than the one the device itself is located in. In addition it is possible to cover large areas with just a small number of devices. While a vision-based approach, for example, might need more than one camera just to cover a single room, an RF-based system could potentially cover an entire floor or building with a single access point.

One of the major disadvantages in most vision-based systems is their dependency on good light conditions. Most of these systems fail to extract enough information from an image when the environment is not lit brightly enough or when there is too much light. RF-based approaches do not have this dependency and as such can also be used at night, in dark rooms or in bright sunlight.

A less technical advantage of RF signals is their omnipresence in our world today. They are dense around us in the form of Wi-Fi, celluar networks or TV broadcasting signals and as such their infrastructure is already widely deployed. From a financial point of view it is interesting to reuse this infrastructure for new applications rather than having to install a lot of additional hardware. RF-based systems thus require no or only little instrumentation of the environment, which is an advantage over all other approaches mentioned above and gives the user more freedom of use. Since part of the Internet of Things is about smart devices communicating with each other, most of these devices are equipped with some kind of wireless network interface. Due to constraints on space and energy on these devices it is beneficial to use this interface for an additional purpose rather than adding power-hungry devices such as cameras or microphones.

THE EMERGENCE OF RF-BASED GESTURE RECOGNITION SYSTEMS

In this section we introduce four projects from recent research that bridge the gap between wireless communication and HCI. For each of them we highlight their applications, their potential in the context of HCI and their current limitations.

Wi-Vi

Wi-Vi [10], which is short for *"Wi-Fi Vision"*, introduces a system which aims at detecting the number of humans and their relative movement in an adjacent room without having line-of-sight. The setup consists of three directional antennas, two of which act as transmitters and the third as a receiver, pointed towards a solid wall or opaque obstacle. The antennas operate in the 2.4 GHz ISM band which is typically used by standard Wi-Fi.

When the transmitters send out an RF-signal a small fraction of it would traverse the wall, reflect off humans or objects on the other side and travel back to the receiver. From these received reflections Wi-Vi can then extract information about what lies behind the wall.

Key Technology Enablers The main challenge that Wi-Vi has to overcome is the so called *"Flash Effect"*. The reflections off the humans and objects behind the wall are many orders of magnitude weaker than the direct reflection off the wall because they had to traverse the wall twice. As such Wi-Vi's ADC is oversaturated with the strong signals caused by the direct reflection and fails to register the small changes in the reflections from beyond the wall. To solve this problem, Wi-Vi relies on *Multiple-Input and Multiple-Output* (*MIMO*), which is a concept frequently used in modern wireless communication. The key idea of MIMO is to use multiple transmitters and multiple receivers to increase throughput by effectively transmitting multiple signals in parallel. To achieve this, MIMO has an initial phase in which all transmitters send a known preamble signal one-by-one. Each of these signals is received by all receivers and can thereby be used to estimate the channels, i.e., after the initial phase each receiver knows the channel parameter for each transmitter. It can then use these parameters to obtain the signals sent by the transmitters in subsequent phases.

There is a special mode called *Interference Nulling* [11] in which MIMO is not used to increase throughput but instead to null, i.e., to cancel out all signals at a specific receiver. After having estimated the channels, Wi-Vi makes use of this by sending a signal from the transmitters in such a way that the two signals are nulled at the receiver. This means that, if the channel estimates don't change, the receiver will not receive a signal. In that sense, static objects such as the furniture in the room or the wall itself are ignored and the Flash Effect is eliminated. However, if a human moves between two consecutive signals, the channels change and the signal is no longer nulled, thus the movement can be detected by the receiver. By iteratively repeating the nulling and the detection phase Wi-Vi can effectively track motion.

Unlike many previous tracking systems, Wi-Vi does not rely on the use of an antenna array but instead uses a technique called *Inverse Synthetic Aperture Radar* (*ISAR*). ISAR makes use of the target's movement to simulate an antenna array. Instead of sampling the reflections from the human at different receiving antennas, the signal is sampled at different points in time at a single antenna. By assuming the human's speed to be around 0.5 m/s Wi-Vi can use the samples in time to estimate the human's relative movement, i.e., it can detect whether she is approaching or retreating from the device.

