Advanced IOT Applications

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Lecture – 08
RFID based localization – I

So our next goal is to use another very popular IOT technology and design a localization algorithm. In other words, we are trying to see if we can use RFID systems for localization. So, when you talk about this, you talk about several items which are tagged and then there is a reader which is able to read off the tag id.

This is a very simple system and the good thing about this RFID is that there is a large number of tags which do not need any battery power. Although you can also have BAP (Battery Assisted Passive) tags, they will respond only in the event there is a reader. But they are assisted by a battery, which means range can improve vastly. But that is one special case. Do not worry about it, just take the case of totally passive tags.

And in the previous course we spoke so much about those tags, the protocol of RFID, the different type of tags that are there, different applications for RFID so on and so forth. It is good for you to go and refresh that before you start looking up anything related to RFID here, because I am just going to get into localization directly.

Now, when you say a localization of tag, why do you need it first of all and what are the scenarios? Thing is you can have a scenario where you take the case of a factory environment. It is a production place and there is an assembly going on of a certain large part. Let us say an assembly of an aeroplane (just as an example): you are trying to put together the fuselage, the different components of the aeroplane, the wings are getting assembled and different parts are coming together and moving towards a final goal; you are trying to get the aeroplane out.

So, there are parts coming from sub systems and sub parts coming from different parts of the factory. They are manufactured at different places: perhaps within the factory, or also sometimes away from the factory some other place and are coming in.

So, what is typical? Typical is that there are multiple cartons on a vehicle and there are readers essentially pointing towards a door. For instance, it could be the entrance to the place where integration is happening and tags are being read. The carton is having many many tags; many small subsections are there and your issue is that they are all packaged in one.

And readers are placed in one place, the vehicle is moving across, carrying those cartons; which is the imagination. Now issue is if the carton is moving, the tags are moving and this reader has to identify or read tags. But now if you are asked a question, where in that large carton is a particular subsystem that you want to pull out? Or even imagine that within that subsystem has to directly get integrated into the major system, you want to know whether all parts of that subsystem are localized; they are all available; they are all placed and you want to know the location of each one of them. Both possibilities exist.

So, in other words, at a high level let us assume you are interested in localizing the parts, subparts, subcomponents: the component level localization of that large carton which is likely to be part of a major system, then you need a localization algorithm. Now if you go back and look at the previous lecture, and you will realize that RSSI is a good indicator which tells you that you can do some sort of ranging method. Let me show you a small picture of such a system.

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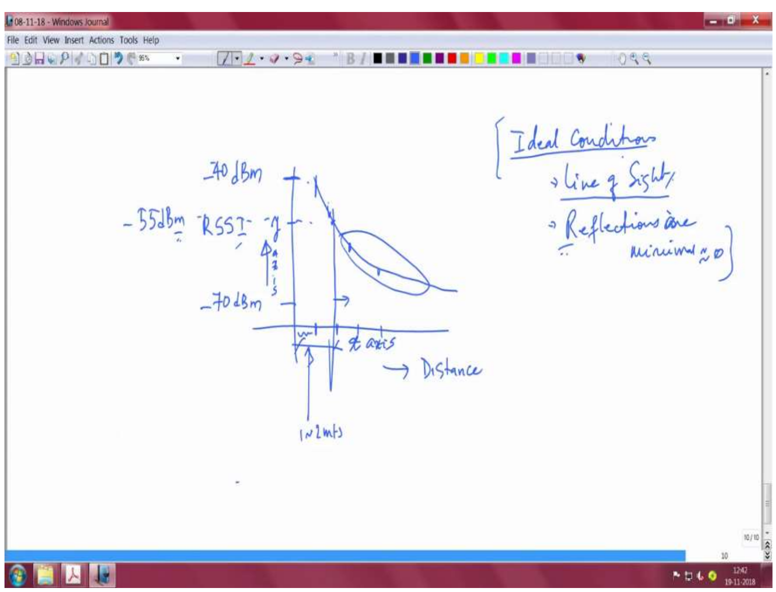

The x-axis has distance and the y-axis is the Received Signal Strength Indicator, which is a nice indicator available at the reader saying how far the tag is. For instance, you can say if the RSSI is high that you read, then you sort of know how much far the tag is from the reader and you could essentially keep marking them and then try to find out how. So, you can actually map somehow. Although this is not a linear relation, somehow you should be able to establish some sort of relationship between RSSI and distance.

However this picture works only under very ideal conditions. Then what are those ideal conditions? You should have line of sight and you should ensure that there are no reflections. The reflections component is minimal, in fact zero. There is also one problem with this graph I can tell you this. Whatever you do in terms of estimation of distance to RSSI, all distance-RSSI measurement: high reliability is achieved only up to some distance. From -40 to about -55; at best about 15 dB is all that actually works. This I would say is 55 for argument sake.

So, your ability to read accurately is not very high. You really do not know whether your -60 that you read is really mapped to a certain distance or is it coming because of any other condition (may be due to reflections or lack of line of sight). So, this is the problem. While it is useful to plot versus x-axis distance and y-axis RSSI, it is not so useful very from a practical perspective because the range prediction that you can do or the distance prediction you can do is over a very small fall in signal strength; beyond that would almost be impossible.

You may now ask the following question that in the example that we are talking about; the carton is just passing by and then there is a reader here. Where is the question of having line of sight? But that is a very ideal way of imagining right, because there can be lot of people, lot of other kind of traffic that is coming in between the reader and the carton. You cannot have reader wherever you wish in a manner you make the technology suitable for making a measurement; that is not the way. A factory floor has certain rules; certain areas which are marked as dangerous and there are safe areas where you can place things. There is a protocol. There is a rule by which vehicles move from a safety perspective.

There is a safety officer in every production floor who is just observing what are the kind of violations that people are doing and if it crosses certain threshold, action is taken. Because it costs a lot of money to companies if there is a worker who has got into an accident situation due to oversight of certain safety measure. So, therefore, you cannot place the antenna wherever you like; there are positions in the factory floor where you can place such antennas.

This may actually stress the whole system that typical RFID tags read range is something in the range of 20 - 22 feet, which is roughly between 5 and 7 meters So, this 5 - 7 meters is essentially might actually fall in region with different slope.

So, now you arrive at a situation where RSSI is almost impossible to be used. Because if it is mapping between 1 to 2 meters; a more linear slope is obtained. Beyond 2 meters, then you obviously have a problem that this picture (slope) cannot be used anymore and this is reality. This is reality even if you have readers facing the tags. In fact on the factory floor, because you are at such a distance there is no way by which you can actually predict the distance of a particular component because ranging is a first step in towards localization. So, ranging with this kind of RSSI signature is not going to work. Fine.

