All Things Wireless: A Collection of Essays

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Wireless Communications 101

Our first topic, *Wireless Communications 101*, was meant to help us look at some of the fundamental concepts in wireless communications. Covering topics ranging between the existing wireless networks and network architectures all the way to signal propagation and protocols, we sought to develop a solid foundation in the concepts that would be the bedrock for the research we plan to explore this term.

In the first paper that we read we learned that it was very common until recently to assume that radios were only capable of operating in half-duplex mode (i.e., a radio cannot both transmit and receive on the same frequency at the same time). Choi et al. [13], however, introduced a new cancellation technique known as *antenna cancellation* to address this problem. The idea was that by combining multiple self-interference cancellation techniques to reduce the transmit signal noise from the local transmit antenna(s), it could be possible to effectively eliminate the transmit signal at the receiver, allowing a radio to both transmit and receive simultaneously and thus, implement a full-duplex radio. The technique itself merely requires the addition of an additional transmit antenna and fairly simple placement of the transmit/receive antennas with respect to each other which can create a *null point* at the receiver where it cannot hear the signal from the transmit antennas due to signal cancellation that results from the placement of the antennas.

It was quite apparent that the implementation shown by Choi, though clever, would not scale to support devices with more powerful transmitters due to insufficient interference cancellation techniques. I also have concerns regarding their requirements for the separation of antennas and how this impacts the physical size of the device — their novel antenna cancellation technique requires the ability to separate the the transmit/receive antennas by some distance that is dependent on the frequency at which the radio is transmitting/receiving; their prototype solution which works for the 2.4GHz band, for example, would not be feasible for devices smaller than laptops or access points such as many Internet of Things (IoT) devices or wearable devices. Regardless of one's opinion about the implementation/outcomes of this paper, one of the primary takeaways from this topic, and this paper, should be to not be afraid to challenge existing assumptions in a particular field — Choi and the other authors successfully challenged the assumption that full-duplex radios were not feasible. Because of this work, many follow-up research papers have been published [19, 10, 9, 12] that further improve upon the aforementioned techniques and show more feasible, cost effective, and robust implementations of full-duplex radios which will likely become a standard for radio technology in wireless technologies due to the problems they solve (e.g., hidden terminal, congestion, end-to-end delay in multihop networks) and the gains they provide (e.g., increased throughput, reduced/eliminate self-interference).

Radio Spectrum Management

The second part of this week was spent discussing various issues in the realm of *Radio Spectrum Management*. As we learned this week, successfully managing the radio spectrum requires (1) *sensing* the current usage in order to identify available channels, (2) devising methods for *sharing* the spectrum that minimize interference/avoid conflict while being fair and scalable, and (3) effectively *enforcing* spectrum allocation—only allowing permitted users to utilize allocated channels and detecting spectrum misuse.

This week we had the opportunity to look specifically at a couple of works which aimed to improve sensing capabilities in various parts of the radio spectrum and, to be honest, I've actually been most surprised at the (seemingly) underdeveloped mechanisms for measuring and understanding (i.e., sensing) the current radio spectrum usage. For example, currently, spectrum sensing systems capture only coarse data about spectrum occupancy and are known to miss signals that are not frequent or regular [28]. Also, until recently it appears that there have been significant inaccuracies in existing databases which attempt to maintain centralized information about "whitespace" spectrum usage [35].

At the core of the current issues seems to be the fact that existing sensing systems and techniques are too rigid, failing to accurately account for environmentally-induced variations such as shadowing and multipath effects, or simply don't attempt to understand more fine-grained information about spectrum usage. In light of these shortcomings, Zhang et al. proposes a measuring framework which can enhance existing databases with more detailed signal strength information as well as localized information about primary and secondary devices. Also noteworthy, Shi et al. proposes a learning-based solution for learning spectrum usage patterns and using to adaptively scan approximately 4GHz of bandwidth. These sorts of solutions attempt to sense radio spectrum usage as it really appears in the real world which is, in many ways, a huge step in the right direction regarding developing meaningful systems and techniques which sense radio spectrum usage.

It should be noted, however, that these solutions do have limitations. The evaluations done in the above mentioned works consist of a fairly restrictive setup whereby a centralized node is responsible for performing all of the sensing; even though there was an effort to make the sensors mobile by attaching them to a public bus [35], these solutions are limited then by public transit routes and hours of operation. In some cities, it is not uncommon to discontinue bus routes on weekends or in the evenings—both of which are times where spectrum usage may be high. I believe the ultimate success of radio spectrum usage sensing will be dependent on its adoption by the general population. Crowd sourcing apps for providing dynamic, real-time information about things like traffic patterns and gas prices [3] have shown great success, being both reliable and cost-effective.

I don't, however, want to completely discredit the work that was done in the above works. Even in the light of the issues I pointed out, I think this type of work is vital for the future of wireless technologies. Radio spectrum sensing must be more representative and adaptive. Also, I should note that I was quite impressed with the amount of data that was collected, and the amount of work that was done, in the evaluations of solutions for improving radio spectrum management. I also think the authors "set the bar" in a good way—any proposed improvements to our existing wireless infrastructure and the management of resources should be backed up by thorough analysis that demonstrates the ideas working in a realistic wireless context.

Interference Management

With the increasing amount of devices that utilize the radio spectrum for wireless communications, it comes as no surprise that it is necessary to discuss methods for dealing with *interference.* As has been discussed in our seminars, there are two main ways to address the challenge of radio interference: avoid it (e.g., MAC protocols, channel allocation) or embrace it (e.g., interference cancellation, interference alignment, combining cancellation/alignment). From what I can see, avoiding interference is easier to do and many solutions for this exist today. I don't, however, think that interference avoidance is scalable in the long term since the trend is for devices to move towards wireless connectivity—to this end, I'm more intrigued by the promise of interference management solutions that attempt to embrace the existence of wireless interference.

We had the opportunity this week to look at two papers that addressed solutions for interference management. One being FlexRadio which shows that by unifying MIMO and full-duplex radio techniques, a flexible radio can be designed that allows each of the N active RF chains to be arbitrarily dedicated to transmitting/receiving [12]. The novelty of this work is found in the benefits of having a flexible radio. Prior to this design, radios could operate in either MIMO or full-duplex mode, not both. These designs are rigid and allow a radio to either only transmit/receive at any given moment (MIMO), or to simultaneously transmit and receive but with half the throughput in either direction (full-duplex). By having a flexible radio (FlexRadio), however, that measures the signal-to-noise ratio (SNR) of the RF chains, FlexRadio can adjust the number of RF chains dedicated to transmitting and receiving in order to maximize the throughput. Another work that addresses issues in interference management is *AirExpress*, a system that enables in-band wireless cut-through transmission [11]. Cut-through transmission is a method for packet switching systems, wherein the switch/router starts forwarding a frame/packet before the whole frame has been received (typically only the destination address needs to be processed before forwarding—the destination device is responsible for error handling). It has been reported that wireless cut-though can reduce latency and improve throughput performance of the network. AirExpress attempts to address various *types* of interference that results from the multi-hop cut-through problem, specifically addressing the challenges of additional interference types that come from multi-hop cut-through with more than two hops. In their work, Chen et al. call out three specific types of interference that need to be considered in the multi-hop cut-through scenario:

1. *Self Interference (SI)*: Interference at a receiver on the same node that is transmitting.
2. *Forwarder Interference (FI)*: Interference from forwarding nodes later in the cut-through path that interferes with a preceding node's reception.
3. *Cross-Hop Interference (CFI)*: Interference from nodes more than one hop away (further ahead or behind in the cut-through path).

