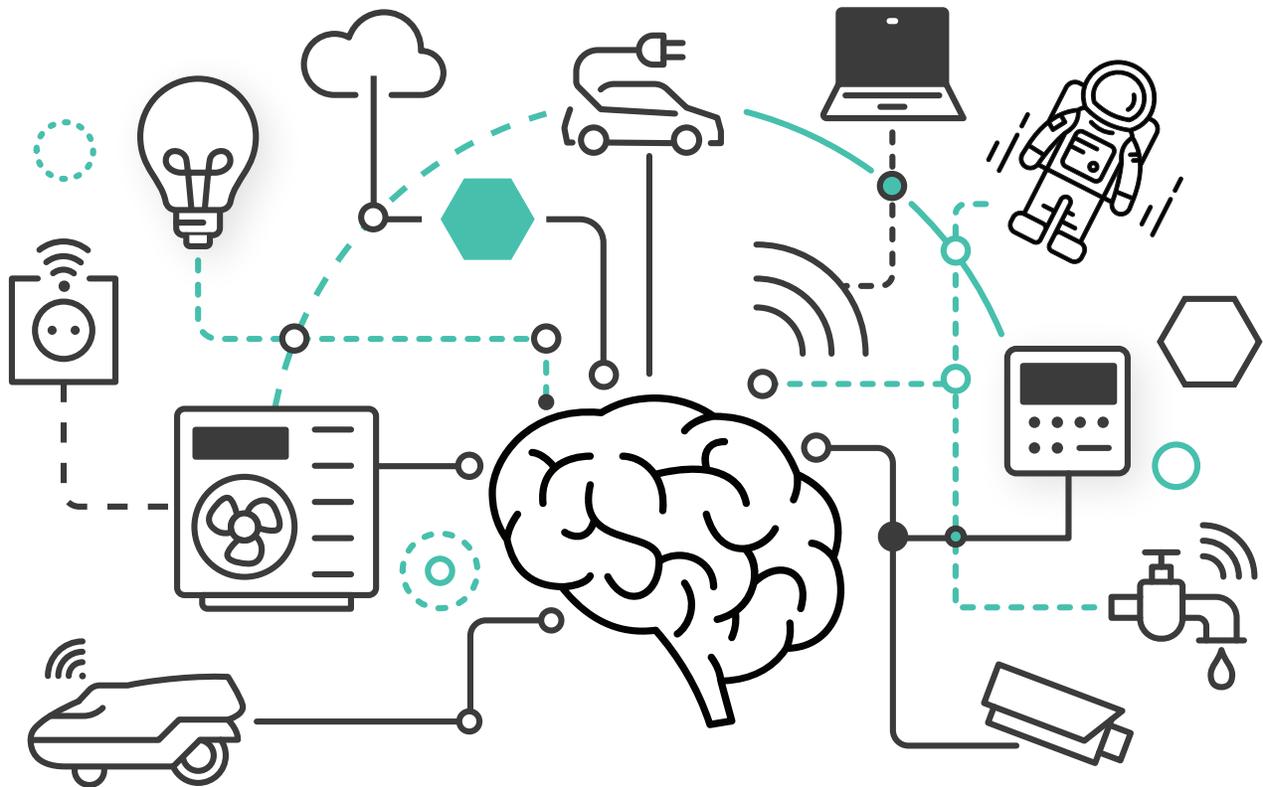


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Editor: Jeremy Gummesson



Ultra-wideband (UWB) Radios for Spatial Intelligence

Length is one of the seven fundamental physical quantities. For several centuries we have measured distances using calibrated physical objects, and more recently using light, sound, and radio waves. These measurements and the tools we use have enabled advances in several different domains, from the construction industry to space travel, from GPS localization to tracking of airplanes. With advances in electronics, clocks, miniaturization, and development of new algorithms, *wireless* distance measurement has now become possible. Measuring distances using wireless sensors offers the option

of locating objects across rooms, through walls, and without visual line-of-sight. The measurement accuracy improves with larger bandwidth, which has resulted in the ultra-wideband (UWB) radio technology gaining significant traction. Seeing an opportunity in this capability, smartphone manufacturers such as Google and Apple have incorporated UWB radios in their offerings, setting the stage for future innovation using this versatile technology. [10] In this article we look beyond the UWB object-finding use-case and explore how a modest radio can transform mobile computing for decades to come.

