Paramvir Bahl *Microsoft Research*

Editor: Carla Schlatter Ellis

INDOOR LOCALIZATION: Are We There Yet?

Wi-Fi–based indoor localization is a solved problem — given a space with enough Wi-Fi access points (APs) and a set of radio frequency (RF) signal strength measurements that profile the environment, we can provide a service that can accurately locate uncalibrated devices in that space. No one would argue with this assertion, yet after more than 15 years of research, there are no pervasive products and the research community continues to work on this problem. Why?

REFLECTING BACK

It was the summer of 1997, I had joined Microsoft Research (MSR) after completing my PhD. I remember being excited. I wanted to do something big, work on ideas that would have a broad impact. This was around the time when IEEE 802.11 hadn't yet been standardized. There were very few companies that sold wireless LAN network cards and access points and, of those that did, the cards were pre-standard and expensive — costing several hundred dollars, and targeted at niche markets.

Like most new hires, I wanted to make a strong positive impression on my employer. So my first bold idea was to turn Bldg. 31, which was Microsoft Research's home, into a giant .11 lab where I would pursue wireless research at scale. After some diligence, I settled on a product by a small company called Aironet Wireless Communications. Two years later, this company was bought by Cisco Systems Inc. for $800 million. The ability to program a wireless network card was critical for me to pursue my research ideas but I wasn't able to do this because Windows NT 4.0 and all other popular operating systems of the time exposed the wireless card to higher layer networking protocols, operating system, and applications as an Ethernet card. This severely limited my ability to do anything substantial in terms of improving the performance of the network or enabling new wireless features. It hampered my big plans to write code that would be broadly adopted, code that would gracefully handle the impact of changing channel conditions and would allow developers to write novel applications.

Being a good researcher, I wrote an internal technical paper titled "Wireless is not Ethernet" and approached the Windows operating systems team about this issue. In this paper I laid out all the different reasons why the existing programming interface for network cards, called NDIS, needed to be expanded to accommodate the differences between wired and wireless networking. I went to great pains to write an application programming interface (API) specification in a format that the Windows operating system kernel group was familiar with. The engineers and program managers appreciated my effort but didn't move on it because it was all theory.

Disappointed but unfazed, I began scheming. How could I prove to the skeptics in the product groups that a programmable wireless interface would be a valuable feature that would contribute to the bottom line of their product?

About two years earlier, while working on my PhD, I spent some time at Boston University working with another PhD student on a pattern recognition problem. We worked on the problem of trajectory prediction of a mobile in wireless cellular networks. Our idea: if our system could learn the pattern of movement for users and use that to predict their future trajectory, the cellular network would pre-allocate resources at the upcoming base stations and there would be fewer dropped calls during call handoff. My electrical engineering education had equipped me with a useful bag of signal processing tools that I could draw from. I drew from these and developed a modified self-learning Kalman filter to predict the next state space, which included the position and speed of the mobile. I was inspired by how military radar systems tracked and predicted enemy missiles and aircrafts. This research led to my first journal paper on location determination in an IEEE Journal [1]. With this experience, I thought of building a location determination system in MSR's IEEE 802.11 building network.

I had recently hired a bright young PhD from Berkeley, Venkat Padmanabhan. He expressed interest in pursuing this line of research so we began working together. We knew about the inspirational work from Olivetti Research on the Active Badge system [2]. As part of my research I also uncovered a nice 1993 paper by Christ and Goodwin on a Duress Alarm Location System (DALS) [3]. Unlike the Active Badge systems, which used infrared signals, DALS used radio frequency signals but both systems were similar in that they required specialized hardware, which made them expensive. From the very beginning, we were very clear that our system had to be built on top of existing, already deployed hardware, providing additional value through the magic of software and this led to RADAR [4].