I largely think these works provide significant and interesting contributions to the domain of interference management. One of the limitations that I have the hardest time with, however, is that part of the FlexRadio solution relies on their ability to implement *interference alignment.* This requires each participating node to compute its SNR between itself and every other node, and then share that result with the other nodes (they used a reliable ethernet connection to handle communicating this information to other nodes). It should also be noted that the alignments must be synchronized in time. These requirements aren't surprising given their goal, however, in a real-life setting these communication requirements are known to be quite error-prone. In addition to these issues, it also seems that the proposed interference alignment only pertains to "interference limited networks." Their considerations for interference—even in the limited sense—are limited to

the fact that interference occurs only at the other passive nodes in the network; they do not consider the interference from nodes not participating in the interference alignment operation, which doesn't seem to be a reasonable issue to ignore.

It seems that more flexible radios are the future—as more devices communicate wirelessly, an increasing amount of interference will occur; we need methods of enhancing our devices to work together to best use the available radio spectrum. I also think that the AirExpress work was a good effort at addressing issues such as network latency. Their assumptions and evaluation were representative of a real world deployment (i.e., addressing > 2 nodes in a cut-through path) which is important if these research efforts are ever going to be adopted in our world.

mmWave

This week we also discussed *millimeter waves (mmWave)* which refer to radio waves with wave lengths between 1-10mm. Specifically, we looked at a couple of works that addressed the 60GHz mmWave band that includes the portion of the spectrum between 57GHz and 64GHz—this band is appealing because it is unlicensed in most places around the world due to the fact that it suffered the severest attenuation due to oxygen absorption. This band of the spectrum is also appealing for many reasons though; the 60GHz band is ideal for short transmission distances due to fast signal attenuation, its small interference footprint, good (well understood) reflective properties, and, due to the wavelength, the antennas are small and idea for relatively compact form factors such as mobile devices. In light of this, one of the more notable benefits of using the mmWave band is the increased throughput capabilities for wireless communications as this band can offer almost 7Gbps of throughput! There are, however, many other applications of 60GHz waves including in the home/indoor setting where wired connections can be replaced with wireless connections (e.g., HDMI) due to their directionality and high throughput capabilities. Also, 60GHz waves could be used in data centers to replace fixed wires, allowing them to dynamically connect servers based on demand.

On the topic of indoor networking, Sur et al. presented work which identified many of the benefits and challenges that arise when trying to use 60GHz signals indoors. Specifically, they set out to better understand the actual bit-rates that can be achieved as well as the vulnerability of 60GHz signals to attenuation due to common indoor objects such as walls/human bodies and device mobility. In their work they found that 60GHz links *are* highly sensitive to human blockage and device motion (not altogether surprising) but they also concluded that their results show promise for using 60GHz signals to sense environmental elements which may be causing poor performance, enabling wireless technologies to be more adaptive in light of these scenarios to improve network conditions.

I found this paper to be quite interesting and helpful to this field of study—I believe effective utilization of the 60GHz band will bring about great applications in the home and beyond and I think work such as this is helpful for the adoption of this technology as it displayed tangible examples of 60GHz "limitations" but also showed how these limitations can be exploited for gain. Also, I think what I found most surprising about this work was to learn that until recently, most research in the 60GHz band was performed using simulations. Sur et al. was one of the first works to provide an actual proof of concept implementation on actual hardware.

A new and interesting use of mmWaves was displayed in *Reusing 60GHz Radios for Mobile Radar Imaging* [36]. In this paper, Zhu et al. used mmWaves as a means for performing radar imaging. By utilizing the reflective properties of mmWaves, reflected signals can be captured and used to understand the surrounding environment. This solution can be used to accurately navigate

unmanned vehicles (e.g., cars, drones) with high precision and is not susceptible to limitations that other solutions have—as it stands today, light imaging systems are known to perform poorly in bad lighting conditions (e.g., at night) and acoustic solutions work reasonably well but only over short distances but they are known to suffer from noise in the environment and fail over long distances. While I do think the use of mmWaves for radar-like imaging was a clever application of these types of signals, I think a fair number of challenges remain that must be solved in order for this type of solution to be feasible in the real-world; the biggest of which, in my opinion, is their solution's dependence on two separate but nearby TX/RX components.

nmWave

This week we had the opportunity to look into the topic of *nmWaves* (nanometer waves), which are radio waves with wavelengths in nanometers. Of particular interest to us is that fact that nmWaves include the visible light spectrum (430THz - 790THz) which, as we discussed this week, has produced a lot of attention in recent years as various novel uses of visible light have been explored. Some of the attention around visible light as of late is centered on using it for communications. Some of the interest in using visible light for communications stems from that fact that the "transmitters" (e.g., LEDs) and "receivers" (e.g., light sensors, cameras) can theoretically achieve throughput on the order of 10Gbps or more—and indeed, researchers have built a prototype known as 'Li-fi' using custom LEDs [31] that has achieved more than 10Gbps! Also appealing is the fact that LEDs and light sensors are very cheap (e.g., reasonable light sensors can be purchased for less than $1) and super low-power electronic components, and high-quality cameras are now available in all sorts of consumer devices. In fact, *visible light communications*, or VLC, has gained enough traction that it has already been standardized (PHY and MAC) as part of the IEEE 802 standards for wireless personal area networks (802.15.7) [33].

One work that we looked at this week involved the invention of *PIXEL* [34], a light-weight indoor localization system that can support indoor navigation on smartphones and wearable devices such as smart glasses. In their work, Yang et al. encode data in *polarized* light which can be captured by a mobile device's camera. Encoding data this way allows them to encode data in a low enough *pulse rate* that minimizes the computational/processing burden on the receiving devices (i.e., mobile devices) and do so in such a way that is not generally perceivable by the human eye, unlike existing visible light positioning systems which rely on intensity-based modulation to encode data and can exhibit a sort of light "flickering" effect—they do however address that persons wearing sunglasses indoors would be able to see "flickering" due to the fact that sunglasses have polarized film which would make it possible for human eyes to perceive the changes in light polarization; people wearing sunglasses indoors, however, is believed to be rather uncommon by the authors.

