PROFESSOR: Good morning. I'm often hungry for an audience, so I came here with eight presentations. So I've condensed it down to three, which have been merged here, and I'll try to be through my section in 10 minutes because I have some very other-- very knowledgeable people to speak after me.

I was supposed to speak about evolution of RFID systems. And I was trying to capture the notion of how these systems evolved under the various constraints that have regulated the revolution and how they might evolve under future research. And there won't be any time to say much about what we're doing at Adelaide.

The sorts of topics that I thought we might collectively talk about are here, something on RFID regulations, something about antennas, something about propagation and protocols, and higher functionality tags. Now, I have other speakers that are very good on some of those issues. So I'm going to talk a little bit about antennas and also propagation studies. And I'll move to that almost immediately.

So talking about antenna issues, I'll say a little bit about electromagnetic theory and maybe something about how antennas work, largely through diagrams, talk about near and far fields, and talk about what I think are important conclusions that you might draw about what you can do with antenna in the near field and the far field. I think there'll be time for me to talk a little bit about the [INAUDIBLE] limit on efficiency and maybe show you a couple of simple tag designs.

I never give a presentation without showing this slide, which shows an encapsulation of Maxwell's equations in the source and vortex interpretation of Helmholtz, which I think the more you look at it, the more you realize that it contains the secret of life. But it boils down to these pictures, which show you the source nature of an electric field coming from a charge distribution. Also shows you the boundary conditions you have to contend with when it gets near a conducting surface.

This shows you the vortex nature of a magnetic field caused by a current or displacement current. And again, the boundary conditions you have to contend with when that becomes near a magnetic surface. I think this is a picture which will show you how an electric field might excite an antenna and how a magnetic field might excite an antenna. Unfortunately, these are really useful for small antennas. When the antennas get a bit big, it gets to be a bit more complicated than that.

Well, these are the fields of a small magnetic dipole. You should only look at the red and the blue parts, which show you that there's one field that diminishes rather slowly and is the first power of distance, and another field that diminishes rather quickly. That's the third power of distance. That shows you that there are near fields, which is the blue part, or the far field, which is the red part that we should think about when we're trying to design systems to couple to them.

We're not going to talk about that slide. This is a glimpse of how radar engineers work out power transfer between antennas. And you can see towards the bottom, there's a dependence upon wavelength and a dependence upon inverse square power of distance.

And if you look about that and you think about it, you say, well, I'm going to do best if I have a very long wavelength and that means I should be at a low frequency. So the question we should ask is, why is that not true. And I think you can come to an answer on that question by focusing attention on what happens when you're close to an antenna, you've got stored energy.

So I have what I call a near field coupling theory with some of those concepts within it, but I think these are the significant conclusions. An antenna can be characterized by a coupling volume, not really an effective area, and it's proportional to the third power of its largest physical dimension.

And you can also characterize it by a quality factor which tells you how narrowband the antenna is. And that, unfortunately, the quality factors are inversely proportional to the third power of the distance. So I think that this gives us a clue as to why we shouldn't always go to low frequencies when we're designing antennas because the low frequencies have very large betas in the-- have very small betas, actually. So the quality factors go up and the bandwidth over which are untenable work is impossibly small.

This leads you to conclusions you can draw about optimum operating frequencies. And it's really the lowest frequency in which your antenna will still be efficient, and that often happens to be about the UHF region. So that's no surprise, of course, why there's a lot of tags working at the UHF region where range is required.

We're also recently interested in what the [INAUDIBLE] theorem tells us about over what sort of bandwidth you ought to be able to make a UHF tag work, and there's the theorem there in a few slides here about what it means in terms of making yourself a bad match over frequencies you're not interested in and a very good match over frequencies you-- well, as good a match as you can manage over frequencies you're interested in.

And I think you conclude that if you look at the different problems we face, like the USA, which has got one bandwidth, the Japanese, which has a smaller bandwidth, but a different part of the spectrum, or the European countries, we can ask ourselves, can we do a good match over those frequency ranges.

And I think the conclusions are, it does depend a bit upon the characteristics of a circuit. And you're not troubled by the theorem, I think, if your microcircuit has a relatively low impedance of 1,000 ohms in parallel with a picofarad. But once it starts to become a very low power circuit, it's still about one picofarad of input capacitance, but less power consumption, it isn't practical to make the antenna work optimally without some inefficiency.