Having motivated ourselves into the RSSI part that it is not a good indicator of ranging of physical distance, what is the other signature that you can get from a signal? It is clear if you take a sine wave: one is the amplitude. In a way, this amplitude is power. More like power RSSI (Received Signal Strength Indicator) is actually power of the signal. If you look back at the basics of any signal: one is power of the signal, the other is the phase of the signal. Phase can be a good indicator. Any literature survey for RFID related localization essentially looks at phase based approaches towards localization.

Now, let us see, what are those algorithms? What are those techniques? Before even getting into algorithms, what are those techniques that are that can be used for the purposes of phase based localization of RFID tags; that is the first part. Second part is you cannot imagine that all scenarios with respect to localization fall under the paradigm of a fixed reader or multiple readers and a carton that is cutting across; that is moving across getting into the factory floor. That is one scenario.

The second scenario is there are objects inside a warehouse: it could be garments, it could be kitchen items, it could be any big departmental store right having kitchen items and so many other related things which are all placed on racks and then there is a reader that moves trying to localize.

So, both possible scenarios will have to be taken into account; one is tag moving and the other is the reader moving. So, it could be one reader or it could be multiple readers.

Let us start with some very simple situations even before getting into any demonstrations, we must know little more about phase based localization and understand what are the different types of phase based localizations that are involved and after that narrow down to one of them and then try and show a demonstration of that essential approach which will sort of summarize the phase based localization. You may have to come up with novel algorithms if you have to use the phase signature in a very effective manner.

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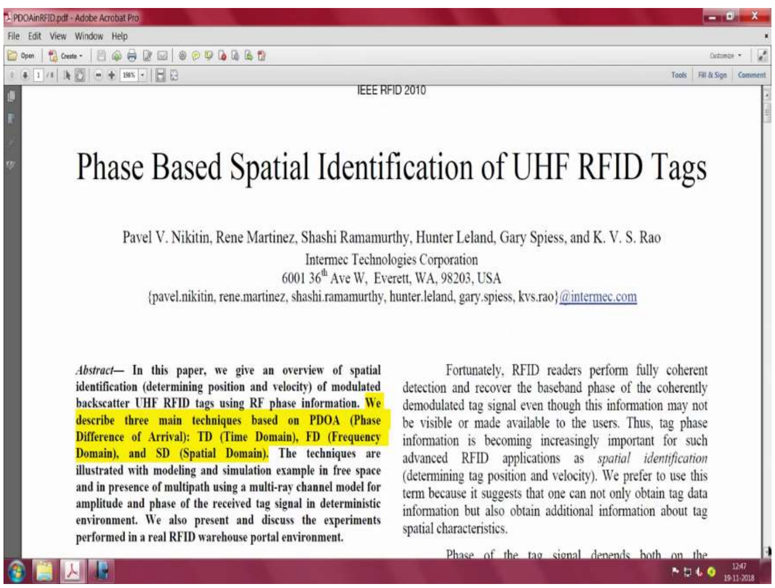

So, with this in mind let me now draw your attention to a paper which I read recently along with my 2 project staff, Tejeshwini and Sanmay Patel, who helped to understand and mark out areas in this paper which essentially talk about RFID localization. Look at the title it says we are looking at UHF RFID tags. Again I do not want to get into the detail because you should look at the previous course which talks about UHF RFID tags. These are all sub-1GHz tags; we are all also talking only about passive tags, which do not have any battery associated with it and just that there is a reader that is throwing power on the tags.

If you look at this, this paper is interesting because it talks about some very basic stuff .We describe 3 main techniques based on PDOA (Phase Difference Of Arrival). So, what are the 3 ways? One is Time domain, the other is Frequency domain and the third one is Spatial domain. Let us jump into and look up directly what we mean by the PDOA: TD- PDOA, FD-PDOA and SD-PDOA. So, let us jump to that part.

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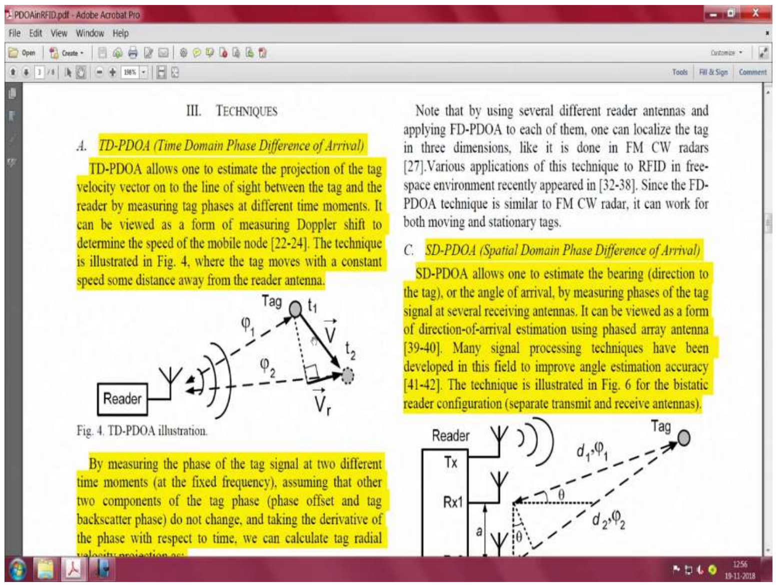
III. TECHNIQUES

A. TD-PDOA (Time Domain Phase Difference of Arrival)

TD-PDOA allows one to estimate the projection of the tag velocity vector on to the line of sight between the tag and the reader by measuring tag phases at different time moments. It can be viewed as a form of measuring Doppler shift to determine the speed of the mobile node [22-24]. The technique is illustrated in Fig. 4, where the tag moves with a constant speed some distance away from the reader antenna.

Fig. 4. TD-PDOA illustration.

By measuring the phase of the tag signal at two different time moments (at the fixed frequency), assuming that other two components of the tag phase (phase offset and tag backscatter phase) do not change, and taking the derivative of the phase with respect to time, we can calculate tag radial

Note that by using several different reader antennas and applying FD-PDOA to each of them, one can localize the tag in three dimensions, like it is done in FM CW radars [27].Various applications of this technique to RFID in free-space environment recently appeared in [32-38]. Since the FD-PDOA technique is similar to FM CW radar, it can work for both moving and stationary tags.

C. SD-PDOA (Spatial Domain Phase Difference of Arrival)

SD-PDOA allows one to estimate the bearing (direction to the tag), or the angle of arrival, by measuring phases of the tag signal at several receiving antennas. It can be viewed as a form of direction-of-arrival estimation using phased array antenna [39-40]. Many signal processing techniques have been developed in this field to improve angle estimation accuracy [41-42]. The technique is illustrated in Fig. 6 for the bistatic reader configuration (separate transmit and receive antennas).