Application Scope Wi-Vi coarsely allows a user to look through solid walls. As such it can be used in non-line-of-sight scenarios instead of using normal cameras. This includes law enforcement or military scenarios, where the device could be used to look into a room before entering to detect whether there might be an ambush. In a similar way it could be used to find missing people buried under rubble in an emergency situation.

In a home environment it could be used for intrusion detection in combination with an alarm system as well as occupancy detection to control lighting and heating.

The authors of Wi-Vi built a special messaging system on top of it, where they defined two simple gestures for sending a 0-bit and a 1-bit through the wall. The 0-bit consists of first stepping towards the device followed by stepping back again, while the 1-bit is the opposite. By performing a sequence of these gestures a human can send messages through the wall without carrying a transponder. Such a system might prove useful in law enforcement or military scenarios as a backup communication system in cases where a police officer or soldier is forced to give up all of his communication devices.

Potential and Limitations In comparison to previous systems one of the major innovations of Wi-Vi is that it does not require ulta-wideband solutions but instead operates in the 2.4 GHz ISM band and as such also requires much less power. Furthermore, due to ISAR, it requires only three antennas. Given these two factors, Wi-Vi can be built small and cheaply and can therefore be made available to the general public. The authors do not mention details about the physical size or the portability of their prototype in their paper but we imagine that the device could be built into standard Wi-Fi access point or a device of similar size, given the fact that the accuracy depends on the distance between the receiver and the two transmitters.

When pointed against a wall, Wi-Vi was shown to reliably tell whether the adjacent room was empty or not. Furthermore it was able to distinguish between 1, 2 or 3 people moving in the room with high accuracy. Wi-Vi is currently limited to detecting 3 humans, mostly because there is too much noise with larger numbers of humans. It also fails to detect humans that move very slowly or do not move at all, e.g., because they are sleeping, because their reflections are removed in the MIMO nulling phase.

Another limitation is the thickness of the wall. Wi-Vi's limit to reliably detect humans and recognize gestures behind concrete walls lies around 20 cm, as accuracy drops substantially when the walls are thicker. Similarly the accuracy depends on the distance the subjects have to the wall. Results have shown that the current prototype fails to recognize any gestures when the human moves more than 8 meters away from the device. In future work it might be possible to increase this distance as well as the potential thickness of the wall, for example by increasing the power.

WiTrack

Inspired by Wi-Vi, *WiTrack* [12] is a system which aims at tracking a human's exact location in 3D space by using Wi-Fi signals, especially in non-line-of-sight scenarios. The setup consists of four directional antennas, three of which act as receivers and one as a transmitter. They are arranged in a T-shape with the receiver located at the intersection.

To locate a human subject in an adjacent room, the transmitter sends out a signal which traverses the wall and reflects off the human's body back to each of the three receivers. By measuring the time-of-flight (TOF) of each of these three received reflections, i.e., the time it took the signal to travel from the transmitter to the receiver, it can calculate the subject's location by applying a geometric model.

Similar to Wi-Vi WiTrack has to deal with the Flash Effect and with reflections from static objects. It does this by relying on the fact that the measured distance to these objects does not change from one measurement to the next. This allows WiTrack to simply subtract subsequent frames from each other, thus only leaving the reflections from moving objects.

Key Technology Enablers Wi-Fi signals propagate at the speed of light. Therefore, in order for WiTrack to distinguish between distances in the order of a few centimeters, the system has to be able to measure delays in receiving the signals in the order of hundreds of picoseconds. To achieve this WiTrack relies on a technique called *Frequency Modulated Carrier Wave* (*FMCW*). The idea is to avoid directly measuring the arrival difference in the time domain, which would require high speed ADCs, but instead the transmitter sends out a narrowband signal while its carrier frequency increases linearly over time. By looking at the frequency shift between the original and the received signal WiTrack can then calculate the TOF for each receiver.