In general, I rather enjoyed this paper. I felt their solution was clever and their prototype implementation was sound. One aspect of their work that I have to commend is their evaluation: not only did they design a simulator to perform more flexible prototyping that allowed them to evaluate a wide range of parameters easily and demonstrate the robustness of their solution, but they also implemented an actual prototype of their solution on a popular commercial device to show that their solution really can work on off-the-shelf devices with minimal changes (they did place a polarized film strip over the camera lens since cameras today don't have the ability to perceive changes in light polarization; they also installed a software implementation of VLC decoding and positioning algorithm which came out to have a small footprint of about 320kb).

Another paper that we spent time in was *RollingLight: Enabling Line-of-Sight Light-to-Camera Communications* [23], a system that enables a device with a camera to visually associate received

information with the transmitter's identity. To do this, RollingLight exploits the *rolling shutter* mechanism that is common in most commodity cameras today and allows them to sample the received optical signal multiple times in a single captured image. Data can then be encoded into square waves communicated at different frequencies which compose a set of data symbols. Noteworthy is the fact that their techniques have allowed them to achieve a throughput of 11.32 bytes per second, which is believed to be sufficient to support various indoor applications such as localization, augmented reality for navigation, etc., and do so on a diverse set of cameras.

One of the aspects of this work that I found especially compelling is their realistic usage model in which their proposed/evaluated solution is supported on a diverse set of cameras. By doing so they devised a solution that is robust even in light of different camera frame rates and rolling shutter read-out durations.

The papers discussed in detail above both address solutions towards the indoor localization problem. Other interesting applications of nmWaves/VLC can be seen in *sensing* (e.g., using light to tracks hand/finger movements to enable touchless UI interactions), and *screen-to-camera communications* (e.g., hiding the communication layer behind/within the content layer so that the user does not perceive modulations to the visible light being used for communication)). In our brief study of this topic it is clear that there are many interesting areas of active research, illustrating that people really do believe that nmWaves can be successfully leveraged to enable a new and effective form of communication. There are, however, some practical concerns with VLC; namely, light is very diffusive so multiple devices using VLC in the same environment may cause significant interference—though visible light is more predictable and easier to model when compared to radio frequencies. Also, VLC is not ideal for outdoor settings since it is possible that light-sensors (i.e., receivers) can become saturated with light from the sun or reflections of light off of other surfaces. There is also the issue with blockage—VLC is rendered useless if an object (e.g., paper, walls, people) physically comes between a transmitter/receiver. Many recent works also suggest that VLC can reuse existing lighting infrastructure; this, however, is non-trivial as modifications do need to be made to that infrastructure to support many VLC schemes and, also relevant, is the fact that commercial LEDs are non tailored to VLC—they are optimized for power consumption and thus implore techniques that limit the bandwidth that can be achieved while using these LEDs for VLC.

Backscatter

We began this week by delving into the topic of *Backscatter*, a fairly new technique that utilizes ambient radio signals (e.g., WiFi) for communication. One of the primary usage models for Backscatter is to enable low-power devices (e.g., wearables, sensors, tags) to communicate with an Access Point (AP) by modulating information into the ambient signals which the AP can decode.

One specific work that we looked at this week was *BackFi: High Throughput WiFi Backscatter* [8], a novel communication system that demonstrates drastic improvements in throughput capabilities at increased distances when compared to existing backscatter systems; in particular, Bharadia et al. showed it was possible to achieve rates of up to 5Mbps at a range of 1 meter and 1Mbps at a range of 5 meters. Remarkably, the authors were able to accomplish this in an energy efficient manner, with negligible impact on the overall network throughput ($< 5\%$), and with minimal changes to the AP. Specifically, to realize their system they construct a model of the signal that the reader in the AP receives after the tag backscatters the signal. Their model accounts for environmental distortion due to nearby objects, as well as what the signal looks like when it is sent to the tag/when the signal interacts with the tag and returns. Ultimately, understanding the variations in the signal

due to these effects allows them to cancel self-interference and estimate parameters that enable the decoding of the data that has been modulated into the backscatter signal.

In another recent paper on backscatter, *Laissez-Faire: Fully Asymmetric Backscatter Communication* [17], a communication protocol is described which allows backscatter nodes to blindly transmit data as soon they see the carrier signal. LF-Backscatter, as they call it, is a proposed improvement to supporting backscatter communication from multiple tags. Their communication model essentially moves as much burden as possible away from the low-power tags and onto the backscatter reader. The challenge then is to build a capable enough reader to decode the (potentially) concurrent communication streams. Hu et al. address this challenge of separating individual signals in three dimensions: time, in-phase, and quadrature. In their evaluation, they demonstrate LF-Backscatter supporting up to 16 nodes with bitrates of 100Kbps (though signal separation is more accurate with lower bitrates).

The obvious argument against backscatter systems is that backscatter devices can only communicate when there are ambient radio signals that can be utilized. It has, however, been stated that in times of inactivity and AP can enable backscatter communication by sending dummy packets out. Since APs are generally not resource constrained (i.e., they usually have unlimited access to power, are computationally capable, and so forth) this argument is likely to not prevent backscatter systems from becoming widely adopted. In favor of this technology, I would also add that backscatter is remarkably clever (e.g., re-using ambient radio signals to enable communications, implications for low-power computing) and I see a lot of potential for it due to the growing interest in the Internet of Things (IoT).

Beyond the Conventional

In the latter part of this week we had the opportunity to explore communication methods that are *Beyond the Conventional* methods that we've looked at thus far. Some of the techniques we saw this week seem to be more viable than others, but regardless of future adoption, the important thing to note is the value in exploring new communication methods for the purpose of discovering new applications or even finding better ways to enable communication in specific situations.

In one paper, *Capacitive Near-Field Communication for Ubiquitous Interaction and Perception* [15], we saw a proposal for a general framework for Capacitive Near-Field Communication (CapNFC) and an evaluation of this communication method in ubiquitous computing. Specifically, the authors describe typical operating modes, a communication protocol, recommendations for electrode placement, and a reference implementation which they evaluate in terms of the SNR and BRE over varying distances; the authors also show through a series of case studies that CapNFC is a suitable technology for ubiquitous interaction and perception. What I like about CapNFC is the fact that this low-power communication technology can provide touch and proximity interactivity, and can be easily enabled in existing smart objects by utilizing features that most microcontrollers have today. I also find the body-coupled communication that CapNFC can enable to be extremely fascinating and useful in a mobile health device context due to the privacy-preserving nature of this method. It does seem, however, that this communication method has a ways to go in terms of becoming robust and reliable enough for reasonable communication/adoption; I didn't find the presentation of their framework all that useful—I would have preferred to see a more formal and thorough discussion on this, but the reference implementation they do provide surely serves as a good start. All in all I'm optimistic about the future of CapNFC and believe that the benefits of it will draw more attention and further developments in standardizing it as a method of communication.