Let us look at TD - PDOA which is the time domain phase difference of arrival. So, first look at the picture. It says the reader is fixed to a position; it is fixed to one position. Typical of what I mentioned about the factory floor and then there is a carton carrying a number of tagged components and you are interested in localizing these tags. So, the tag is moving across and then so let us see what exactly you have to do now. The idea is that you have to estimate the projection of tag velocity vector V on the line of sight between the tag and the reader by measuring the tag phases at different time moments.

You are measuring φ1 at this instant and φ2 at a slightly later instant because the tag has moved to some other distance moving along. So, you will get another tag reading measuring the tag phases at different time moments. So, you are assuming that this tag is moving at a constant speed some distance away from the reader.

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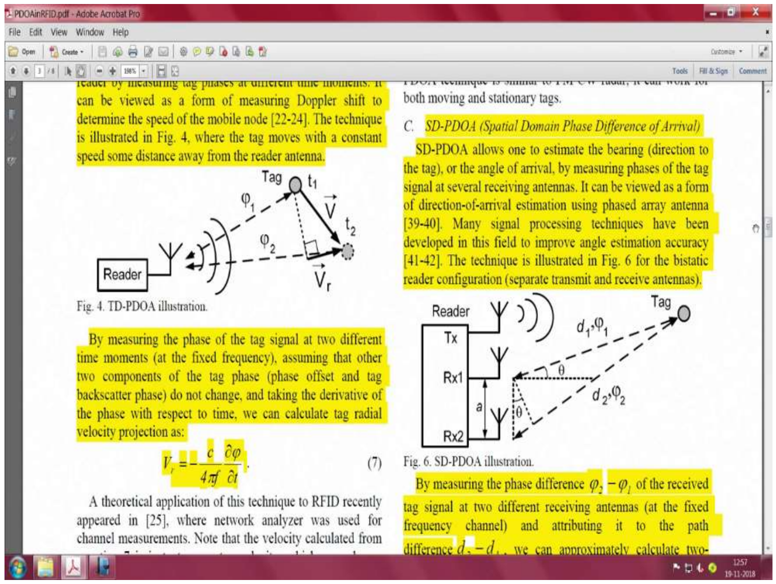
reader by measuring tag phases at different time moments. It can be viewed as a form of measuring Doppler shift to determine the speed of the mobile node [22-24]. The technique is illustrated in Fig. 4, where the tag moves with a constant speed some distance away from the reader antenna.

Fig. 4. TD-PDOA illustration.

By measuring the phase of the tag signal at two different time moments (at the fixed frequency), assuming that other two components of the tag phase (phase offset and tag backscatter phase) do not change, and taking the derivative of the phase with respect to time, we can calculate tag radial velocity projection as:

$$V_r = -\frac{c}{4\pi f}\frac{\partial \varphi}{\partial t}, \quad (7)$$

A theoretical application of this technique to RFID recently appeared in [25], where network analyzer was used for channel measurements. Note that the velocity calculated from

...both moving and stationary tags.

C. *SD-PDOA (Spatial Domain Phase Difference of Arrival)*

SD-PDOA allows one to estimate the bearing (direction to the tag), or the angle of arrival, by measuring phases of the tag signal at several receiving antennas. It can be viewed as a form of direction-of-arrival estimation using phased array antenna [39-40]. Many signal processing techniques have been developed in this field to improve angle estimation accuracy [41-42]. The technique is illustrated in Fig. 6 for the bistatic reader configuration (separate transmit and receive antennas).

Fig. 6. SD-PDOA illustration.

By measuring the phase difference $\varphi_2 - \varphi_1$ of the received tag signal at two different receiving antennas (at the fixed frequency channel) and attributing it to the path difference $d_2 - d_1$, we can approximately calculate two-

Now the idea is if by measuring the phase of the tag signal at 2 different time moments where you are taking the derivative of the phase with respect to time essentially gives you the velocity projection. So, the formula is

$$V_r = -\frac{c}{4\pi f}\frac{\partial \varphi}{\partial f}$$

The base principle is to estimate the velocity of the tag with using this phase signals that you measure at 2 different time intervals .This is essentially the core idea of TD - PDOA.

Now, let us look at FD - PDOA which is essentially the frequency domain phase difference of arrival.

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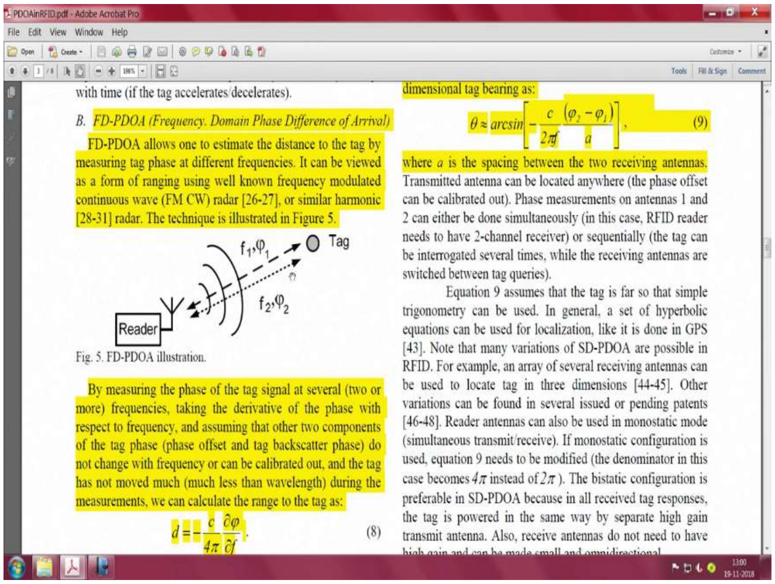

with time (if the tag accelerates/decelerates).

B. FD-PDOA (Frequency. Domain Phase Difference of Arrival)

FD-PDOA allows one to estimate the distance to the tag by measuring tag phase at different frequencies. It can be viewed as a form of ranging using well known frequency modulated continuous wave (FM CW) radar [26-27], or similar harmonic [28-31] radar. The technique is illustrated in Figure 5.

Fig. 5. FD-PDOA illustration.

By measuring the phase of the tag signal at several (two or more) frequencies, taking the derivative of the phase with respect to frequency, and assuming that other two components of the tag phase (phase offset and tag backscatter phase) do not change with frequency or can be calibrated out, and the tag has not moved much (much less than wavelength) during the measurements, we can calculate the range to the tag as:

$$d = -\frac{c}{4\pi}\frac{\partial\varphi}{\partial f}, \quad (8)$$

dimensional tag bearing as:

$$\theta \approx \arcsin\left[-\frac{c}{2\pi f}\frac{(\varphi_2 - \varphi_1)}{a}\right], \quad (9)$$

where a is the spacing between the two receiving antennas. Transmitted antenna can be located anywhere (the phase offset can be calibrated out). Phase measurements on antennas 1 and 2 can either be done simultaneously (in this case, RFID reader needs to have 2-channel receiver) or sequentially (the tag can be interrogated several times, while the receiving antennas are switched between tag queries).