We showed RADAR to our product group colleagues and they were visibly impressed. As I had hoped, they assigned a program manager to oversee NDIS extensions for wireless and to investigate commercializing of indoor localization. To us it looked as if things were moving in the right direction so we focused on making our system bullet-proof. The Windows program manager talked to several potential customers while coming up with a resource ask,

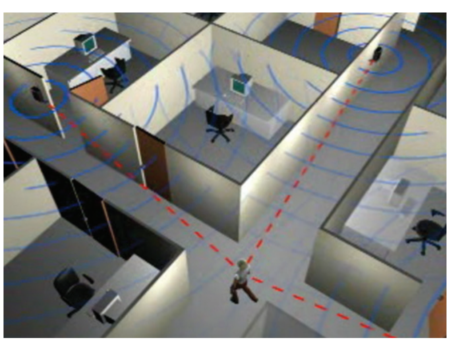

FIGURE 1. A video of RADAR in operation was first shown by Rick Rashid, the head of Microsoft Research, as part of his keynote talk on Aug. 17, 1999 at the fifth annual MobiCom conference in Seattle, Wash., USA.

development plan, and deployment strategy. Unfortunately, after all this, the product group decided not to pursue further because their market research revealed that their customers did not see enough of a value for the amount of time and effort needed to get the system up and running.

This was frustrating. Since then, over the years I have seen hundreds of researchers, from all over the world, publish thousands of papers on indoor localization. I have read numerous marketing reports that look into the crystal ball and predict that indoor localization will have a "revolutionary effect" on mobile applications and services, and I have evaluated numerous start-ups that have emerged and died. Broadly, these researchers and companies focused on three things: (1) Improving the positioning accuracy by exploiting new hardware capabilities (2) Tracking user's motion by using device sensors such as compass, gyroscope, and accelerometer, and (3) Making it easy for indoor positioning systems to be deployed and managed. With the emergence of SmartPhones, I have also seen researchers and entrepreneurs energetically advocate new indoor location scenarios — all in the backdrop of making the value proposition compelling. (Note: my focus in this paper is on Wi-Fi based localization techniques, though most of my observations carry over to other indoor localization technologies, such as those based on Bluetooth Low Energy, Infrared, ultrasound, vision and hybrid systems. However, with specialized hardware, the value proposition bar goes up even more.)

THE SUSTAINABILITY PROBLEM

In experiments conducted by colleagues in a MSR building approximately two years ago, immediately after profiling a space, the room-level localization repeatability was over 95%, i.e., in more than 95% of times, the researchers correctly located which room the device was in. However, one month later, this accuracy had dropped to less than 50%. This is a manifestation of a real-world problem, which our product groups experienced in the course of their evaluation in a popular shopping mall. There was an occasion when the Apple store in the Bellevue Square Mall in Washington was relocated to a different floor, resulting in a large scale change in the Wi-Fi landscape in the mall, literally overnight. This significantly changed the location accuracy of their system as the previous RF fingerprints were no longer valid. Periodic surveying, while possible, not only means additional effort and cost but also cannot always be anticipated (for example, the change could happen a day after resurveying is completed, crippling localization accuracy until the next resurvey, possibly months later).

So the technical problem is, how can we efficiently and continuously (progressively) maintain the RF signal strength (signature) database. Researchers have proposed a few approaches but none has emerged as a clear winner. Examples include dedicated profiling, where companies hire individuals to walk inside the shopping malls to update their maps regularly, this is equivalent to what large companies such as Microsoft, Google, and Nokia/Navteq do for outdoor mapping software. Generally speaking, this is time consuming and costly and it still does not solve the problem of unanticipated changes in the environment as explained previously. Such human-intensive methods can take as much as 12 person-hours to profile a midsize American mall. Another idea is to do profiling via crowdsourcing, where users participate in updating the RF signature database [10]. But crowdsourcing techniques can create a privacy problem. Updating the RF signatures along with the device's location can divulge information about the user, and this, when combined with sophisticated data mining techniques, can potentially lead to serious undesired consequences. Unfortunately, as I examine the large number of start-ups and established companies that are working on indoor localization, none provides a guaranteed accuracy because continuous profiling continues to be an unsolved problem.

HOW MUCH ACCURACY IS GOOD ENOUGH?