Another work that we looked at, *Ripple: Communicating through Physical Vibration* [26], explores the use of vibrations as a method of communication. Roy et al. showed that by modulating the vibrations produced from motors that can be found in devices like mobile phones, it is possible to use accelerometers to decode the data and communicate small packets of information. Through this method it has been shown that Ripple can achieve up to 200 bits/s of secure transmission using off-the-shelf vibration motor chips, and 80 bits/s on Android smartphones. What I like most about this paper is its useful application to security; using intimate, on-body communications that are difficult to observe from a distance is often an appealing idea in the context of mobile computing and interacting with nearby devices. This method does, however, come with its drawbacks. The authors were clever enough to mask the acoustic leakage due to vibrations with a transmitter that cancels the sound and superimposes a jamming sequence, effectively thwarting acoustic eavesdropping attacks—this is good. Their method, unfortunately, is still vulnerable to attacks where an observer may use a high-speed camera to observe the vibrations of the transmitting device and correlate those images vibrations, enabling the observer to decode communications. Nevertheless, Ripple could lend itself well to being a new, intuitive, and even fun way to enable relatively secure communication between devices in a peer-to-peer/ad hoc context.

Localization

This week we had the opportunity to look at papers in the area of *Localization*—a area of work detected to accurately locating objects in space.

One of the works we looked at this week was *Caraoke: An E-Toll Transponder Network for Smart Cities* [4]. Caraoke is a system for delivering smart services using existing e-toll transponders (infrastructure). Specifically, the authors envision that a city could deploy readers on traffic lights to query the transponders and track the number of cars at every intersection, adapt the timing of traffic lights to minimize the average wait time for a green light, localize cars, detect cars that run a red-light and automatically charge their accounts for a ticket, or even deliver smart street-parking systems, where a user parks anywhere on the street, the city localizes his car, and automatically charges his account. Simply put, caraoke works by exploiting carrier frequency offset (CFO) to identify different transponders (despite interference). Using CFO, they show how to localize cars/their transponders by using a combination of information such as the angle of arrival (AoA) between a given transponder and reader, and the fact that cars always live in a fixed plane (on the road). Caraoke can also detect the speed of a moving car carrying a transponder by using the localization estimates mentioned before and can decode the ID of an individual transponder in the presence of others by using channel information and signal combination to decode the target transponder.

Other great aspects of their work were the presentation of a MAC protocol to handle interference in situations with multiple readers and that their prototype seems to yield good results. Caraoke can, with high confidence, guarantee that it won't miss a car when counting cars (i.e., probability of missing a car even in high-density situations is $> 95\%$), demonstrates that their localization is more than sufficient for localizing parked cars, can accurately detect the speeds of moving cars (within $1 - 4$ m.p.h), and that desired transponders are easily decodable with their signal combining/averaging technique—all in (near) real-time! This work in and of itself is quite interesting, but I find it especially appealing due to large presence of transponders in cars already and the increasing requirements for cars to have them in many states across the US—gaining such a foothold is often difficult. There are also compelling applications that are enabled as a result of cars being mandated to have RFID technology such as paying for food at some drive-through

restaurants [2], and to automating payment at parking garages [14].

Another paper that we looked at this week, *SpotFi: Decimeter Level Localization Using WiFi* [22], presented an indoor localization system that can be deployed on commodity WiFi infrastructure. Their system, SpotFi, achieves a median accuracy of 40 cm and demonstrates robustness even in the presence of obstacles and multipaths. In the presentation of the solution presented by Kotaru et al., *SpotFi*, they posit that indoor localization systems that leverage existing WiFi infrastructure should be **deployable** (i.e., work without modifying hardware and utilize only common information that is available today such as RSSI & CSI), **universal** (i.e., capable of localizing any WiFi-enabled target device using only a commodity WiFi chip), and **accurate** (i.e., can localize objects within 10's of centimeters).

At a high level, SpotFi works by estimating the angle of arrival (AoA) and time of flight (ToF) of different multipath components of a target?s signal arriving at the AP by using the CSI information that is exposed by commodity WiFi APs. SpotFi then estimates the likelihood that each AoA and ToF pair is the one corresponding to the direct path between the AP and the target without any reflections. Finally, all of the collected information is used to calculate the most likely location of the target that could have produced the observed RSSI and estimated AoA. The prototype for SpotFi includes a central server that collects CSI from each AP—it is here that multipaths can be resolved and it is possible to identify the direct path for each AP. This information can then be combined with RSSI and AoA information from all APs to localize target.

Also part of their work was a concise but representative presentation of existing work in the indoor localization domain. Indoor localization using wireless infrastructure is a well-studied problem. According to Kotaru et al., past works in this area can be classified into four categories: RSSI based, fingerprinting based, antenna array based, and time based approaches. There have also been other, less conventional, approaches to "solving" indoor localization which uses RFID, ultrawide band, ultrasound, IR, visible light, and beacons (similar to Apple's iBeacon)—it is believed, however, that these approaches are unlikely to be as ubiquitous as the existing WiFi AP infrastructure. The RSSI based approaches seem to be easy to deploy since they only utilize RSSI—which is available in most WiFi cards today—but they reportedly can only localize objects accurately between $2-4$ m on average. Other approaches (time-based, fingerprinting based, and AoA based) require synchronization between all of the APs—which is difficult to do—or require expensive hardware changes and/or expensive recurring operations, making them not ideal for a reasonable indoor localization system. My argument in favor of RSSI approaches is that they are easier to implement in more devices today due to the information they require, while still achieving reasonable localization performance—there aren't yet applications that warrant extremely fine-grained localization, suggesting that median localization accuracy of $2-4$ m is probably good enough!

The paper itself is interesting, however, I couldn't help but fixate on some of the limitations that I noticed. The authors take pride in the fact that their system would be ideal for commodity WiFi infrastructure, however, it also requires more than one AP making it less than ideal for most home environments. Also, while the WiFi card that they used for the SpotFi prototype does provide information such as CSI—which is required for their solution—most WiFi cards today do not actually provide this information.

Sensing

One of the interesting topics that we had the opportunity to explore this week was *Sensing*; what this meant this week in the context of our course on wireless communications technologies, is that some groups have researched the ability to use existing wireless communications (e.g., WiFi signals)

to perform other tasks such as indoor localization or movement tracing, for example.