Equation 9 assumes that the tag is far so that simple trigonometry can be used. In general, a set of hyperbolic equations can be used for localization, like it is done in GPS [43]. Note that many variations of SD-PDOA are possible in RFID. For example, an array of several receiving antennas can be used to locate tag in three dimensions [44-45]. Other variations can be found in several issued or pending patents [46-48]. Reader antennas can also be used in monostatic mode (simultaneous transmit/receive). If monostatic configuration is used, equation 9 needs to be modified (the denominator in this case becomes 4π instead of 2π). The bistatic configuration is preferable in SD-PDOA because in all received tag responses, the tag is powered in the same way by separate high gain transmit antenna. Also, receive antennas do not need to have

Any time you read such paragraphs you have to keep imagining what are the assumptions under which such a measurement is done: this is absolutely critical in such a course. What are the assumptions? What are the underlying assumptions? Look back at TD-PDOA, look at the assumptions that it has made. Now let us see, what is the assumption here and how do you do a measurement. It is not a setting where the reader is fixed and the tags are moving. It does not make that assumption; it is trying to do a localization using another technique for some other scenario.

So, let us look at here. It allows to estimate of distance to the tag by measuring tag phases at different frequencies. To understand, you have to go back to your fundamentals. What are the sweep frequencies that a reader can provide support? By the way, this technique is also something that FMCW radars use which are very popular and also in automotive applications.

So, the technique is quite simple: you measure the phase of the tag signal at several frequencies, two or more frequencies; taking the derivative of the phase with respect to frequency. And assuming that other two components of the tag phase i.e phase offset and tag backscatter phase do not change with frequency or can be removed (nothing, but calibrated out) and the tag has not moved much: this is important during the measurement. We can calculate using this very simple expression given here.

$$d = -\frac{c}{4\pi}\frac{\partial\varphi}{\partial f}$$

Note that using several different reader antennas and applying FD-PDOA to each one of them, one can localize the tag in 3-dimension like it is done in FM CW radars. This makes one critical assumption that you have a large sweep bandwidth; only then this is a good technique for you to try. Now that brings us to the third way of localizing which is based on the spatial domain phase difference of arrival.

The moment you see such a picture you have to look at it and say what the assumptions are, under which this technique can be applied. Now let us see you have reader with multiple receive antennas Rx1 and Rx2, and they have a separation. "What should be the separation?" You have to ask yourself is there a limitation on this, or how should I set "*a*", the small "*a*", how do I set this? And you see there is a transmit antenna which is throwing power on the tag and these two receive antennas are reading off the tag response. Of course, RSSI will be there, but we do not use it. But we are interested in the phase information that the readers antenna actually the antennas actually read off, one is φ1 and that the other is φ2.

Now it is quite simple if you have a separation of "*a*" between this Rx1 and Rx2: d1 is the distance between the tag and Rx1 and d2 is essentially the distance between Rx2 and the tag. It is now simple that if you take by measuring the phase difference φ2 - φ1 of the received tag signal at two different receiving antennas and attributing it to the path difference d2 - d1, we can approximately calculate 2-dimensional tag bearing using following arc sine expression.

$$\theta \approx \arcsin\left[-\frac{c}{2\pi f}\frac{(\varphi 2 - \varphi 1)}{a}\right]$$

Now, essentially this brings us to a very important point which is "*a*", how is this "*a*" to be used? "*a*" is the spacing between the 2 receiving antennas and it can be set in certain ways. The transmitter antenna can be located anywhere (not important), but phase measurements on antenna 1 and antenna 2 can be done simultaneously. This is a very simple technique where you are essentially trying to convert the phase difference into path difference; this is the crux of the story and then using given expression you can actually approximately calculate $\boldsymbol{\theta}$ by just measuring φ2 and φ1 and knowing "*a*".

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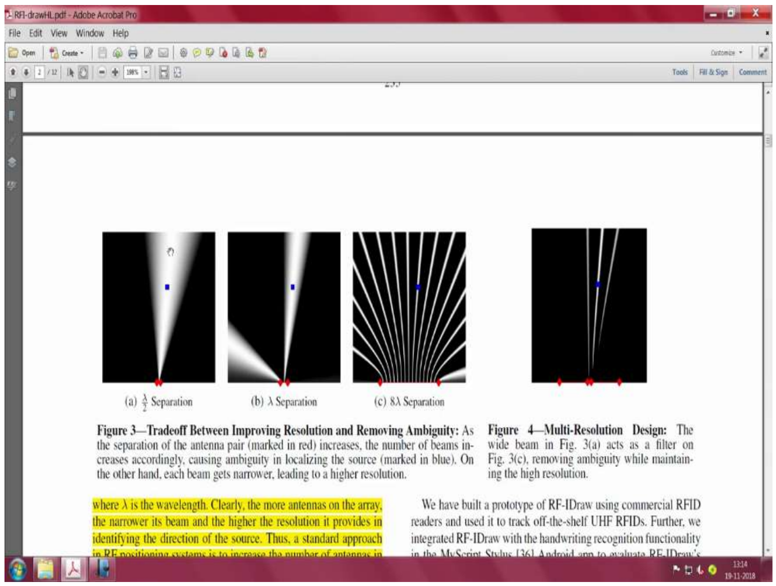

Now, we spoke about this receive antenna separation and "*a*". Now question is how should you set this "*a*" right? There is a full paper theory on how this should actually be set; it is quite intuitive actually.

Let me show you some pictures on setting of this "*a*" and how you will trade off resolution with ambiguity.

So, let me point it out. Supposing you have "*a*", the separation between the 2 antennas set to λ/2. You know the frequency of operation of RFID; from there you find out λ and then you do λ/2. Suppose you have λ/2, just look at this picture: there are 2 antenna as 2 dots here. Similarly if you have λ separation, you have 2 beams going out divergently. Suppose you have 8 λ separation in "*a*" and what if you had a separation like the white beam in figure 3a; this is 'a' acts as a filter on figure 3c on this, has a filter on figure 3. It is a removing ambiguity while maintaining high resolution.

Now, you must understand this picture and keep the following in mind the take away indeed is it is nothing but the tradeoff between improving resolution and removing ambiguity. As the separation of the antenna pair increases, the number of beams also increases, that is obvious, causing ambiguity in localizing the source which is marked in blue, which is nothing but the tag of interest. On the other hand each beam gets narrower leading to higher resolution. If 8 λ is used, the resolution is very high but ambiguity is extreme, it is very highly ambiguous. In other words the resolution is good, but ambiguity is also very high.

If you do λ separation, you have λ separation of between the 2 receiver antennas. Please note again that you have a problem of one beam going in a different direction and the other beam is actually holding onto the tag. So, you have a lot of problem there as well and although the ambiguity is just down to either it is in this beam or in that beam.