THE PAST: UWB'S EARLY DAYS

UWB stands for ultra-wideband radio technology that uses large bandwidth wireless signals to send short pulses. The technology was first standardized in the 2007 IEEE 802.15.4a standard where a bandwidth of 500MHz or larger, or bandwidth larger than a fourth of the carrier frequency was defined as ultra-wideband. While the standardization efforts in 2007 paved the way for UWB to be used in mobile computing and IoT systems, signal level innovations and UWB timing analysis were already mature before this time. An introductory treatment titled *“Impulse Radio: How It Works,”* authored by Moe Z. Win and Robert A. Scholtz appeared in the *IEEE Communications Letters* in 1998 [1], where the frequency range used by the impulse radio was expected to be from near-zero frequency to a few gigahertz. Of course, overlapping so many licensed bands would have been a problem, which was solved by keeping the energy spectral density extremely low, and eventually shifting the large bandwidth signal to a higher frequency range. Intermittent well-defined and bandwidth limited pulses are used in UWB transmissions today (see Figure 1), which can easily co-exist with other higher power narrow band technologies such as Wi-Fi and Bluetooth. The sharp quick-rising pulses facilitated by the large bandwidth makes it easier for UWB receivers to detect exactly when a preamble (a predefined known set of bits) arrived. Such precise timing information is crucial in ranging and localization. Data is encoded by shifting a burst of polarized pulses to indicate a ‘0’ or a ‘1’, allowing UWB to be used as a communication technology, in addition to a sensing modality. Ranging, or distance measurement, between two devices (A and B) is performed by exchanging *three* timestamped messages to compensate for the different clock offsets and clock drifts between the ranging pair (see Figure 2). Originally, it was recommended that the turn-around duration (changing from being a receiver to a transmitter), D_A and D_B , be kept identical, since a simple averaging formulation was used by the standard to calculate the propagation delay ρ :

$$\rho = \frac{(R_A - D_B) - (R_B - D_A)}{4}$$

The formulation was improved in 2016 by Dries Neiryck, Eric Luk, and Michael

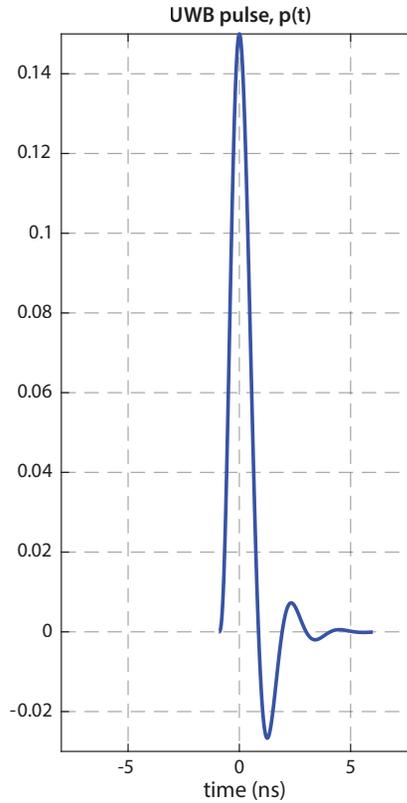


FIGURE 1. A UWB pulse (from the IEEE802.15.4a standard).

McLaughlin in their seminal work, *“An Alternative Double-Sided Two-Way Ranging Method”*, where clock drift mitigation was ensured through a new multiplicative formulation instead of averaging [2], removing the need for identical turn-around duration:

$$\rho = \frac{R_A R_B - D_A D_B}{R_A + R_B + D_A + D_B}$$

This new formulation was adopted in the IEEE802.15.4z standard in 2020, paving the way for a large number of applications, faster update rates through cascaded ranging, and messaging flexibility allowing interchangeable device roles (switching from anchors to tags and back again) in UWB ranging, ushering in a new chapter for UWB.

THE PRESENT: WHAT IS UWB ALREADY ENABLING TODAY?

Today, UWB radios have already been incorporated by Apple, Google, and Samsung in their smartphones for enabling the object finding use-case (AirTags), keyless doors and cars, with the expectation that these new use-cases will become a differentiating factor from previous generation smartphones.

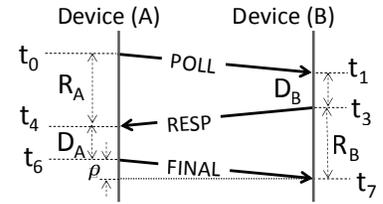


FIGURE 2. Distance measurement through two-way ranging; removes effects of clock offset and clock drift between ranging devices. Messages carry timing information.

UWB research has ventured further, though, and we will touch upon some of it in this section.

UWB has the capability to transform the mobile computing landscape. While indoor localization is an application that gets the most attention, UWB has been shown to improve fine-grained sub-cm level tracking in 2D and 3D, bring distance bounding to two-factor authentication (stopping phishing attacks), record body gestures through wearables, act as a physical security system detecting intrusions, identify materials by carefully studying their effect on wireless signal propagation, and even monitor thawing of food. Figure 3 shows an overview of UWB capabilities and the applications that these capabilities enable.