So-- but based on those principles, we have designed some small antennas with simple matching circuits. So down at the bottom here, you can see a tag chip, and behind it, there's a capacitance in parallel with it. Up here, there's another capacitance also in parallel with that gap, and that provides a reasonable match between the circuit and the radiation impedance.

So that's I think all I want to say about tags, and I think about antennas. And I think Rich Fletcher will give you something substantially more widespread in that. But I think I've got time to talk a little bit about higher functionality tags. And I think the interesting questions to me seem, can you merge electronic article surveillance and data tags.

And I think I'm pretty convinced the answer is not easily for the reasons that, to turn them off, you're going to lower the queue inevitably and you can't get the high quality factors that you need in EAS tags if you're turning on and off the resonance. But I think we've also become interested in that second topic, turning on battery-operated tags, and I just want to show you some simple results for both low power consumption circuits and what I call zero power consumption circuits for those operations.

This is what you might do if you have a turn-on circuit down at the bottom right and you have a label antenna, which you want to both resonate, because resonance has the desirable properties of magnifying voltages. And so you might want to resonate your available induced voltage to produce the maximum voltage across the depletion layer capacitance of a rectifying diode and then use the DC voltage to apply a turn-on circuit.

There's a couple of contexts here. You might want to apply-- get about a volt out of the system so you can turn a transistor from desaturation to conduction, or you might want to just get about 10 millivolts so you can operate the input of a very, very low power consumption amplifier.

This shows some experimental work that we were doing to reveal the fact that, if you're working at relatively low powers, you can get a nice resonance curve as you see on the left. But as soon as you start to increase the power levels, the nonlinear capacitance variation with developed voltage of the diode becomes interplay and you end up with that kind of resonance curve when the right hand side is quite vertical. As it goes off resonance, it suddenly drives itself away in operating frequency.

That's the idea of a low power consumption circuit, which will consume about 10 nano amps and turn on at about a few millivolts. And this is a totally different concept in which a vibrating magnetic field might shake a magnet, which will distort the piezomaterial, which will generate about a volt.

The analysis of that involves things like looking at charge, and displacement, and voltage, and torque on the device. You can relate material properties to structural properties if you know the dimensions of the structure, and I think eventually produce this expression for the turn-on voltage, which will allow you to work out that the concept is feasible at frequencies of about 100 kilohertz and magnetic fields of the kind that you can use to create a stored energy in the foyer.

And the obvious application is theft detection. So if I were to try and walk away with this PC and it had such a theft detection tag based on these principles in it, it would raise an alarm. So I thank you very much. I now have pleasure in introducing my other colleagues.

[APPLAUSE]

Yep.

AUDIENCE: So our next speaker is Dr. Rich Fletcher, who's a visiting scientist here with the AutoID Labs and was involved back at the Media Labs at MIT when Sanjay, and Dave Brock, and so on were in the basement over here. Rich was working in RFID in the Media Labs, which was a little bit more glitzy at the time, I believe.

RICH FLETCHER: Yeah. We had more money back then. That's for sure. All right. Oh. Hello? OK.

All right. I'm happy to be here today and give you-- have a chance to tell you a little bit about some part of some aspects of RFID and some of my work. I am a visiting scientist at MIT, but I work also with MIT Media Lab. So some of the slides that I'm going to show you and some of the pictures are from different projects at MIT as well as some of my company projects as well.

The basic topic or theme of my talk is looking at different electromagnetic issues and how they vary depending on different frequencies. And there's a lot of slides. I'm just going to go through it very quickly. But just to give you some sort of flavor of the different RFID frequencies that are out there and some of the issues involved.

So as we all know, RFID, is the main goal is to send out some sort of signal from the reader to the tag and to get some sort of response, either reflected power or some modulation from the tag, to get information or to use this tag as a sensor. And obviously, if there's no power or if there's problems with electromagnetics, it affects either the turn-on of the tag, or the signaling is corrupted, or you have some other types of errors.

I'm going to start by just giving you a very brief, fundamental introduction to some of the electromagnetic effects that we look at. Obviously, we have different sort of reflections depending on what frequency you're looking at. The signal also spreads in space. It's not like a laser that goes in a straight line, so you have spreading loss. And every time you go through an interface, you get different types of loss just through the impedance mismatch.