But if you take the λ/2 separation, the resolution is poor. You do not know where in the particular beam the tag is actually located. But ambiguity is not there; is almost eliminated. So, essentially we are trying to trade the ambiguity to resolution by having different separations between the antennas.

All of this is captured in this beautiful paper which is called RF-IDraw.

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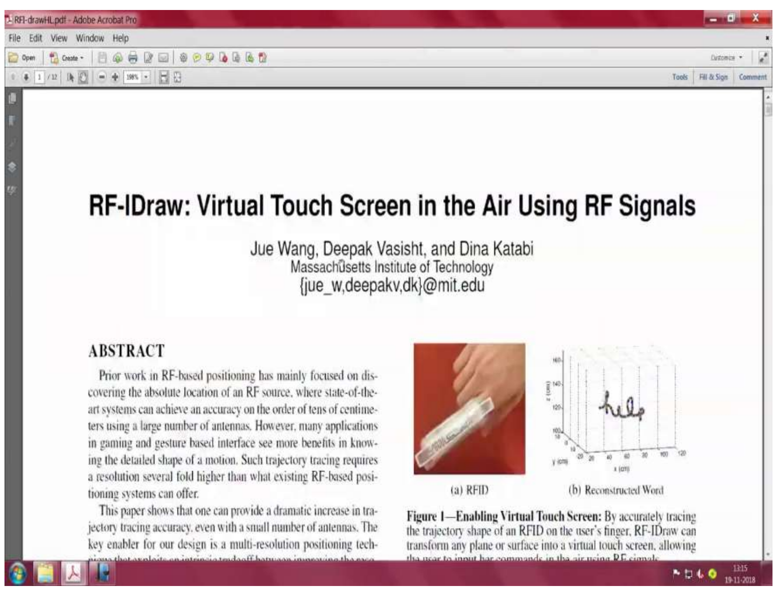

This paper was published in one of the SIGCOMM conferences and I encourage you to essentially read this paper in great detail, so, that you will appreciate the evaluation done in this paper.

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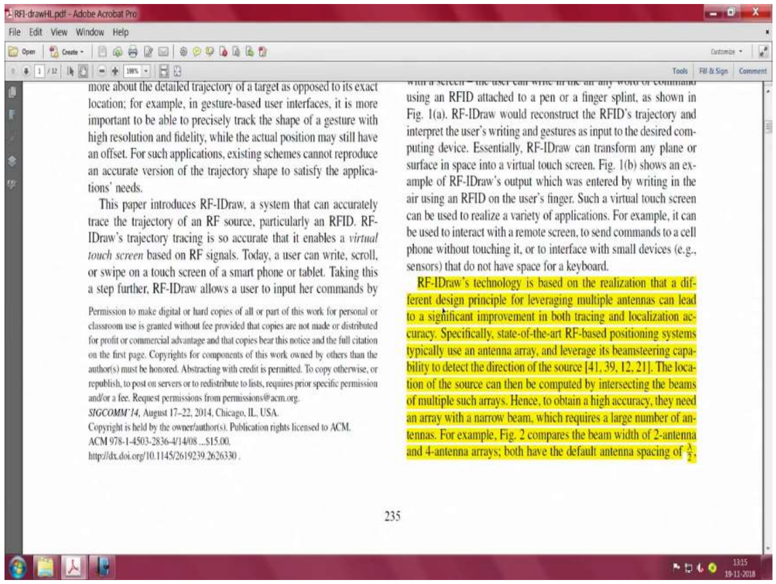
more about the detailed trajectory of a target as opposed to its exact location; for example, in gesture-based user interfaces, it is more important to be able to precisely track the shape of a gesture with high resolution and fidelity, while the actual position may still have an offset. For such applications, existing schemes cannot reproduce an accurate version of the trajectory shape to satisfy the applications' needs.

This paper introduces RF-IDraw, a system that can accurately trace the trajectory of an RF source, particularly an RFID. RF-IDraw's trajectory tracing is so accurate that it enables a *virtual touch screen* based on RF signals. Today, a user can write, scroll, or swipe on a touch screen of a smart phone or tablet. Taking this a step further, RF-IDraw allows a user to input her commands by

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using an RFID attached to a pen or a finger splint, as shown in Fig. 1(a). RF-IDraw would reconstruct the RFID's trajectory and interpret the user's writing and gestures as input to the desired computing device. Essentially, RF-IDraw can transform any plane or surface in space into a virtual touch screen. Fig. 1(b) shows an example of RF-IDraw's output which was entered by writing in the air using an RFID on the user's finger. Such a virtual touch screen can be used to realize a variety of applications. For example, it can be used to interact with a remote screen, to send commands to a cell phone without touching it, or to interface with small devices (e.g., sensors) that do not have space for a keyboard.

RF-IDraw's technology is based on the realization that a different design principle for leveraging multiple antennas can lead to a significant improvement in both tracing and localization accuracy. Specifically, state-of-the-art RF-based positioning systems typically use an antenna array, and leverage its beamsteering capability to detect the direction of the source [41, 39, 12, 21]. The location of the source can then be computed by intersecting the beams of multiple such arrays. Hence, to obtain a high accuracy, they need an array with a narrow beam, which requires a large number of antennas. For example, Fig. 2 compares the beam width of 2-antenna and 4-antenna arrays; both have the default antenna spacing of $\frac{\lambda}{2}$,

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So, this paper essentially is a realization of different principle of leveraging multiple antenna and how it can improve both tracing as well as localization accuracy, diffuses state-of-art positioning systems and a situation is developed where you need an array of antenna. Because you will be able to do SD-PDOA provided you have multiple receiving antenna. So, if you have to obtain a high accuracy you need to have a narrow beam. And therefore, you need large number of antenna and how the separation should be.

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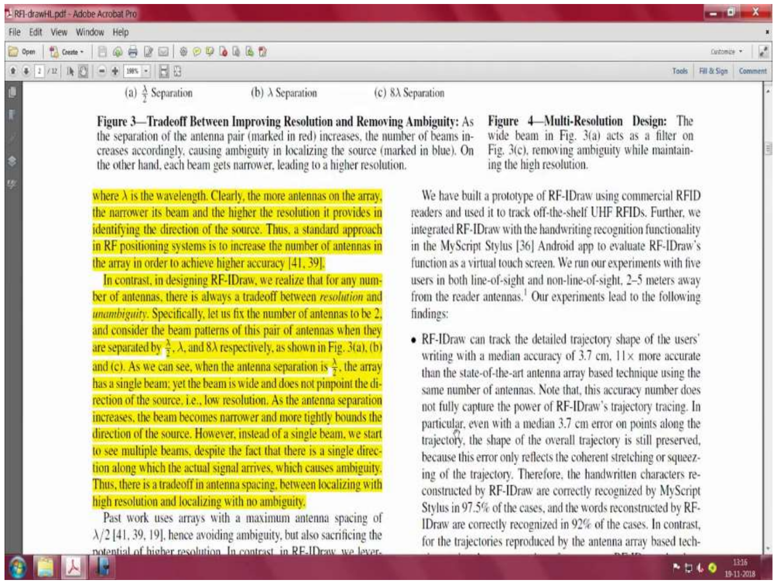
(a) $\frac{\lambda}{2}$ Separation (b) λ Separation (c) 8λ Separation

Figure 3—Tradeoff Between Improving Resolution and Removing Ambiguity: As the separation of the antenna pair (marked in red) increases, the number of beams increases accordingly, causing ambiguity in localizing the source (marked in blue). On the other hand, each beam gets narrower, leading to a higher resolution.