This plethora of applications has become feasible primarily due to easy access to the raw timestamps (openness) and the channel impulse response (CIR) deducible from UWB’s large bandwidth (exposing the PHY layer) even in commercial UWB chips such as the [9]. When required, UWB can also encrypt messages and smudge the detection of the first arriving peak, providing location privacy from eavesdroppers while still providing correct location information to authorized devices. Next, we dwell on current research innovations which elevate UWB from an object finding tool to a versatile platform ready for a broad future scope.

Infinitely Scalable, Privacy Preserving, Synchronization-Free Indoor Localization

Ranging between two UWB devices, that provides the inter-device distance, is a foundational primitive for localization. Traditional approach for indoor localization requires a UWB tag to range with several

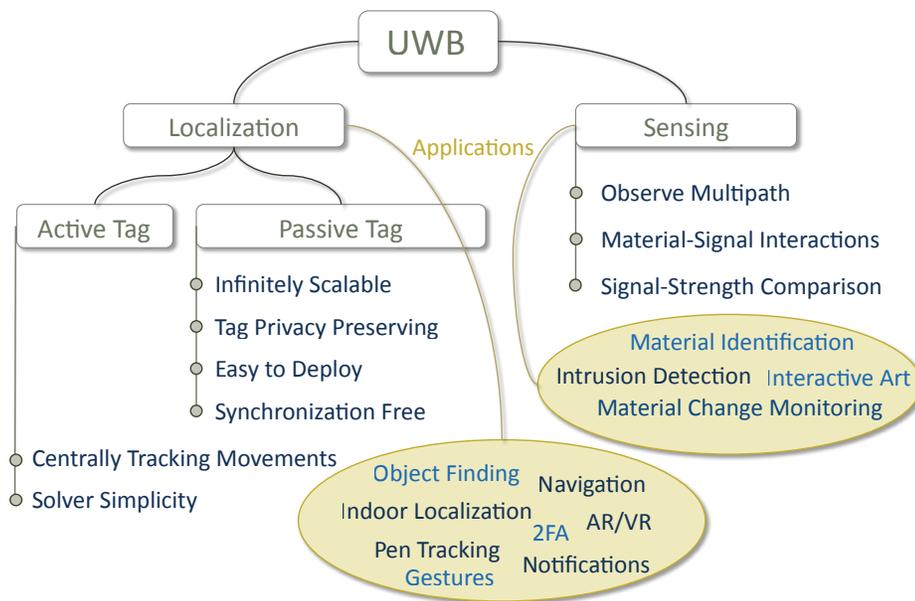


FIGURE 3. Various UWB capabilities and the applications already enabled by UWB.

infrastructure anchors, using a technique called two-way ranging (TWR), shown in Figure 2, and perform trilateration for obtaining location. However, every actively ranging tag consumes airtime, thus limiting the number of tags that can be supported for localization. Further, since the tag actively transmits wireless packets in this ranging process, the tag’s presence is known to the infrastructure, compromising privacy of the tags. We wonder: *Is it possible to create an infinitely scalable privacy preserving indoor localization solution?*

In answering this question in the affirmative, an obvious solution emerges: let the infrastructure nodes transmit packets in a synchronized manner and the tags can derive their own location using time-difference of arrival (TDoA) methods. Since clocks on individual anchors drift over time, the anchors need to be synchronized for TDoA. However, synchronizing anchors requires additional hardware and increases maintenance overhead for the building. It also makes deployments slow and cumbersome since laying wires to synchronize anchors is non-trivial effort.

In exploring an alternative which would satisfy all the indoor localization requirements while keeping deployment overheads low, we discovered that *if anchors could perform two-way ranging with each other*, the timing information exchanged would allow overhearing tags to obtain

TDoA information without explicit anchor synchronization [3]. Figure 4 shows the message exchange and timing information that the smartphone overhears. Effects of clock drift between anchors and the tags are mitigated through a novel formulation calculating individual TDoAs. The smartphone obtains the time difference of arrival for signals from anchor A and anchor B, called T_{AB} , using:

$$T_{AB} = \frac{D_A R_{T1} - R_{T2} R_A + R_B R_{T1} - R_{T2} D_B}{2(R_{T1} + R_{T2})}$$

This work, called PnPLoc, won the best paper award at IPIN 2022.