Specific to this topic, this week we looked at two works, *Multi-Person Localization via RF Body Reflections* [5] and *WiDeo: Fine-grained Device-free Motion Tracing using RF Backscatter* [21]. In the first work, Adib et al. presented *WiTrack2.0*, a multi-person localization system that operates in multipath-rich indoor environments and is capable of pinpointing users' locations based purely on the reflections of wireless signals off their bodies. Of particular interest is that their prototype, which was evaluated in a standard office environment, showed that it can successfully localize up to five people simultaneously with a median accuracy of 11.7 cm in each of the x/y dimensions. WiTrack2.0 can even track particular body parts and perform tasks like identifying the direction of a pointing hand, for example. This is actually very impressive in light of the challenges that this sort of work faces. WiTrack2.0 overcomes indoor multipath effects, proposes and implements a solution for the *near-far* problem in which one person obfuscates a signal and makes it difficult to detect other people/objects in the environment, and addresses the problem of localizing a static user within the environment which has thus far been hard or impossible to do since current methods specifically look for successive motion between measurements and subtract out static objects—in this case making the system overlook the presence of a person not in motion. Simply put, WiTrack2.0 works by transmitting RF signals and capturing their reflections after they bounce off different users in the environment. Upon receiving the reflected signals, WiTrack2.0 uses two primary components to realize its objectives: *Multi-shift FMCW* followed by *Successive Silhouette Cancellation* (SSC), to deal with multipath effects and allow WiTrack2.0 to overcome the near-far problem.

All in all I found this paper and work to be quite impressive. Adobe et al. claim that this WiTrack2.0 is The first device-free RF-localization system that can accurately localize multiple people to cm-scale in indoor multipath-rich environments and demonstrate the feasibility of their solution through their physical prototype; I especially like the fact that this system can work in real-time! The other characteristic of this system that I like—perhaps the most—is the non-invasiveness of their system (i.e., the user is not required to wear a device that enables them to be tracked—everything is done completely passively). I also find it interesting the authors allude to the fact that technology such as this could enabled people to control the Internet of Things as it manifests itself in our homes; I believe this is absolutely true and look forward to seeing this technology come to life in the coming years. WiTrack2.0 isn't without limitations though. The authors confess that their system can track at most 4 moving user and 5 static users—probably sufficient for most home environments, but not ideal for more populous environments such as work places, schools and so forth. They also admit that WiTrack2.0 has limited range (10 m)—it is likely that even in a home environment one would need to deploy multiple devices to cover a larger area, introducing the need to coordinate "hand-offs". Lastly, though it is unclear for now if this is truly a limitation or a feature, WiTrack2.0 cannot uniquely identify a user; there may be privacy issues here (i.e., if a system can track you and know things about you and connect that to a specific person) but it could also lead to more meaningful interactions with IoTs devices if the larger ecosystem could know which specific user(s) were interacting with specific devices. I actually believe this feature isn't unrealistic either. Though I wasn't able to find the paper reference, I've heard of work suggests that individuals can be uniquely identified based on their heart rate and other heart rhythm information. WiTrack2.0 claims to be capable of locating users so precisely that it can even go as far as to monitor the breathing of people in the environment. Breathing is easily connected to observing one's heart rate. These facts combined suggest that it is quite realistic to envision a system that can track and uniquely identify people in the environment!

The other, related, paper presented *WiDeo*, another system that can realize motion tracing of people in the environment based RF backscatter. The paper presents WiDeo by using a camera

analogy: The AP serves as a sort of camera and WiFi signals are the light source—the AP can introduce "light" as needed and/or leverage existing WiFi signals which can then be captured at the AP after those signals have interacted with the environment. The challenges/issues that face this work are similar to those discussed above. Joshi et. al. primarily seek to design a system that is device free (i.e., the user being traced need not wear any special devices for the system to work) and can be implemented using standard WiFi or LTE APs. In order to realize this vision, WiDeo works by utilizing natural reflections of the transmitted signals as they interact with human bodies (i.e., RF backscatter) and compact (standard) antenna array that consists of no more than four antennas per AP.

Specifically, WiDeo accomplishes motion tracing through three main components: the **backscatter sensor** that utilizes natural sparsity in indoor environments to tease apart individual reflections coming from each significant reflector in the environment, the **declutterer** that is responsible for analyzing a raw set of reflection parameters estimated by the backscatter sensor in order to cluster them into groups that correspond to static and dynamic reflectors while also eliminating reflectors that are not useful for motion tracing, and **motion tracing** which is the actual process of analyzing reflections that arise from moving objects and predicting the underlying motion being observed in the environment.

To be honest, I found this paper less interesting to read and its results were comparable at best to the previous paper, thus the majority of my focus on this topic was directed at understanding the previous paper's presentation of their work.

Wearables

The other topic that we examined this week was *Wearables*. In the past few years, wearable technology has exploded in popularity and it seems researchers and companies are throwing massive amounts of effort and resources into studying and solving problems in the areas of health, finance, social interactions, and many others. One especially interesting and important aspect of wearables is their ability to communicate. Possibly more interesting, however, is the utilization of communication technologies to solve other problems in the wearable domain. This week we looked at a couple of papers that touched on both of these ideas.

In one paper, *U-Wear: Software-Defined Ultrasonic Networking for Wearable Devices* [27], Santagati et al. present a first of its kind networking framework for wearable medical devices based on ultrasonic communications. This device category that this framework is proposed for is is important to keep in mind as, in their work, the authors assert that most wearable medical devices are connected through radio frequency (RF) electromagnetic waves—be it through standards such as Bluetooth or WiFi, or some other proprietary solution; they insist that there are many limitations and issues with relying solely on RF-based communications. Some of the reasons identified in this work included the fact that RF spectrum is scarce and crowded, it can be easily jammed or eavesdropped on, it is already strictly regulated, and, probably most significant, there exist health concerns about electromagnetic waves and their affect on human tissue (which is an obvious issue when addressing wearable devices that communicate with other on-body devices). Thus, U-Wear presents an ultrasound-based approach to on-body communications which has a number of benefits over RF-based communications. The first being that, obviously, U-Wear operates on non-RF channels so there is no (at least less) conflict in this spectrum today. Also, the spectrum that includes ultrasound is currently unregulated, ultrasound does not propagate through walls so it is more secure in nature (i.e., it is harder to eavesdrop without being physically close to communicating devices), and is regarded as safe for the human body—indeed ultrasonic waves are

commonly used for medical purposes today.