There's shielding and detuning of the antennas. At the higher frequency, RFID, you have multipath reflections from other things in the room, including the floor. When you go through different slits, like layers on the pallet, you also have other types of interference. The wave interferes with itself. You probably experience some of that with your cell phone.

I'm now going to tell you a little bit about the different RFID frequencies that exist. Some of these are only used today for EAS or antitheft applications, so I don't know how familiar you are with those. But I thought it would be interesting just to give you a flavor of that.

As we all know, the RFID tags come in many shapes and sizes and they've been around since the '70s. At the very low end, we have, at 77 Hertz, which is an extremely low frequency, that's used for library books or certain CDs, antitheft tags, little strips that are made by 3M.

The advantages of this is that it's a magnetic material. It's a very thin film, a very low cost. It's good for making different types of sensors. The disadvantage is that it's shorter range, and to generate those magnetic fields, you generally need a larger antenna and sometimes higher power. That's a picture of what some of those tags look like. I worked in some of these areas to make sensor tags. We made item level temperature sensors using these materials.

Moving up to slightly higher frequency, this is your common 125 kilohertz sort of tag. It's sort of the classic RFID tag. What's great about it is that it penetrates liquids and other materials very well, so it's used a lot in industrial applications. And has a worldwide frequency. It's pretty easy to find, to be able to use it anywhere in the world. The disadvantage is that it's also somewhat shorter range and you need larger coils and antennas.

There are magnetic versions that work in this frequency as well. And let's see. I'll just give you-- I'll play this. This is one of the very early demos that I did at MIT. This was at the Media Lab in 1995. We were looking at using some of these magnetic materials as exploring how they could be used for RFID sensors.

And there's-- we were looking at using it to measure the displacement of a piston, and also detect other objects, and also, in this case, detect the squeezing of a toy. So as you squeeze it, you can see the little figure animates over there. So there's a lot you can do with just different types of magnetic materials.

This is the more common form of these sort of tags. And these are still by far the largest RFID market, even today, used for mostly access control, car mobilizers, cattle tagging. And the cattle tagging actually started-- was invented by an MIT here, Mike Beigel, in the late '70s.

Because this works pretty well in proximity to metal and it's pretty robust, we also used it to do some of the early smart shelf work back at the Media Lab, this was in the late '90s, where we had to read tags either through an LCD display or through other types of materials.

Something else which I'll just mention briefly. For a brief time while I was at Motorola and also in collaboration with the Media Lab, we developed capacitively coupled tags. Now, most tags work with magnetic fields and inductive coupling with coils.

For a brief time, we did develop capacitively coupled tags. And what's nice about this is that it uses electric fields instead of magnetic fields, but what's nice about it is that you can make a printed antenna and it's very flexible and robust. It doesn't require soldering. You could rip up the antenna and it still works. But unfortunately, Motorola, they were losing a lot of money in the late '90s due to iridium and other projects, so they sold their RFID division. But this technology is still out there and it's a pretty interesting technology.

Moving up to slightly higher frequencies. HF, for example, 13.56 megahertz. This frequency-- you need fewer antennas on your coil, so you can make a lower cost tag. You can make it out of foil, however, because the penetration depth is still rather thick. You need a thick metal layer. And also, it requires a crossover to do a coil. So it's not as low cost as, say, a UHF tag.

But it does enable a very low cost reader. You can make extremely low cost readers at this frequency. And this is used a lot in toy applications. You can buy a reader for a couple of dollars in Hong Kong that's used in the toy market. And it's also very nice for making different types of sensors because the value of inductances and capacitances at these frequency range is just right for different types of-- for integrating it into a tag and for different types of sensors.

This is some of-- another type of reader that was developed in my lab for exploring how cell phones can be used as a reader and also as a tag. So you can transfer data from one cell phone to another. You can also load up a variety of IDs onto your phone and read it. So this sort of near field applications is what's possible and convenient to do at low frequencies. And obviously, another market that's growing very fast is payment. It's growing all over the world. I don't need to really talk about that.