It is worth noting that anchor-anchor TWR combined with the novel TDoA formulation solves several localization pain-points: (1) Anchor-anchor ranging makes it easier to ensure link quality and detect environmental changes; (2) Anchors can be deployed sequentially, with anchors automatically determining their relative geometric topologies. Meaning, anchors can be placed in a manner that will reduce geometric dilution of precision, and anchors can self-localize without need for an anchor location survey. (3) Individual TDoAs depend only on communication between one anchor-anchor pair. Tags can overhear any set of such pairs to infer their own location giving them the choice of links to use in their localization solutions. Tags can thus choose high quality links and link combinations that are expected to produce

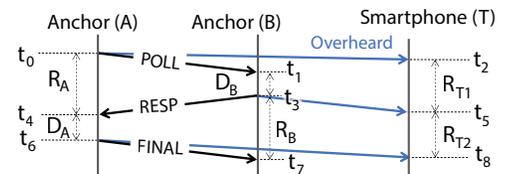


FIGURE 4. PnPLoc: anchor-anchor two-way ranging passively overheard by the smartphone.

the lowest dilution of precision. (4) The mains powered infrastructure nodes can perform inter-anchor localization at a very high update rate, since there will be only a few anchors. Individual tags can choose to overhear the ongoing anchor-anchor communication at whichever rate they prefer, allowing significant energy savings for the tags. (5) Tags never transmit, only overhear ongoing message exchange, thereby preserving their privacy. Since tags do not take up any airtime, there is no limit on how many tags can simultaneously localize, providing infinite scalability. (6) Since all information being transmitted by anchors is public, no UWB encryption is required for the messages, greatly reducing the setup overhead for users.

How PnPLoc May Influence Current Trends with UWB?

This work is a unique tipping point in how we have been using UWB. In the object finding use-case, that is being advanced by Apple AirTags, for example, the tag is explicitly paired with the user’s phone. This pairing operation establishes ownership, even though the tags do communicate with other phones to periodically report their location to the Apple cloud. In our PnPLoc work, smart phones only overhear the infrastructure’s broadcast UWB message exchanges without any pairing with the infrastructure. The mobile phone can use this location information for navigation, or for deriving spatial intelligence or context. We need not worry about the user’s privacy since the mobile phone only overhears. However, we do hope to ensure that these broadcast infrastructure messages being overheard for location information are authentic. Authenticity can be verified by using a public-key verifiable hash of the broadcast messages. Smartphone users could obtain the public-key of the indoor space through other means, such as by scanning a

QR code on the doorway or through codes registered with mapping service providers such as Google Maps.

Fine-grained Localization for AR/VR

Building-scale indoor localization and navigation enabled by PnPLoc has substantially different goals than the precise localization of a few objects, such as hand controllers or the headset, in a virtual or augmented reality setting. Traditionally, such fine-grained tracking has been performed using cameras. However, camera-based tracking has several disadvantages: (1) requires optimal lighting conditions; (2) the tracked objects can be easily occluded; (3) similar looking tracked objects can be easily confused (identification problem); and (4) processing images is a compute intensive and energy intensive process. In contrast, wireless localization using UWB may provide an alternative: (1) it is unaffected by lighting and is immune to occlusions with certain everyday materials such as clothing, cardboard, and plastics; (2) Each tracked object can be individually identified using addressed wireless packets (this is also an advantage over wireless radar technologies such as mmWave); (3) processing UWB packet information uses significantly less power and is less compute intensive than computer vision based processing. The primary shortcoming, of course, is UWB's lower precision. Is there a way to improve location precision within the confines of this small-scale tracking problem?

Ultra-wideband radios inherently provide a detailed channel impulse response (CIR) due to their large bandwidths. The CIR, also called the power-delay profile, shows *when* different copies of the transmitted signal arrived at the receiver, and with *how much* intensity. Each delayed reflected signal also has a different *signal phase*, since the delay

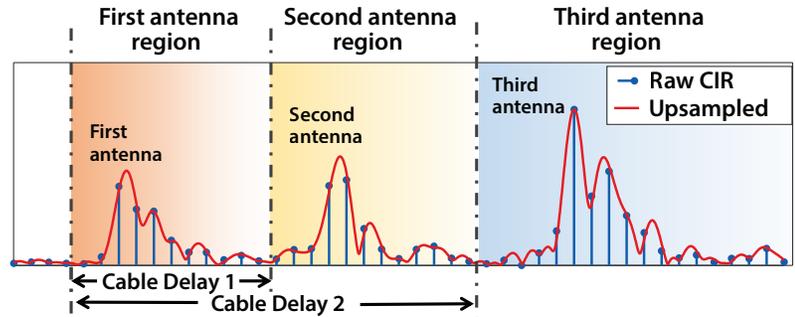


FIGURE 5. Signal transmitted from three antennas connected by long delay cables is observed in the CIR as three separate peaks.

is effectively a longer path-length that the carrier signal had to cover to reach the receiver. Of course, the absolute value of the carrier phase has little utility, since the transmitter may begin signal transmission at any phase, and we do not know how many times the phase has wrapped till it reaches the receiver. However, when the *phase difference* between the first path and a reflected path is calculated, we can detect even tiny movements.