The U-Wear work presents quite a significant contribution. In order to demonstrate the effectiveness of U-Wear, the authors built two prototypes which can operate in the near-ultrasonic frequency range using commercial-of-the-shelf (COTS) speakers and microphones, and can (1) achieve data rates up to 2.76 kbit/s with bit-error-rate lower than 10^{-5} using a transmission power of 20mW; (2) enable multiple nodes to share the medium; and (3) implement reconfigurable processing to extract medical parameters from sensors with high accuracy. This work is made possible through their efforts to implement a proof of concept for the "full-stack"—showing how ultrasonic communications can be enabled at the physical layer, data link, network, and application layers. Specifically, a lot of their work on U-Wear was done at the lower layers. PHY layer libraries were created to define the signaling scheme, channel estimation, equalization, synchronization and forward error correction (FEC) functionalities. Also, their data link layer provides a set of functionalities that allow multiple nodes to efficiently access the medium under the challenges posed by the ultrasonic in-air channel, e.g., long propagation delays, and so forth. At the network layer, U-Wear has IPv4 and IPv6 support and offers content-centric networking (CCN) functionalities that make the network content directly addressable and routable. At the application layer, U-Wear was designed to be reconfigurable and modular, and it offers fetch and push modes for data collection purposes.

This is one of the most interesting papers I believe we have looked at all term. U-Wear incorporates ideas from traditional networking, interesting wireless communication ideas, and a meaningful solution to security and privacy issues in communication specific to a health context. Their work showed reasonable results on relevant devices and even helped to show the versatility of their work by prototyping with very different devices (i.e., the well-known iPhone and a more builder-friendly mote). I don't believe that the limited bandwidth rules out ultrasonic communications—indeed, the authors set this communication method up not as a replacement for the higher throughout RF, but rather as a method that solves specific problems in a health context.

In another paper, *CIDER: Enabling Robustness-Power Tradeoffs on a Computational Eyeglass* [24], authors explore the power-robustness tradeoffs inherent in the design of wearable eye trackers, and propose a novel staged architecture that enables graceful adaptation in light of varying illumination present in everyday situations. Specifically, this work addresses challenges that arise in continuous high-rate sensing applications (e.g., image capture and processing) and dealing with variable lighting conditions that occur in natural environments. At a high level, CIDER (CIrcle Detection of Edges with Reinforcement) is a system that, interestingly, operates in a highly optimized low-power mode under indoor settings by using a fast Search-Refine controller to track the eye, but is capable of detecting when the environment switches to more challenging outdoor sunlight and switches models to operate robustly under this condition. With their solution, they show that they can track the pupil center and pupil dilation both with accuracy of roughly 1 pixel, and adaptively adjust to indoor and outdoor lighting conditions with ease.

In the end, what I actually ended up taking away from this paper was the underlying principle which drove their work; the authors claim to do something common in systems research: "The principle underlying our architecture is well-known to systems researchers — we optimize heavily for the common case but provide more power-hungry features to deal with the more difficult but uncommon scenarios that occur." As someone fairly new to systems research, I actually don't think that many researchers in this area call this guiding principle out or even adhere to this in lots of systems research today. Going forward, I'd like to incorporate this principle into my own research in an effort to find a balance between solving the challenging problems and actually building something that improves the state of the art—many works try to solve the challenging problems but don't consider factors that would prevent their solution from ever seeing wide-spread adoption, while

others don't do enough to solve the menacing problems that show up in everyday situations.

Drones

One of this week's topics for exploration was *Drones*. Drones, in our context, are unmanned aerial vehicles (UAVs) which have become widely available to everyday people. Until recently, drones were primarily used by the military but are increasingly finding uses in civil applications such as search and rescue, photography, dynamic sensor networks, and so forth. The increasing relevant to civilian applications has, naturally, led to more public research on advancing drone technology. This week we looked at a few papers which addressed various contributions to drone-related research such as an evaluation of drones being used in emergency response applications, using drones as "smart" link to a base station, and using drones to measure wireless interference.

One of the aforementioned papers presents *SensorFly*, a controlled-mobile aerial sensor network platform for indoor emergency response applications [25]. In their work they described various hardware design trade-offs, their software architecture, and their implementation that enables limited-capability nodes to collectively achieve application goals. The authors of SensorFly especially wanted to demonstrate the value of using drones to create a dynamic sensor network which could offer more flexibility when compared to static sensor nodes, as well as encourage new applications; to do so, Purohit et al. use indoor fire monitoring as a motivating application scenario and they validated that the SensorFly platform could achieve coverage and sensing accuracy that matches or exceeds static sensor networks and provide higher adaptability and autonomy.

Of particular noteworthiness was the form factor/size (i.e., a miniature 29g drone) and cost (approximately $200) of their aerial sensor networking platform. I also found their software architecture to be quite interesting while also managing to be simple. Specifically, the node system software consists of three major modules corresponding to the capabilities of the platform, the **sensor controller**, which provides access to on-board sensors and expansion ports. Includes filtering modules to mitigate noise caused by motors and motion; the **network controller**, which provides peer-to-peer aggregation and broadcast communication, with support for inter-node range estimation through RToF; and the **flight controller**, which provides a high-level navigation API for hover, turn and single-direction flight. A biased random-walk dispersion and exploration algorithm is implemented utilizing the node ranging capability. The algorithm enables nodes to navigate and deploy in unknown environments without need for localization.

With that said, I did have a few rather significant concerns about this work. First, cheap and dynamic sensor networks don't have localized information that would be necessary (i.e., where they are with respect to other rooms in a building, etc.). This sort of local information is extremely useful and, in light of an emergency response scenario, critical to its overall usefulness! To give the authors credit, however, they did note this as a challenge in their work—though they didn't do a great job instilling confidence in the reader that this could be addressed in a meaningful way. Second, I'm also concerned about the overall flight time of SensorFly; the low cost aspect of their device is appealing, but according to their paper, their devices can only fly for short sessions (i.e., 5-6 minutes). This may be appropriate in small buildings, but given that they attached their work to the emergency response scenario, they really should have thought more critically about the implications of the limitations of their system in light of their target scenario. On that note, during our in-class conversation, some students also expressed concerns with the durability of a device like this in a fire, suggesting that it would be likely that a device like SensorFly could easily melt due to the temperatures that are reached indoors or, at the very least, malfunction.

The other papers we looked at were short papers that were geared towards addressing or further

analyzing very specific problems. In one paper, we saw the presentation of a Quadcopter Controller that could be used to maintain radio link quality [6]. Their solution primarily speaks to the fact that drones are a popular option for surveillance systems and that most such systems need a real-time high quality video stream from the cameras on the quadcopter back to the base station which requires a stable and reliable radio link to be maintain; this type of radio link is also important in order to ensure a controlled flight from the base station to the quadcopter. The challenge here is that the quality of the radio link link depends on the distance between base station and quadcopter as well as the ambient noise. The quadcopter itself was meant to be a dynamic component that could measure the quality of the radio link between the quadcopter and the controlling base station and could be told where to hover based on the signal to noise ratio (SNR) between them. I struggled to find this work particular interesting since the idea itself is not new, nor are the techniques really. The authors point out that there are existing solutions for this sort of work already in the field of robotics (i.e., link aware mobility), but this is the first link-quality aware mobility implementation on a quadcopter.