Figure 4—Multi-Resolution Design: The wide beam in Fig. 3(a) acts as a filter on Fig. 3(c), removing ambiguity while maintaining the high resolution.

where λ is the wavelength. Clearly, the more antennas on the array, the narrower its beam and the higher the resolution it provides in identifying the direction of the source. Thus, a standard approach in RF positioning systems is to increase the number of antennas in the array in order to achieve higher accuracy [41, 39].

In contrast, in designing RF-IDraw, we realize that for any number of antennas, there is always a tradeoff between *resolution* and *unambiguity*. Specifically, let us fix the number of antennas to be 2, and consider the beam patterns of this pair of antennas when they are separated by $\frac{\lambda}{2}$, λ, and 8λ respectively, as shown in Fig. 3(a), (b) and (c). As we can see, when the antenna separation is $\frac{\lambda}{2}$, the array has a single beam; yet the beam is wide and does not pinpoint the direction of the source, i.e., low resolution. As the antenna separation increases, the beam becomes narrower and more tightly bounds the direction of the source. However, instead of a single beam, we start to see multiple beams, despite the fact that there is a single direction along which the actual signal arrives, which causes ambiguity. Thus, there is a tradeoff in antenna spacing, between localizing with high resolution and localizing with no ambiguity.

Past work uses arrays with a maximum antenna spacing of λ/2 [41, 39, 19], hence avoiding ambiguity, but also sacrificing the potential of higher resolution. In contrast, in RF-IDraw, we lever-

We have built a prototype of RF-IDraw using commercial RFID readers and used it to track off-the-shelf UHF RFIDs. Further, we integrated RF-IDraw with the handwriting recognition functionality in the MyScript Stylus [36] Android app to evaluate RF-IDraw's function as a virtual touch screen. We run our experiments with five users in both line-of-sight and non-line-of-sight, 2–5 meters away from the reader antennas.[1] Our experiments lead to the following findings:

- RF-IDraw can track the detailed trajectory shape of the users' writing with a median accuracy of 3.7 cm, 11× more accurate than the state-of-the-art antenna array based technique using the same number of antennas. Note that, this accuracy number does not fully capture the power of RF-IDraw's trajectory tracing. In particular, even with a median 3.7 cm error on points along the trajectory, the shape of the overall trajectory is still preserved, because this error only reflects the coherent stretching or squeezing of the trajectory. Therefore, the handwritten characters reconstructed by RF-IDraw are correctly recognized by MyScript Stylus in 97.5% of the cases, and the words reconstructed by RF-IDraw are correctly recognized in 92% of the cases. In contrast, for the trajectories reproduced by the antenna array based tech-

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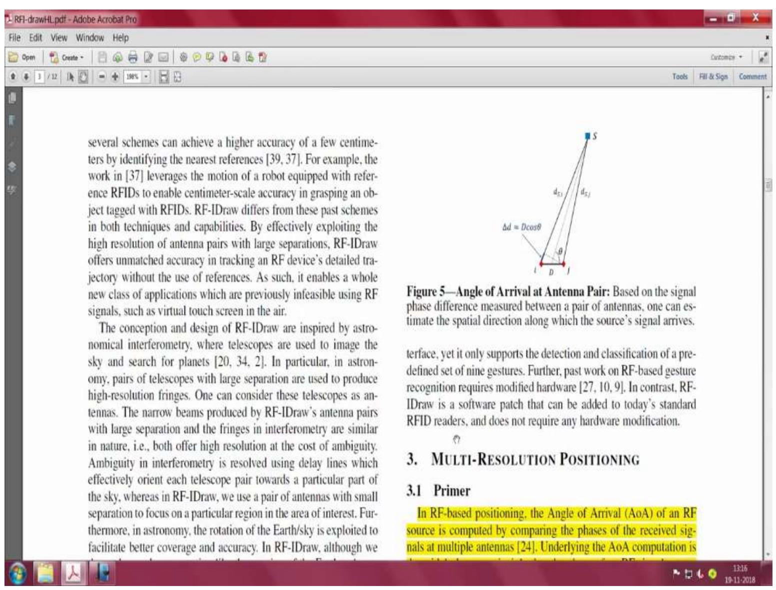
several schemes can achieve a higher accuracy of a few centimeters by identifying the nearest references [39, 37]. For example, the work in [37] leverages the motion of a robot equipped with reference RFIDs to enable centimeter-scale accuracy in grasping an object tagged with RFIDs. RF-IDraw differs from these past schemes in both techniques and capabilities. By effectively exploiting the high resolution of antenna pairs with large separations, RF-IDraw offers unmatched accuracy in tracking an RF device's detailed trajectory without the use of references. As such, it enables a whole new class of applications which are previously infeasible using RF signals, such as virtual touch screen in the air.

The conception and design of RF-IDraw are inspired by astronomical interferometry, where telescopes are used to image the sky and search for planets [20, 34, 2]. In particular, in astronomy, pairs of telescopes with large separation are used to produce high-resolution fringes. One can consider these telescopes as antennas. The narrow beams produced by RF-IDraw's antenna pairs with large separation and the fringes in interferometry are similar in nature, i.e., both offer high resolution at the cost of ambiguity. Ambiguity in interferometry is resolved using delay lines which effectively orient each telescope pair towards a particular part of the sky, whereas in RF-IDraw, we use a pair of antennas with small separation to focus on a particular region in the area of interest. Furthermore, in astronomy, the rotation of the Earth/sky is exploited to facilitate better coverage and accuracy. In RF-IDraw, although we

Figure 5—Angle of Arrival at Antenna Pair: Based on the signal phase difference measured between a pair of antennas, one can estimate the spatial direction along which the source's signal arrives.

terface, yet it only supports the detection and classification of a predefined set of nine gestures. Further, past work on RF-based gesture recognition requires modified hardware [27, 10, 9]. In contrast, RF-IDraw is a software patch that can be added to today's standard RFID readers, and does not require any hardware modification.