We extend this general idea of observing phase difference between different peaks in the CIR to fine-grained tracking in our works [11] and [12]. Instead of relying on reflections, though, we force multiple peaks to appear in the CIR by transmitting the same signal through different spatially placed antennas with a fixed short delay (a few nanoseconds apart) between the transmissions. Such peaks have an artificially introduced cable delay, in addition to the in-air propagation delay between the antenna and the receiver. Even with a single transceiver, multiple antennas function like multiple vantage points with the propagation delays describing the distances between the individual antennas and the receiver. All the antennas are fed the same transmitted signal, just over progressively longer delay

cables, forcing a clean separation between the observed CIR peaks while keeping their phase synchronized. The received signal can be analyzed based on the phase difference of arrival for a single CIR, as well as phase differences can be tracked over time providing fine grained location estimates and tracking. With the right number of antennas and placed strategically, both 2D and 3D tracking is possible with sub-cm precision (see Figure 6 showing 2D and 3D tracking precision).

What prevents phase-based tracking from working for larger spaces?

Perhaps engineering advances in the future will allow such single-transceiver multi-antenna to function at the room scale or building scale. However, currently, we are limited by dynamic range of the receivers. When substantially closer to one antenna, the signals from that antenna appear much stronger on the receiver's CIR. This drowns signals from other antennas, limiting this multi-antenna idea to smaller spaces today. These dynamic range issues can be mitigated by using variable attenuators, antenna switching instead of continuously sending pulses from all antennas, and by improving dynamic range or masking at the receiver.



FIGURE 6. Multi-antenna systems for precise 2D and 3D tracking. Tracking accuracy is sub-cm at the 90th percentile.

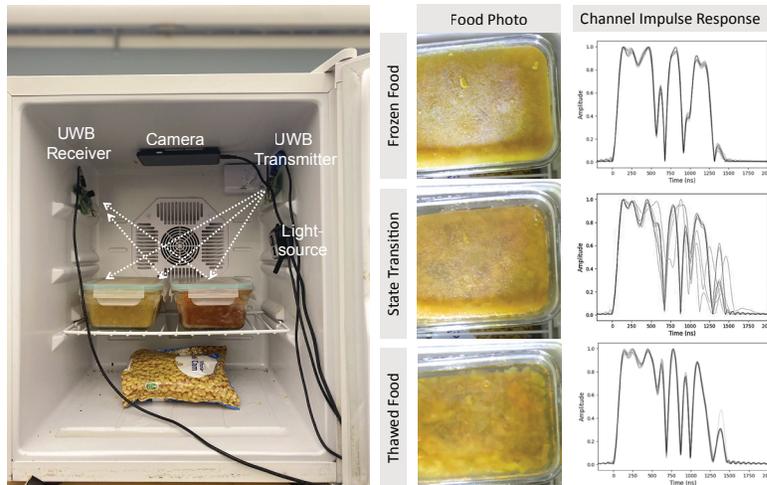


FIGURE 7. Observing food thawing through changes to the UWB reflection patterns.

This is an invitation to other researchers to explore some of these possibilities, advancing the foundations laid by ITrackU and UTrack3D.

Ranging and Localization for a Variety of Existing Applications

Indoor navigation and precise localization for AR and VR are only the tip of the iceberg when we think about the possibilities enabled by wireless ranging. Here is a list of topics from various domains that have been shown to benefit from UWB ranging and localization.

Range Bounding for Two-Factor Authentication

One of the primary reasons for the success of phishing attacks today is that the legitimate server sends an out of band confirmation message to the user's 2nd factor (typically a phone). Instead, if the server demanded a proof that the user's token is physically in proximity to the login device, phishing attacks cannot succeed. We have shown in our work [6] that such local proximity can be checked even before the user enters the password, thus also securing the password despite phishing attacks.

Gesture Recognition with UWB wearables

Wearable-based gesture recognition has typically used inertial sensors. A significant effort has been expended in deducing human pose and gestures using orientation data from different appendages. However, when

orientation data is coupled with inter-appendage distance, the pose and gesture recognition problem becomes much simpler. Particularly when the person whose gestures are to be recorded is of central importance, such as a sports player or referee, or a law enforcement officer directing traffic, or a construction worker giving directions to a crane/lift operator, or an aircraft marshaller directing a plane to its gate, a set of wearable devices make the problem much simpler and highly reliable. Our work [15] shows one such wearable-based approach, which devises an innovative ranging algorithm for fast multi-device all-to-all distance measurements.