The other (final) paper that we looked at purported that an important cornerstone for the development of civil UAVs is communication technology [30]. In terms of cost and deployment, it would be ideal for UAVs to use existing commodity communication technologies and chip-sets for communications. Their work, however, shows that there are unique challenges to understanding the performance of wireless communication systems at high altitudes; it turns out that the propagation models are entirely different for this type of communication. In their paper, Van den Bergh et al. analyzes the performance of IEEE 802.11 communication, both experimentally and by means of simulation and conclude that interference to and from aerial Wi-Fi systems is higher than we know in typical Wi-Fi systems, which causes aerial communication performance to be lower (i.e., worse) than expected—one of the direct causes is that it is possible for more APs "overheard" which results in more accumulated interference at the aerial system.

Energy

One of the most interesting topics we've had the opportunity to address in this course is that of *Energy* and how it relates to the world of wireless communications.

In the first paper we looked at as part of this topic, Shi et al. presented *MultiSpot* [29], a new wireless charging technology that can charge multiple devices, even as the user is wearing them or carrying them in their pocket. *How does this relate to wireless communications?* you might ask; MultiSpot is based on a very simple idea that is actually remarkably similar to NFC. In short, like with NFC, A transmitter (coil) is driven by AC current to generate an oscillating magnetic field, however, instead of using the magnetic field that is generated by the transmitter to power—and in turn communicate with—the receiver, the magnetic field passes through the center of a coil on the receiver when the device is brought near and this field induces an AC current on the receiver which can be used to power/charge the device.

This work isn't new. In fact, the same group at MIT presented *Magnetic MIMO: How to charge your phone in your pocket* at MobiCom in 2014 [18], which this work builds atop in some respects. Specifically, in the MultiSpot work the authors show that they can charge more devices (i.e., up to 6) at further distances (i.e., up to 50cm) and their solution requires no changes to the receiving devices (apart from their having a coil to interact with the magnetic field generated by the transmitter which charges the device—this is already common in some commercial devices today [1]). The impressiveness of their work, I think, is found in the adaptive beam forming algorithm they present. They describe the parameters they must estimate in order to optimize the power

that their transmitters can deliver to nearby receivers. They show that they can do the estimation purely on what is observed at the transmitter (i.e., there is no need to communicate with any of the receivers which would introduce overhead), and they show that their adaptive algorithm allows for things like sending more power to the less charged devices simply due to the underlying physics! In their evaluation of MultiSpot shows that it outperforms all wireless charging solutions in existence today in, in some situations, is even comparable to wired charging solutions. This work is pretty extraordinary, pushing the state-of-the-art for wireless charging performance and, possibly more important, greatly improving the user experience of such a system. The authors hope to extend this work to support more mobile devices in the future as well as enable the system to control how much power it can deliver to a particular receiver—I'm personally very excited to see this work!

While I believe the work is great, it should be stated that I (and others) have some practical concerns. First and foremost, I worry about the presence of ubiquitous, highly directional/more concentrated magnetic fields being produced by everyday objects like tables and chairs (i.e., the supposed ideal locations for transmitters); this could introduce health concerns or other issues that should be better understood before large-scale deployments. Another concern I have has to do with the transmitter itself. First it is well understood that the surface which has the transmitter should not be conductive, as it would end up generating quite a bit of heat. That is all well and fine, use wood desks, etc., but the authors don't speak to the impact of the transmitter coils being near other conductive surface (e.g., most computers are metal and thus conductive—does that mean our devices could end up getting much warmer? possibly even warm enough to burn a user of said device?). Lastly, the authors don't address the "smarts" of this device. Will the transmitter generate large amounts of energy which is dispersed into the environment without actually charging devices? It seems to me like we could end up introducing very power-hungry transmitter devices for the sake of having a slightly more convenient charing paradigm—this is not ideal in the big picture.

In the last paper we looked at this week, *Software Defined Battery* (SDB) [7], presented a system that allows heterogeneous batteries with different chemistries to be integrated into a mobile system in order to create a system which can adaptively use the best battery for the type of computation needed. This work is motivated by the fact that there are a growing range of battery chemistries that are under development, each of which delivers a different set of benefits in terms of performance. The authors believe that the combination of multiple types of heterogeneous batteries, rather than using a single battery chemistry, can allow a mobile system to dynamically trade between their capabilities and thereby offer attractive tradeoffs. Combining different battery types, however, is not trivial due to the fact that they may have different capacities, charging rates, and so forth. To that end, SDB consists of hardware and software components to achieve its goal. The HW enables fine-grained control over the amount of power that passes in and out of each battery by using smart switching circuitry and the SW resides in the OS and implements a set of policies and APIs, giving more flexibility and power to the user/system in making decisions about how best to utilize battery resources.

I think what I really took away from this paper was not all of the details about how their specific solution works—indeed it is quite complex—but rather, they made a compelling argument for their work by claiming that we use different types of chipsets for communication and different types of processors for computations—why not use different types of batteries for computing as well? Simple. Logical. And, best of all, Badam et al. gave meaningful insight into the state-of-the-art for battery technologies, showing that the rate of development in this area is much slower than with processors (as in Moore's law) and that we, therefore, need to be much smarter about how we use our batteries rather than depending on huge breakthroughs in the battery technology that enable longer lifetimes for all of our battery-powered devices.

Security & Privacy

One of this week's topics, *Security & Privacy*, was easily one of the most anticipated topics of the term (at least by me). On a serious note though, many of our discussions this term had at least some amount of discussion focused on security and/or privacy related thoughts—mostly concerns. Needless to say, reading papers authored by security-minded researchers led to thought-provoking in-class discussion.

One of the papers we looked at as part of our survey into this topic was *Securing RFIDs by Randomizing the Modulation and Channel* [16], a paper presented at *NSDI '15* earlier this year. In this paper, Hassanieh et al. presented *RF-Cloak*, a modified RFID reader that demonstrates how it is possible to secure simple RFIDs from eavesdropping attacks, without modifying the RFID cards[1] themselves.

RF-Cloak does two primary things to achieve this: first, the modified reader introduces random modulation into the carrier wave which it transmits in order to communicate with nearby RFID cards; since the data is modulated by random values generated at the reader, the reader can remove the "noise" from the signal it receives back from the RFID card, however, an eavesdropper is unable to do so given the same signal. Second, RF-Cloak introduces antenna motion (i.e., rotating the antennas) and rapid antenna switching to randomize the wireless channels—this effectively prevents eavesdroppers with MIMO capabilities from leveraging multiple receive antennas in order to cancel the random modulation (mentioned above) and decode data sent from an RFID card.