3. MULTI-RESOLUTION POSITIONING

3.1 Primer

In RF-based positioning, the Angle of Arrival (AoA) of an RF source is computed by comparing the phases of the received signals at multiple antennas [24]. Underlying the AoA computation is

So, then let us go slowly into this picture which is SD- PDOA. What is this picture saying? There is a tag which is S in this paper; they use S as a notation and there are 2 positions for the receiver antenna, one position is this "*i*" and the other position is "*j*" and they are separated by a distance D. dsi and dsj are essentially distances from the source to point "*i*" and dsj is from the distance between the source to the point "*j*".

The distance dsi is greater than dsj by Δd, which is given as Δd = Dcosθ.

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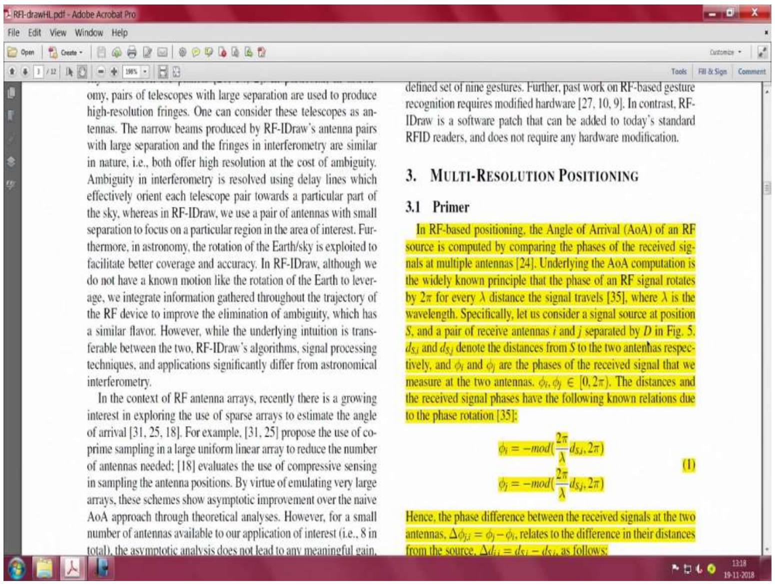
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In the context of RF antenna arrays, recently there is a growing interest in exploring the use of sparse arrays to estimate the angle of arrival [31, 25, 18]. For example, [31, 25] propose the use of co-prime sampling in a large uniform linear array to reduce the number of antennas needed; [18] evaluates the use of compressive sensing in sampling the antenna positions. By virtue of emulating very large arrays, these schemes show asymptotic improvement over the naive AoA approach through theoretical analyses. However, for a small number of antennas available to our application of interest (i.e., 8 in total), the asymptotic analysis does not lead to any meaningful gain.

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3. Multi-Resolution Positioning

3.1 Primer

In RF-based positioning, the Angle of Arrival (AoA) of an RF source is computed by comparing the phases of the received signals at multiple antennas [24]. Underlying the AoA computation is the widely known principle that the phase of an RF signal rotates by 2π for every λ distance the signal travels [35], where λ is the wavelength. Specifically, let us consider a signal source at position S, and a pair of receive antennas i and j separated by D in Fig. 5. $d_{S,i}$ and $d_{S,j}$ denote the distances from S to the two antennas respectively, and ϕ_i and ϕ_j are the phases of the received signal that we measure at the two antennas. $\phi_i, \phi_j \in [0, 2\pi)$. The distances and the received signal phases have the following known relations due to the phase rotation [35]:

$$\phi_i = -mod(\frac{2\pi}{\lambda} d_{S,i}, 2\pi)$$
$$\phi_j = -mod(\frac{2\pi}{\lambda} d_{S,j}, 2\pi) \quad (1)$$

Hence, the phase difference between the received signals at the two antennas, $\Delta\phi_{j,i} = \phi_j - \phi_i$, relates to the difference in their distances from the source, $\Delta d_{i,j} = d_{S,j} - d_{S,i}$, as follows:

This paper is essentially looking at the underlying computation of angle of arrival using the rotation of RF signal by 2π for every λ distance. Let me take a new sheet to explain this.

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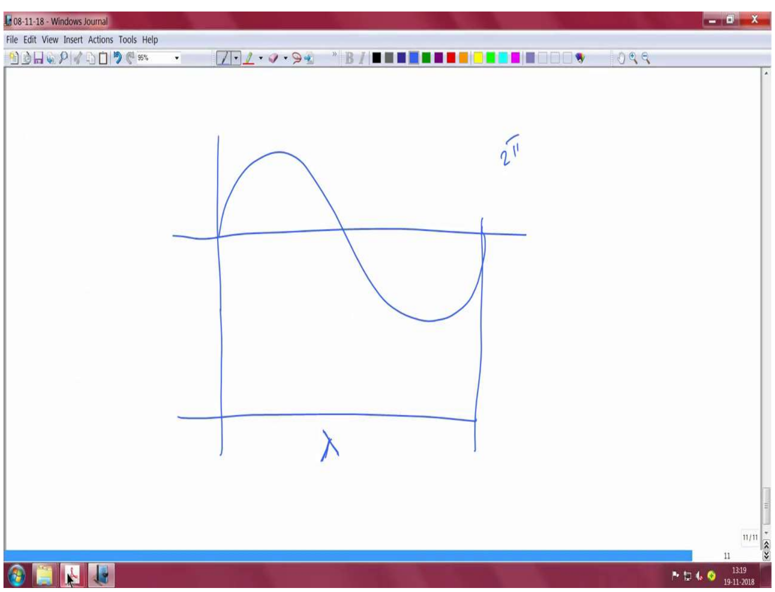

If you take a sine wave of one cycle, what should be the length? This should be λ. So, this 2π of phase is indeed λ. So, let us go back and connect back to this picture here. The phase of an RF signal rotates by 2π for every λ distance, where λ is the wavelength. Specifically let us consider a signal source at position S and a pair of receive antennas *i* and *j*. You have φi and φj: lie between 0 and 2π. The distances and the received phase signal phases have the following known relationships due to estimated phase rotation.

$$\phi_i = -mod(\frac{2\pi}{\lambda} d_{S,i}, 2\pi)$$
$$\phi_j = -mod(\frac{2\pi}{\lambda} d_{S,j}, 2\pi)$$