Generating Secure Keys using UWB

Ephemeral and incidental communication between devices is often hindered by lack of a secure channel between them. The rich multipath laden channel impulse response obtained by UWB, which is typically a problem to be solved for most wireless communication, can itself be used to generate a seed for deriving random shared secret keys. Shared secret keys, though an age-old idea, can be made robust even against quantum attacks and are hence being revived. Our latest work called "UWBKey: Using Contrastive Learning for Efficient Secure Key Generation in UWB," [5] shows promise in this idea with keys derived from UWB CIR that are both random (pass NIST's tests for randomness) and reciprocal for communicating devices, while being resistant to inferences by an eavesdropper.

WIRELESS SENSING THROUGH UWB

Signals emitted by a transmitter go out in all directions and interact with the environment around them. These signals get reflected from reflecting objects that are large enough, get refracted within substances that allow the signals to penetrate, and diffract around objects that are too small or around borders of larger objects. This means, just like light, we could also use wireless signals as sensors to understand our environment. Even better, wireless signals interact with the environment differently than light does, because reflection and refraction is dependent on the signal's frequency and not just the substance. Fundamentally, both properties are derived from the substance's complex permittivity at that frequency.

Material Identification using UWB signals

For instance, water, that appears mostly transparent for light, is almost completely opaque for wireless signals, with a refractive index close to 8.5 at UWB frequencies (it is just 1.33 for light). But if water were to turn into ice, the refractive index for wireless signals drops dramatically to about 1.8, while it remains around 1.31 for light. In other words, opaque water turns into transparent ice when observed through the lens of wireless signals. In contrast, thick motor oil, which is almost opaque for light appears transparent to wireless signals. In fact, the range of refractive indices expands so much at wireless frequencies that we can easily *observe the corresponding slowdown of wireless signals* by measuring the time it takes for signals to pass through these substances. If a water-filled container turns into a block of ice, the wireless reflections also change dramatically. Our work, [16], identifies different liquids based on the liquid's complex permittivity which we determine from the slow-down of the wireless signals and the extent of attenuation we observe. Wireless reflections help us observe liquid-solid transition for water in [7], which works even through solid plastic, glass, or cardboard containers.

In-situ solid-liquid transition monitoring has a substantial market in the cold chain industry that moves food between factories and from factories to grocery stores and finally to the customers. It can allow the

entire cold-chain (from trucks to grocery store freezers) to maintain temperatures close to freezing without thawing the food, which dramatically reduces the energy costs of frozen food. At home, microwave ovens that can automatically detect thawing can substantially improve efficiency and can heat food more evenly once all frosted parts are thawed. In the future, this technology can also find usage for autonomous vehicles (AV) where the AV must determine whether the road has water or snow or ice, all with different traction requirements. The liquid identification work can help an AV distinguish between wet roads, an oil-spill, or just a dark shadow.

Presence Detection using UWB signals

Our bodies are made of about 70% water. Wireless signals strongly reflect from our bodies. If a person moves, their movements would disturb the ambient wireless reflection pattern observed by a wireless receiver. We can use these signal disturbances as an indication of presence and take actions accordingly. Such a technology can be used for intrusion detection where a disturbance to the wireless reflection pattern can trigger a camera to record and a warning alarm to go off. Interestingly, it can allow the occupants to move freely in the house while wearing a special UWB device whose movements can be ignored by the system while still monitoring the rest of the house for intrusion.

In a completely different setting, these changes to the reflection pattern can be used to generate interactive art and lively indoor spaces. Our interactive art exhibit called *TechMyMoves* (2022) at the Georgia Tech library was one of the first such UWB-based art exhibit. It responds to people’s movements in its vicinity, purely based on the changes observed to the channel impulse response, without using cameras. This creates a privacy preserving interactive system capable of documenting presence without being intrusive. Figure 8 shows a photograph of our exhibition. An extension of this artwork, titled *TechThrive*, will be on display at the Atlanta Airport until Nov 2026.

Importance of UWB in Wireless Sensing Applications

On the surface, it might seem that all wireless technologies could potentially perform the same tasks that UWB sensing can. However, the large bandwidth available with UWB, and the ease of accessing the channel impulse response creates a unique combination that significantly improves UWB’s utility for sensing. Furthermore, the ability to perform active ranging with user devices while also monitoring the fluctuations to the channel impulse response is an advantage over purely RADAR technologies since the active ranging allows for paying special attention to some users, localizing them and ignoring their movements or enhancing the effects of their movements according to the application’s needs.

THE FUTURE: WHERE IS UWB HEADED?

Almost all core building blocks for UWB are perhaps in place now for UWB to truly enable spatial intelligence. We have enabled privacy preserving large-scale localization, fine-grained localization in smaller spaces, integrated UWB with inertial measurements, we can now detect dishonest ranging devices that report incorrect timing information, have enabled secure peer-peer communication for ephemeral connections, and have also explored sensing opportunities without requiring a user to carry a paired UWB device.