It is extremely important to note that the authors only claim that RF-Cloak can prevent passive eavesdropping attacks; active attacks, whereby an attacker uses their own reader to "excite" a tag and get it to communicate its data are out of scope. In fact, the authors refer the reader to existing solutions that protect RFID cards (e.g., passports, credit cards, public transit cards) by enclosing them in RF protective casing. The issue then, is that the owner of the card must, at some point, remove their card(s) from the protective casing in order to use it with a legitimate RFID reader. It is at this point that an attacker (eavesdropper) could steal information communicated by the RFID card. In light of this scenario, I am led to believe that this paper really does present great work! Their solution is practical in the sense that it increases security while not requiring changes to RFID cards themselves—indeed, solutions that require changes to RFID cards would be quite expensive; imagine every passport owner in the United States having to turn in their existing passports to get new passports! Another aspect of their work that I liked was their presentation of the work. The solution they arrived at was well motivated and they made it very clear why simply randomly modulating the data wasn't sufficient to protect RFID cards from more capable eavesdroppers. All in all, RF-Cloak was a great paper, giving the reader a sense of where RFID technology is today and where it is going in the future.

Another paper we looked at, *Acoustic Eavesdropping through Wireless Vibrometry* [32], was one of those papers that makes you afraid to go out into the scary world where attackers can do seemingly impossible things in order to invade your privacy. To be honest though, this is one of those papers that I am slow to believe or really fear. When you really dig into the assumptions made by certain attacks and think about how technology is really used, it is often hard to think about a situation in which an attacker could successfully carry out some attack. With that said, the idea is interesting and worth discussing.

In their work, Wei et al. postulate that it is possible to use wireless signals to decode loudspeaker sounds from afar. The underlying idea here is that there acoustic vibrations from a loudspeaker can cause fluctuations in radio signals. Apparently, audio emission from a loudspeaker causes

[1] In this text I often refer to "RFID cards" in order to be consistent with the language used in the paper by Hassanieh et al. The RF-Cloak solution presented, however, seems to work with any passive RFID tag/card.

small vibration in the body of the device itself which can resonance with radio waves reflected by the loudspeaker or radio waves from a co-located wireless transmitter. The "contaminated" radio waves can be captured by a receiver (modified by an attacker) and processed in order to recover the original audio which was emitted from the loudspeaker—this is the basic idea behind "wireless vibrometry." In light of this, they consider two types of vibrometry: (1) *reflective vibrometry*, in which the adversary utilizes RF communicated between their own transmitter and receiver to inject RF signals into the environment with the loudspeaker and then decode the audio signals, and (2) *emissive vibrometry*, in which the adversary is a radio receiver and the target is a loudspeaker co-located with a WiFi radio (e.g., a smartphone, smart TV). The primary aspect of their contribution is centered around their evaluation of an attacker's ability to decode audio data from wireless signals in the aforementioned situations; the attackers decoding device runs *ART*, their new acoustic eavesdropping method that penetrates conventional sound-proof isolaters using reflective or emissive signals.

What I appreciate most about this work is that the authors present examples of the attacks which they suggest are possible, but then they propose pragmatic countermeasures for resisting these attacks that are well founded in the research they did on identifying and understanding the vulnerability they present. I also think this kind of work is necessary, especially in today's world where we often use technology to interact, but don't always take the time to understand how technology can be exploited to invade our privacy or compromise the security of information; this paper highlights one such example, namely, that we all rely on RF to communicate (e.g., WiFi, Bluetooth), but it is those very communication technologies which enable attacks such as the ones presented in this paper. My hope is that research such as this will help to inform us on how technology can be abused for malicious intent, but also how we can build more robust technology, buildings, etc., so that we can overcome these issues.

Interplay with Other Disciplines

In the later part of the week we had the opportunity to look at how wireless communications are impacting other disciplines/areas of research. One of the specific topics we looked at in light of this idea was *Augmented Reality*.

In the one paper that we looked at this week on Augmented Reality we saw *OverLay: Practical Mobile Augmented Reality* [20]. In their work, Jain et al. suggest that the implementation of a reasonably well-performing augmented reality system really is a problem that should have been solved by now; however, existing systems don't really suffice because the techniques they rely on have fundamental issues which prevent them from being useful to people (e.g., slow due to highly intensive algorithms, inaccuracies in determining location). Specifically, systems today rely heavily on either *Computer Vision* based or *Sensing* based techniques to recognize objects in the environment and determine where the user of the system is located in space with respect to objects that have been augmented in the environment. Computer Vision based AR systems specifically aim to accurately identify objects—these systems need a lot of "examples" to properly train the system for recognition and the relevant algorithms tend to be computationally intensive, leading to slower feedback to the user of the AR system. Sensing based AR systems typically utilize GPS and Gyroscope sensors to determine a user's location and the general direction that they are facing, respectively; these systems aren't great for highly accurate localization of the person since GPS can "jitter" quite a bit and, worst of all, these systems are completely useless indoors where GPS typically has a weak signal (or no signal at all).

OverLay essentially works by combining these methods. In short, OverLay allows users to

annotate objects (i.e., associate text/images to objects in the environment by taking pictures) and easily look them up later. At the time of annotation, relevant objects (i.e., annotated images) are then processed by the "SURF" (Speeded Up Robust Features) algorithm, which is a performant scale- and rotation-invariant interest point detector and descriptor, and then stored in an annotation database. To optimize the performance (e.g., look-up time) of their system, they track motion such as direction and orientation with sensors on the phone in order to maintain an understanding of where the person is with respect to other known augmented objects in the environment. The aforementioned spacial information is used to reduce the search space of objects in the annotation database to those that are likely to be nearby.

An interesting point in their work is that OverLay's goal isn't trying to focus on a particular object and perform accurate object recognition; rather, they extract features from the entire image and use those features that are present in the scene as a whole when matching images during look-up. My concern with this is that the OverLay system is then inherently constrained as it will not perform well in environments where the same location may experience changes in its scenery (e.g., an object of interest on a desk may be moved to somewhere else, the furniture in a room may be rearranged). My other concern with this work is that, while more responsive, OverLay consumes quite a bit of power between the computer vision and sensing algorithms it runs—this could lead to very poor battery life for the mobile device running the AR system. On the plus side, however, their system does provide a somewhat viable indoor AR system and requires minimum setup burden on the part of a regular user of the system. Also, even though I'm not extremely excited about this work—or augmented reality work in general at present—it should be noted that the authors did achieve their goal—they built a (some what) reliable augmented reality system which they where able to deploy to real users and, best of all, their system appears to be getting good feedback by their volunteer participants.

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