By applying these TOF measurements to a simple geometric model WiTrack can accurately locate the target human's location in 3D space.

Application Scope The authors of WiTrack propose to use WiTrack as an extention to existing motion tracking systems such as the Kinect [3] or Leap Motion [4] to enable them to also operate without having direct line-of-sight to the tracked human.

Furthermore they discuss the possibility of using WiTrack to monitor elderly people in their homes to detect when they have fallen down and are in need of help. For this they make use of the fact that WiTrack can track a human's vertical axis and as such can detect whether she is standing, sitting or laying on the ground.

Apart from tracking the whole body, WiTrack can also coarsly track body parts such as an arm or a leg. The authors leverage this possibility in a prototype application where they use a pointing gesture to control household appliances. A user could, for example, point at a lamp to turn it on or off. Since WiTrack can operate through walls the user can even interact with devices that are in a different room.

Potential and Limitations The authors of WiTrack have shown that their system can track a human's location in realtime with a delay as low as 75 ms. Their prototype runs on relatively low power (0.75 mW) which makes it comply with regulations for consumer devices.

The system can localize a human body to a precision of 10 to 13 cm horizontally and 21 cm vertically. The reason for the decrease in precision for the vertical measurement comes from the fact that human bodies are taller than they are wide.

In the current state, WiTrack's ability to track body parts is very limited in the sense that the body part has to be large, such as an arm or a leg, and it requires the human to be standing still and upright. Furthermore it cannot detect what part of the body is moving, i.e., WiTrack cannot tell whether the human is moving her arm or her leg. This limitation could potentially be reduced by combining WiTrack with complex models of human motion such as the ones used in Kinect.

A major limitation of WiTrack is that it can only track one human at any time and fails if more than one human is present. It also requires the human to be moving in order to reliably locate her. In future work these limitations could be overcome by adding additional antennas, which would introduce new constraints on the geometric model, as well as by adding a training phase in which WiTrack could collect data about the static reflections observed in an empty room. Adding more antennas might also overconstrain the model which would increase robustness against noise.

To perform FMCW WiTrack needs a contiguous frequency band over which it can linearly increase the carrier frequencies. In this sense the system is limited by FCC regulations for spectrum use [15]. The largest band that is available for consumer devices has a bandwidth of 1.69 GHz, which is enough for WiTrack but acts as an upper bound on the resolution. This means that in future work it is not possible to increase the system's precision by using more bandwidth.

WiSee

WiSee [13] is a system that leverages existing Wi-Fi infrastructure in a home environment to recognize whole-body gestures. Since Wi-Fi signals traverse walls WiSee can cover large areas, e.g., an entire appartment floor, with just a single receiving device, potentially built into a Wi-Fi access point, and a small number of regular Wi-Fi enabled devices such as laptops or smartphones. It tracks human motion by measuring the *Doppler shifts* [5] they produce in Wi-Fi signals that reflect off their bodies.

Doppler shifts or the *Doppler effect* is the phenomenon that can be observed when moving realtively to a wave emitting source. When the observer approaches the source the frequency of the waves appears to increase and a positive shift in spectrum is observed. The opposite effect is seen when the observer retreats from the source and the frequency decreases. The classic example for this is the siren of a police car which appears to change pitch when passing by, as the frequency shift moves from a positive shift a negative one.