The UWB Network Stack

The next decade of UWB development will likely focus on a rapid expansion of the application scope for UWB. A primitive to enable this expanding application landscape would be an open UWB stack spanning all layers of networking. Such an abstraction can transform UWB into a cross-application resource for infusing spatial intelligence into the mobile computing ecosystem.

The UWB stack, shown in Figure 9, can enable developers to use UWB as a location sensor similar to how GPS is used today. It can also enable direct access to observed channel impulse response, requests to create a peer-peer secure connection at the transport layer, or routing of UWB data, adding to its capabilities not just as a localization sensor, but also as a communication vehicle. Routing data based



FIGURE 8. Artwork based on CIR changes caused by human movements in the vicinity.

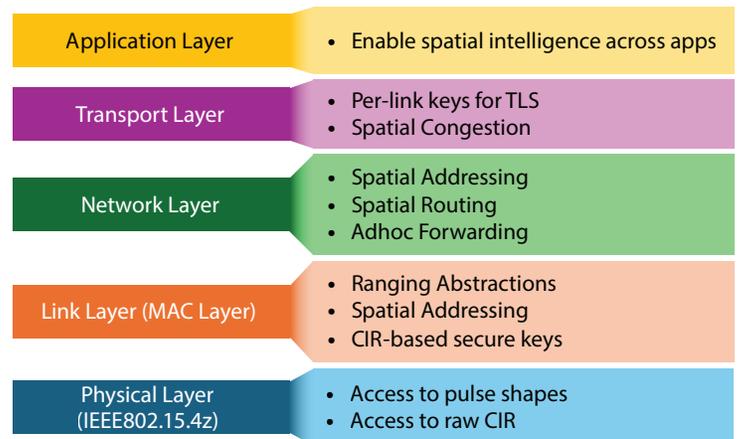


FIGURE 9. UWB Stack for enabling access to UWB functionality at different layers.

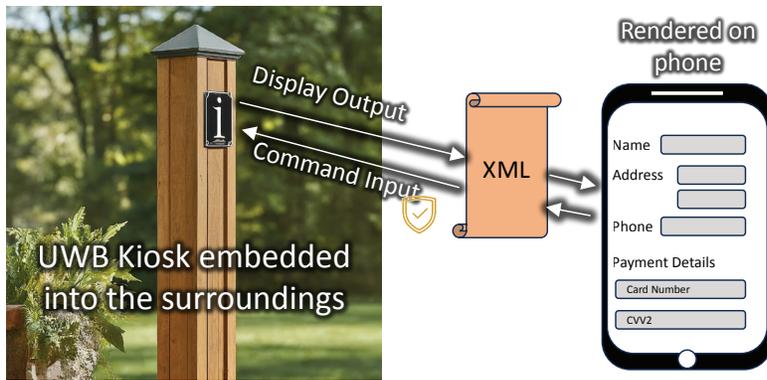


FIGURE 10. UWB short-lived connection replaces touchscreens.

on their location instead of addresses and connectivity can revitalize adhoc wireless networks, for example.

Touchless Things

Today, touchscreens are everywhere, including kiosks for ordering food, on appliances, airport information panels and boarding card printers, and even IoT devices like thermostats. However, touchscreens are fragile and typically the first component to break which results in high replacement costs. In many cases, the entire kiosk or appliance needs to be replaced even though the core functionality of the device is still operational. In the future, when smartphones start using nearby interactions through UWB, we might see a complete transformation where all the appliances can simply be controlled via the smartphone without needing any touchscreens of their own. The smartphone will receive, over UWB, the exact same UI that is displayed on the touchscreens of today's appliances. Anyone proximal enough to the device can access this UI and control the device from their phone (see Figure 10). This would function without any app, user accounts, and even without an Internet connection, since the link between the device and the smartphone will be a locally encrypted UWBKey [5] range-bounded connection [4]. Once again, all the foundational layers to enable such a future already exist today via secure ranging and secure CIR-based secret key generation.

Replacing the touchscreens on appliances with a UWB chip that will export the UI to a nearby smartphone has several advantages: (1) it reduces an expensive component present on almost all devices today, (2) it

reduces e-waste due to replacement of touchscreens or sometimes of entire appliances due to touchscreen breakage, (3) it reduces kiosk power requirements since always-on touchscreens consume large quantities of power, (4) it reduces high frequency touch areas around the house and in public spaces. Of course, such a transition might be a decade away when the existing investment into touchscreen kiosk would have paid off, but we hope to create awareness about what is possible and its immense ecological and economic benefit.