Our work on RADAR done ~15 years ago showed that good indoor localization accuracy could be obtained using pattern matching of RF fingerprints. There is a large body of subsequent work that has made significant improvements in the accuracy while still using radio fingerprinting as the fundamental technique. Furthermore, researchers have added improvements

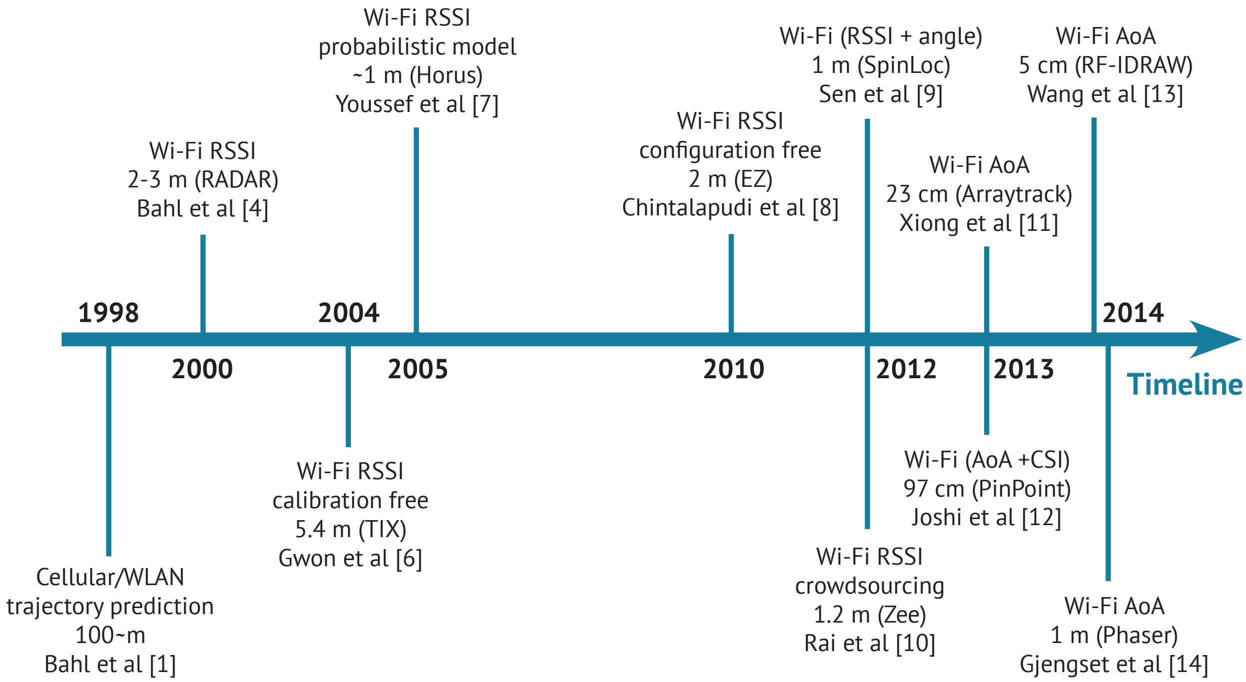

FIGURE 2. A sample of the indoor localization techniques and their target accuracy as claimed by the inventors (RSSI: Received Signal Strength Information; AoA: Angle of Arrival; CSI: Channel State Information).

ranging from probabilistic modelling to sensor-based augmentation and multiple antennas to improve accuracy to within a meter. Researchers have also developed techniques to reduce the calibration effort needed for RF fingerprinting — these techniques range from reducing the number of samples by interpolating between them to crowdsourcing to improve the quality of the fingerprint database. Different amounts of accuracy enable different scenarios which we will discuss later. In the meantime, Figure 2 illustrates my view of the evolution of Wi-Fi based localization and the amount of accuracy researchers have been able to achieve. This figure is not a comprehensive survey, but simply a coarse map of how various technologies have evolved. The one exception in this figure is the very first system on the timeline that I worked on. It was for tracking mobiles in a cellular network, before GPS and Wi-Fi became ubiquitous. Also, as must be clear by now, my bias is towards systems that do not require hardware modifications. Consequently, of the recent systems including PinPoint [12], RF-IDraw [13] and Phaser [14], I like Phaser because the authors claim meter-level accuracy using commodity state-of-art hardware. In contrast RF-IDraw, which boasts better accuracy, requires antennas with an 8-lambda separation, which at 2.4 GHz would be almost a meter, making the form factor of the modified AP much larger than a typical Wi-Fi AP. Finally, it is my understanding that PinPoint requires a large number of packets, at least 100, to infer the location, which makes real-time use harder.