Key Technology Enablers The main challenge for WiSee is that it has to deal with very small Doppler shifts. The Wi-Fi signals travel at the speed of light while a human, acting as a virtual transmitter by reflecting these signals, typically moves at speeds below 1 m/s. The resulting shifts are many orders of magnitude smaller than the original frequency sent by the transmitters. To overcome this challenge WiSee builds on a modulation scheme called *Orthogonal Frequency Division Multiplexing* (*OFDM*), which is widely used in modern communication technologies. To increase throughput OFDM divides a (Wi-Fi) channel into subchannels and multiplexes a signal across these subchannels into OFDM symbols in a way that minimizes interference (see figure 1). WiSee operates on these symbols in three steps. In the first step it receives the OFDM symbols sent by Wi-Fi devices that are present in the environment. It decodes the data they encode using a standard decoder. In the second step WiSee uses the decoded data to re-encode all received symbols such that they all contain the same data as the first symbol. This way all the data is effectively removed from the symbols, leaving only the noise. By performing an FFT over N symbols in the third step, WiSee can reduce the bandwidth by a factor of N. This last step is repeated until the resolution is small enough to detect frequency shifts in the order of a few Hertz.

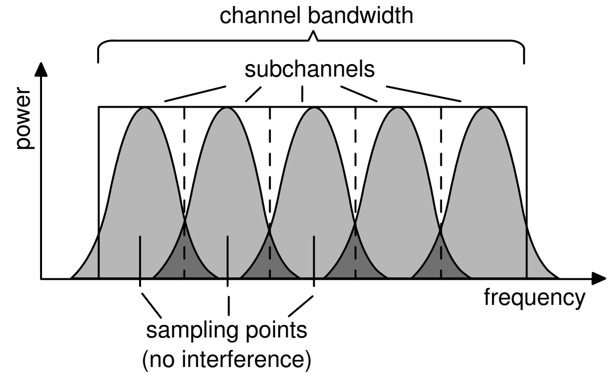

Figure 1: Overview of how *Orthogonal Frequency Division Multiplexing* (*OFDM*) works.

To translate these frequency shifts into gestures WiSee uses simple pattern matching algorithms on the number and order of positive and negative shifts. As such the gestures are speed and user invariant.

To deal with interfering humans in the environment as well as to allow multiple humans to use the system at the same time WiSee relies on MIMO. For each user it selects the MIMO channel that minimizes interference. However, since WiSee cannot control the signals that are sent by the Wi-Fi devices and since all humans reflect the same symbols it is not possible to use known MIMO preambles to estimate the channels. As a solution to this problem the authors of WiSee introduce a special preamble gesture. A user who wishes to gain control over the system has to initially perform this gesture. WiSee would detect this gesture due to its repetitive pattern and use it as a preamble to estimate the channels.

Application Scope WiSee was designed to cover entire homes with a gesture recognition system. These gestures could be used to control various appliances in the home, such as turning the lights on or off, switching the channel on a TV or to control the heating. Similarly it could be used in an office scenario, e.g., to control a slideshow during a presentation, or it could be used for entertainment purposes.

Potential and Limitations WiSee can be built into existing Wi-Fi access points and as such requires no special instrumentation of rooms or the human body. This is a great advantage as it reduces cost and setup time. Furthermore, since it relies on the signals sent by regular Wi-Fi devices it does not introduce any new sources of radiation which might make it easier to advertise the system to the general public.

WiSee's prototype can distinguish 9 different gestures. In an experiment of 900 performed gestures it was shown that WiTrack could classify 94% of them correctly.

Thanks to the preamble gesture WiSee can deal with multiple humans simultaneously. The number of humans in the environment is however limited. Tests have shown that even with 5 antennas on the receiver the accuracy of correctly classifying gestures drops below 60% with 4 interfering humans. This limitation may however be acceptable since the number of moving humans in a home environment is typically low. In future work it might be possible to increase the number of acceptable interfering humans, e.g., by adding more antennas or by making some of them directional.

Finally, WiSee lacks user identification and authentication. This problem is inherent to many gesture recognition schemes but poses a big security risk in WiSee since the Wi-Fi signal traverses through walls and thus might go beyond the home environment in which it is used. In particular this could allow a person standing outside the building to control appliances within without having authorization. The authors propose the use of a secret gesture to allow a user to identify herself, though this is still a rather simplistic approach and will need more work in the future.