Context Awareness in Mobile Computing

AR/VR headsets and eyeglasses constantly record their surroundings to perform simultaneous localization and mapping (SLAM). However, in some contexts, it is important that these devices stop recording, or at least stop sending data to the cloud. For example, as a smart eyeglasses user enters a private area in their house, or enters a public restroom, recording should automatically stop. UWB broadcasts can create a beaconing system that alerts the user's smart wearable devices when they are entering private spaces. Similarly, smartphones can turn their notifications on or off and reduce or increase the call volume depending on the phone's context (is it in the exam hall or is it in an outdoor park?)

Importantly, such context can be deduced from other broadcast UWB signals the smartphone could overhear instead of revealing its own existence, thereby preserving privacy. Context awareness makes spatial relations central to how we work and play, in a manner similar to how we use a calendar today, for timekeeping.

We shouldn't be surprised if UWB becomes a foundation for numerous yet unimagined applications of the future

Location Verification on the Blockchain

The way in which we today approach proof of work, proof of package delivery, proof of origin of goods, proof of chain of custody can all be transformed via verified locations obtained from infrastructure UWB and wearable UWB devices. Such information can then be made part of blockchain to preserve it in a tamper-proof manner. As an example, an important piece of police evidence could be constantly timestamped with location and proximity to other UWB devices. When the evidence package changes hands the new police officer's UWB badge information will automatically be recorded by the sealed evidence package. When opened in court, the package can produce this chain of information providing an unbroken chain of custody as proof that the physical evidence has not been tampered with after it was collected. In a completely different application, the actions of a referee or umpire during an important game could be enshrined into verifiable art-piece and potentially auctioned as memorabilia at the end of the game. The actions can be captured using UWB, similar to how we capture actions in ViSig, and then converted into an artistic rendition.

Improving Spatial AI using UWB

Spatial context, particularly in images is derived only as secondary information in today's AI systems. As a result, physically impossible images continue to be produced by AI agents. If UWB radios can be placed inside appliances and other IoT devices or any set of objects of interest, we could embed actual relative distances between objects into images, making spatial relationships

more obvious to AI agents for training and validation. Even a few such images could train AI models by informing them what to look for. Furthermore, a camera can also wirelessly receive structural information about objects such as their CAD models and dimensions to embed into the image, providing a rich context for data mining, advertising via images and videos, and for AI agents to learn semantic aspects about the real-world (see Figure 11). As an example, in movie studios it will be possible to create rich immersive content by guiding AI agents to focus on particular participants with camera and audio tracking using hidden UWB tags worn by participants.

UWB in Space Applications

We look forward to a future where UWB will be used for several space applications. An obvious use-case is in helping astronauts navigate space walk and return back to a space station by constantly monitoring the astronaut's location. This is particularly useful when astronauts become incapacitated due to unforeseeable reasons. Another use-case is for satellites to use UWB synchronization instead of atomic clocks, saving a substantial amount of weight and costs, particularly for extra-terrestrial localization missions. Relative localization using UWB may also help future space rovers for surface exploration.

CONCLUSION

We are just getting started with UWB. It brings in a vast treasure of possibilities in spatial intelligence and we suspect that UWB will touch every aspect of mobile computing and by extension our everyday life in the future. We also hope that as UWB starts becoming ubiquitous, it will truly weave itself into the fabric of everyday life while helping us achieve greater efficiency and free up our time. We should not be surprised if UWB becomes a foundation for numerous yet unimagined applications of the future. Its wide application base, of course, comes from the fact that *length is one of the seven fundamental physical quantities*. ■

Acknowledgements

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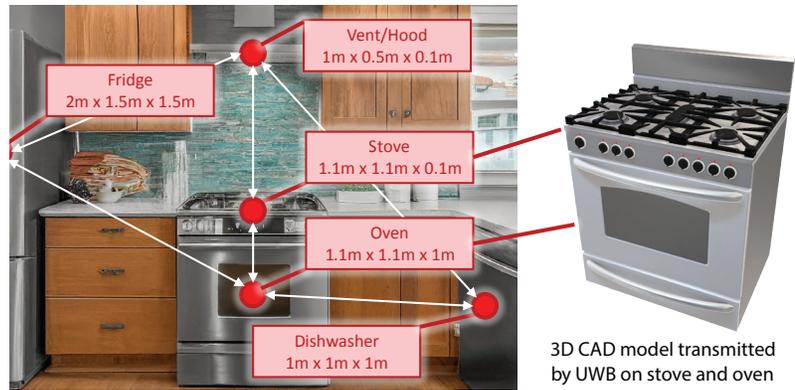


FIGURE 11. Embedded UWB radios can report relative distances between appliances and other devices to cameras for better AI-based scene understanding with physics constraints. Embedded CAD models can improve spatial intelligence.

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