KILLER SCENARIO

So what is the "killer app" for indoor localization? We began our quest in 1999 by focusing on the enterprise, i.e. navigating employees and guests to meeting rooms, nearby printers, and restrooms. At that time people did not have SmartPhones and the smallest mobile device was the laptop. It didn't take long for us to realize that this scenario was not compelling enough. Lately our engagement with the product groups has been motivated primarily by one scenario: navigating in public indoor spaces such as malls, conference centres, and museums, for which the target accuracy is 10 meters or less (see the highlighted examples below). Application developers have expressed interest and excitement in other scenarios such as location-aware advertisements.

Arjun and Shivani make plans to meet in a mall during a certain time window. Arjun is unfamiliar with the mall as he has never been there. Shivani shares her location with him so when he reaches the mall he can see on his SmartPhone a map showing where he is and where she is, enabling him to find her easily.

Higher accuracy systems built by researchers can enable "the retail store scenario," which many believe is monetizable. Retailers are interested in tracking the movement of their customers, to see where in the store they spend most of their time, what attracts them and which product they look at. They are willing to pay good money for this information as it enables them to sell products in a more targeted manner, hence increasing their revenue.

Ritu is running late for a meeting at a large convention centre that she has never been to. Her smartphone displays the building map with her location on it along with the location of the meeting point. She feels better knowing that she will get there quickly.

Alongside, there has also been research centered on tapping alternative sensing modalities, enabling alternative capabilities (e.g., proximity rather than localization), and leveraging specialized infrastructure (e.g., modified APs). This research has also been driven by specific scenarios such as proximity-based alerts and social networking. My own attempt at this dates back to 2010 when we developed Virtual Compass, which creates a relative position map of my friends around me, with me at the centre, using a combination of Bluetooth and Wi-Fi without the need of an infrastructure or environment profiling [5]. The uptake of iBeacons shows that there is significant interest in relative positioning scenarios. Finally, in the United States, the Federal Commission Committee (FCC) recently is pushing a new mandate that requires accurate indoor location for emergency response.

While vacationing in a new country, Victor and Ritu visit a large museum. They are interested in different things so they wander to different sections of the museum but they keep track of each other's location on their SmartPhone feeling secure that they can easily find one another.

Generally, for me, there is no one killer scenario. I believe there are lots of important, stress-relieving and useful scenarios that are equally important. Collectively they have the potential of making indoor localization as popular as outdoor localization is today and therefore a must-have feature on our mobile devices.

SO WHAT DOES THIS ALL MEAN?

Software is becoming smarter as more applications and operating systems use contextual information to predict and fluidly adapt to the user's needs with minimal explicit input. In this emerging world it is increasingly important for the device software to know the user's location. Since people spend a majority of their time indoors, indoor positioning systems provide a fundamental signal that enables context-aware computing. Some marketing studies (source: Strategy Analytics, Wireless Media Strategies 2011 report), estimate the total world-wide revenue from location-based services will be over $10 billion dollars by 2016 but with most of it coming from GPS-based location-aware applications. I believe the potential for revenue from indoor positioning systems is nearly as large.

RADAR-like techniques, in contrast to the numerous other positioning techniques that use specialized hardware, have withstood the test of time because they work with Wi-Fi, i.e., they do not require any additional new hardware and infrastructure. Wi-Fi is everywhere, so if we can get the software right, Wi-Fi based indoor localization should be everywhere as well. But, for indoor localization to take off, it has to become part of the base platform. Only when commercial operating systems such as Windows, Android, and iOS provide localization as a fundamental capability over which application developers can innovate, will it become pervasive and monetizable. For the skeptics, simply look at the number of SmartPhone applications that use GPS since it became part of the platform. Commercial operating system vendors will only include this capability when they believe it is good enough and robust enough to help them sell more devices. A technical reason for their hesitation is the recurring cost of providing guaranteed accuracy in a scalable (i.e., worldwide) manner. As discussed previously, sustaining location accuracy over time requires periodic profiling of the RF environment. Crowdsourcing technologies can help when they don't compromise user privacy. The invention of robots that continuously move around profiling the environment could help as well. Also, businesses willing to take on the responsibility of maintaining an up to date RF fingerprint database for their venues would make it more attractive for the platform vendors to include the capability in the OS. Until we figure out some way to consistently guarantee minimal accuracy, enough to light up some genuinely useful scenarios, our quest for a self-sustaining indoor localization technique must continue. ■

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