AllSee

AllSee is yet another system that leverages RF signals to recognize in-air gestures. The key difference to previous approaches is however that AllSee requires 3 to 4 orders of magnitude less power to do so. It can detect and classify simple hand-gestures performed close to the system's antenna.

Key Technology Enablers As opposed to previous technologies, AllSee avoids the use of power-hungry components such as ADCs or oscilators. Instead it uses analog components only to extract information about the amplitude of ambient RF signals. To recognize gestures AllSee leverages the fact that motion close to the device's antenna results in more changes in the amplitude of these signals than motion occuring farther away. The amplitude measurements are then processed in analog hardware components to decode the gestures performed by the user's hand.

Application Scope Because of its lower power requirements AllSee could be built into smartphones, tablets and similar portable devices to enable always-on gesture recognition, where previous approaches often quickly drained the device's battery. By harvesting energy from the same ambient RF signals used to detect gestures or by drawing power from a renewable energy source such as solar, AllSee could also be built into smart devices that have no battery at all, thus reducing maintenance cost while still allowing a rich user interface.

To give an example application the authors equipped an off-the-shell smartphone with an AllSee device and demonstrated how it can be used to control a music player application by means of hand gestures. Since RF signals can traverse objects the phone could even detect these gestures when it was stowed away in the user's pocket.

Potential and Limitations AllSee's power requirement is negligible to the point that it can run on battery-less devices. Thanks to its small and light-weight form-factor it can be built into mobile devices, where it can enable always-on gesture recognition without quickly draining the battery.

Experiments showed that AllSee can accurately classify gestures from a set of eight with an accuracy of 97%. The response time was below 80 ms. As such AllSee can offer an acceptable user experience.

A limitation of the current prototypes is that they only use TV broadcast signals and signals from RFID readers. It is however possible to extend them to also work with Wi-Fi or cellular signals, thus increasing AllSee's reliability and ubiquity.

AllSee can detect gestures at a distance of up to 75 cm. This is more than is required by most applications and as such may be a disadvantage in terms of security. By tuning the hardware components it is possible to reduce AllSee's sensitivity to only detect gestures at closer distances.

DISCUSSION

In table 1 we list all four projects and compare some of their key features. All four systems are relatively small, low-power and can be built cheaply because they rely on standard hardware components only.

	Wi-Vi	WiTrack	WiSee	AllSee
Purpose	location tracking	location tracking, pointing gestures in homes	whole-body gestures in homes	detect hand gestures
Form factor	built into AP or portable device	built into AP	built into AP	built into mobile devices
Instrumentation	none	3+ transmitters (distributed)	few Wi-Fi enabled devices	none
Power	20 mW	0.75 mW	10 mW	$<6\ \mu$W

Table 1: Comparison of the four projects. *Power* means maximum transmission power, except for AllSee (which does not transmit any signals at all) where it means maximum total power consumption.

In comparison to previous approaches [16][17] which target the military none of them require ultra-wide frequency bandwidth. As such they can be built into consumer electronics and made available to the general public. All four projects can operate in non-line-of-sight scenarios, which is a feature that might prove advantageous in many applications over other systems such as vision or ultrasonic-based approaches.

An open problem which remains is the lack of user authentication. None of the projects presented in this essay incorporate a mechanism to identify the user and to determine whether she is allowed to perform gestures. This is a problem inherent to most gesture recognition systems. In some systems, such as AllSee, authentication may not be important because the user has to be very close to the device. In other systems such as WiSee however, user identification is an issue of importance and may also be needed for reasons other than security. We believe that in future projects this problem can be addressed by combining gesture recognition with other technologies such as RFID tags or voice recognition.