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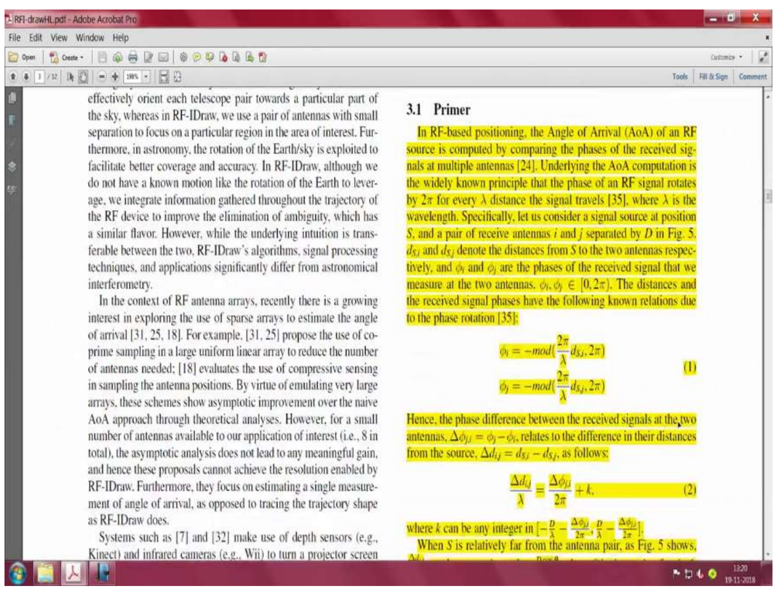

effectively orient each telescope pair towards a particular part of the sky, whereas in RF-IDraw, we use a pair of antennas with small separation to focus on a particular region in the area of interest. Furthermore, in astronomy, the rotation of the Earth/sky is exploited to facilitate better coverage and accuracy. In RF-IDraw, although we do not have a known motion like the rotation of the Earth to leverage, we integrate information gathered throughout the trajectory of the RF device to improve the elimination of ambiguity, which has a similar flavor. However, while the underlying intuition is transferable between the two, RF-IDraw's algorithms, signal processing techniques, and applications significantly differ from astronomical interferometry.

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Systems such as [7] and [32] make use of depth sensors (e.g., Kinect) and infrared cameras (e.g., Wii) to turn a projector screen

3.1 Primer

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$$\frac{\Delta d_{i,j}}{\lambda} = \frac{\Delta\phi_{j,i}}{2\pi} + k, \quad (2)$$

where k can be any integer in $[-\frac{D}{\lambda} - \frac{\Delta\phi_{j,i}}{2\pi}, \frac{D}{\lambda} - \frac{\Delta\phi_{j,i}}{2\pi}]$.

When S is relatively far from the antenna pair, as Fig. 5 shows,

You can calculate ϕ_i and ϕ_j using above expressions. Both are identical as you can see except that this dS,i and this is dS,j and then you find out the phase difference ϕ_j - ϕ_i and relate it to the path difference between the 2 signals.

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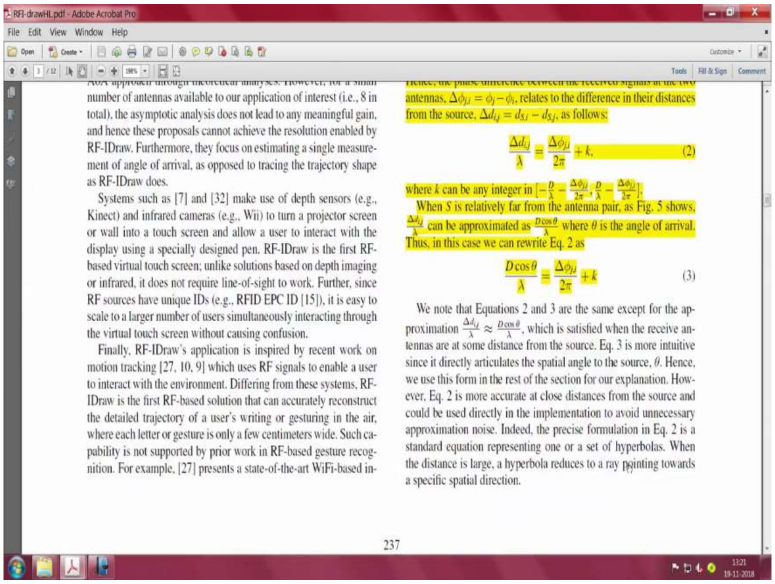

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Systems such as [7] and [32] make use of depth sensors (e.g., Kinect) and infrared cameras (e.g., Wii) to turn a projector screen or wall into a touch screen and allow a user to interact with the display using a specially designed pen. RF-IDraw is the first RF-based virtual touch screen; unlike solutions based on depth imaging or infrared, it does not require line-of-sight to work. Further, since RF sources have unique IDs (e.g., RFID EPC ID [15]), it is easy to scale to a larger number of users simultaneously interacting through the virtual touch screen without causing confusion.

Finally, RF-IDraw's application is inspired by recent work on motion tracking [27, 10, 9] which uses RF signals to enable a user to interact with the environment. Differing from these systems, RF-IDraw is the first RF-based solution that can accurately reconstruct the detailed trajectory of a user's writing or gesturing in the air, where each letter or gesture is only a few centimeters wide. Such capability is not supported by prior work in RF-based gesture recognition. For example, [27] presents a state-of-the-art WiFi-based in-

antennas, $\Delta\phi_{j,i} = \phi_j - \phi_i$, relates to the difference in their distances from the source, $\Delta d_{i,j} = d_{S,i} - d_{S,j}$, as follows:

$$\frac{\Delta d_{i,j}}{\lambda} = \frac{\Delta\phi_{j,i}}{2\pi} + k, \qquad (2)$$

where k can be any integer in $[-\frac{D}{\lambda} - \frac{\Delta\phi_{j,i}}{2\pi}, \frac{D}{\lambda} - \frac{\Delta\phi_{j,i}}{2\pi}]$.

When S is relatively far from the antenna pair, as Fig. 5 shows, $\frac{\Delta d_{i,j}}{\lambda}$ can be approximated as $\frac{D\cos\theta}{\lambda}$ where θ is the angle of arrival. Thus, in this case we can rewrite Eq. 2 as

$$\frac{D\cos\theta}{\lambda} = \frac{\Delta\phi_{j,i}}{2\pi} + k \qquad (3)$$

We note that Equations 2 and 3 are the same except for the approximation $\frac{\Delta d_{i,j}}{\lambda} \approx \frac{D\cos\theta}{\lambda}$, which is satisfied when the receive antennas are at some distance from the source. Eq. 3 is more intuitive since it directly articulates the spatial angle to the source, θ. Hence, we use this form in the rest of the section for our explanation. However, Eq. 2 is more accurate at close distances from the source and could be used directly in the implementation to avoid unnecessary approximation noise. Indeed, the precise formulation in Eq. 2 is a standard equation representing one or a set of hyperbolas. When the distance is large, a hyperbola reduces to a ray pointing towards a specific spatial direction.

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And essentially you come up with the given expression.

$$\frac{\Delta d_{i,j}}{\lambda} = \frac{\Delta\phi_{j,i}}{2\pi} + k$$

You will use this phase difference and convert it to path difference, and construct what are known as multiple hyperbola and look at the intersection of these hyperbolas to determine the exact position of the tag.