As with every new technology, the question remains whether it will be accepted and actually used. People are nowadays used to interact with various different devices equipped with various different user interfaces. A few years ago it may have been unfamiliar to deal with a touch interface, but today we are confronted with such devices on a daily basis without ever questioning it. We image that gesture recognition interfaces will face a similar development and become quite commonplace within a few years. In particular we see great potential in AllSee, where we imagine that similar systems might be available in standard smartphones and tablets but also various smart objects in the near future. We do not believe that gesture recognition will fully replace buttons or touch interfaces but we are sure that it will prove to be a valued extention to the experience of interacting with smart devices and homes.

CONCLUSION

We have seen that RF signals can be leveraged to track motion and recognize gestures, both for small, hand-held devices as well as in whole-home scenarios. Since RF signals can traverse through walls and dense objects they can be used to enable tracking without the requirement for line-of-sight, a feature not available with most other gesture recognition system nowadays. The motivation to use RF-based approaches for gesture recognition is the fact that RF signals are already dense around us and that the infrastructure is already widely deployed, both in the environment and the devices themselves. We have seen that such systems can be made cheap, small and low-power, and require no or few instrumentation of the body or the environment, thus making it interesting for future research and applications for the general public.

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REFERENCES

1. F. Mattern. From the Internet of Computers to the Internet of Things. Distributed Systems Group, Institute for Pervasive Computing, ETH Zurich, 2010 http://www.vs.inf.ethz.ch/publ/papers/Internet-of-things.pdf

2. Koubachi by Koubachi AG http://www.koubachi.com/features/sensor

3. Kinect by Microsoft Corporation. http://www.microsoft.com/en-us/kinectforwindows/

4. Leap Motion by Leap Motion, Inc https://www.leapmotion.com/

5. S. Gupta, D. Morris, S. Patel, D. Tan. SoundWave: Using the Doppler Effect to Sense Gestures. CHI'12, Texas, USA, 2012 http://dl.acm.org/citation.cfm?id=2208331

6. J. Paradiso, C. Abler, K.-y. Hsiao, M. Reynolds. The Magic Carpet: Physical Sensing for Immersive Environments. CHI'97, Georgia, USA, 1997

7. GestIC: electrical near field (E-field) 3D Tracking and Gesture Controller by Microchip. http://www.microchip.com/pagehandler/en-us/technology/gestic/home.html

8. G. Cohn, D. Morris, S. Patel, D. Tan. Humantenna: Using the Body as an Antenna for Real-Time Whole-Body Interaction. CHI'12, Texas, USA, 2012 http://dl.acm.org/citation.cfm?doid=2207676.2208330

9. Myo by Thalmic Labs Inc. https://www.thalmic.com/en/myo/

10. Fadel Adib, Dina Katabi. See Through Walls with Wi-Fi! ACM SIGCOMM'13, Hong Kong, China, 2013

11. K. Lin, S. Gollakota, D. Katabi. Random Access Heterogeneous MIMO Networks. ACM SIGCOMM'10, 2010

12. F. Adib, Z. Kabelac, D. Katabi, R. C. Miller. 3D Tracking via Body Radio Reflections. Usenix NSDI'14, Seattle, USA, 2014

13. Q. Pu, S. Gupta, S. Gollakota, S. Patel. Whole-Home Gesture Recognition Using Wireless Signals. Mobicom'13, Miami, USA, 2013

14. B. Kellogg, V. Tallat, S. Gollakota. Bringing Gesture Recognition to All Devices. Usenix NSDI'14, Seattle, USA, 2014

15. Understanding the FCC Regulations for Low-power, Nonlicensed Transmitters. Office of Engineering and Technology Federal Communications Commission, 1993

16. T. Ralston, G. Charvat, J. Peabody. Real-Time Through-Wall Imaging Using an Ultrawideband Multiple-Input Multiple-Output (MIMO) Phased Array Radar System. IEEE ARRAY, Massachusetts, USA, 2010

17. Y. Yang, A. Fathy. Design and Implementation of a Low-Cost Real-Time Ultra-Wide Band See-Through-Wall Imaging Radar System. IEEE/MTT-S International Microwave Symposium, Hawaii, USA, 2007