Moving up to higher frequencies. So UHF tags, which is obviously what's been getting the most attention for supply chain, and this is what's being used in EPC, in the EPC world, mostly. It has-- its advantages are a very low cost tag. You can now use very thin metal conductors. You can make a single layer antenna, so it brings the cost of tag way down.

It also has an increased read range. The antennas at this frequency have a larger capture-- a larger cross section, which allows you to get a longer range for your reader. But the disadvantages are that there's null spots. Because the wavelengths are on the order of a meter, you get null spots on that sort of scale.

And there are also chipless versions of this that work for EAS and I believe Professor Cole was involved in an early version of this. The cost of UHF technology in general has been plummeting, which is pretty amazing. The tags-- you can now buy tags for less than $0.20 in even low quantities, such as 1,000 tags.

The cost of readers, due to the advent of wireless technologies in commercial products and consumer electronics, the cost of CMOS radio ICs has been coming down dramatically. And you can now build a reader-- there's a reader I designed last summer with just a parts cost of $30 and it could read EPC gen 2 and gen 1 and with a read range of a couple of meters.

So moving up to microwave. So microwave, and particular 2.4 gigahertz or the ISM band, this is very attractive because it's a smaller antenna. It's a worldwide frequency. There's many other standards and wireless technologies that work there. So you have the economy of scale. So the parts and the antennas are already available and you can make RFID systems in this frequency very cheaply as well.

But disadvantages, as with UHF, is that it's easily shielded. Here's an example of a ZigBee tag that I designed. And one big advantage here is just that, obviously, this is battery powered. However, you can make a very tiny reader that's very low cost. And the advantage, for example, for a pallet tracking application is rather than having a $1,000 reader at each portal, you can now have one reader covering 10 dock doors at a fraction of the cost.

Then moving up finally to the next frequency range, you have a millimeter wave or higher microwaves. And these are very tiny dipoles, very tiny antennas. And this is mostly used today for anticounterfeiting because they can embed the materials into things like passports, or fabrics, or other printed media.

You could-- because the antennas are so small, you can make an array of the antennas and you can use-- you can make a phased array so you can steer your beam around. And here's a picture of a little reader, and you can see how tiny that antenna array is.

There's a 26-- this particular one is at 26 and 1/2 gigahertz. And what you see in the background are some of the printed dipoles. This happens to be printed on a polyester sheet, but it comes in many other forms and it's used for food packaging and other things around the world. So in anticounterfeiting in currency and so forth.

Just to tell you briefly of Leena, the next speaker, is going to give you an example of some of the work that's being done here in electromagnetics at the AutoID Lab, but I just wanted to mention the topics that we generally look at that fall under the category of electromagnetics is reader antenna design and also tag antenna design. But things like geometry, the materials interaction, and the overall propagation between the reader and the tag. So one important point I'd like to make here is that it's important to standardize all of that, not just the protocol and the reader.

I'm going to fast forward through some of this. Some of the things that we've done is we've built simulation tools. Some of you have seen this already. We've built probes that we could use to-- it's a semi active or semi passive tag that we can embed inside a pallet that takes readings of the field, it samples a field, and it talks back to the reader using the EPC protocol. So you can sprinkle some of these in with standard tags to give you more information about your reader installation.

And we've done a variety of propagation studies looking at how the different thicknesses, materials, and different properties of the material affect the read rates and the propagation. And, well, surprise, surprise, Maxwell's equations works. And so we've also looked at certain geometries for pallet stacking. How we can use printed inks and try to look at low cost implementations, how packaging can be-- the proper packaging design can be used to improve the read rates. I could tell you more detail in person if you're interested.

And finally, we've looked at how the evolution of packaging over time, how, starting with slap and ship, you can be smarter about the way you place the tags and the way you fabricate your boxes. Maybe eventually, if we get to the point where the tags are actually embedded into the cardboard boxes, we can vastly improve the read rates. And your ROI level depends on your application and depends on the particular company.

So in conclusion, as Sanjay and everybody else has said, there's a lot of work to do. But I just wanted to mention that there's much more to do than just protocol and tag IC design. And there's also-- the EPC sort of RFID is just a very small slice of the potential RFID technologies and frequencies that are available out there. So there's a lot that we can look at as well. I think I'll end there and we'll move on. Thank you.

[APPLAUSE]

STEPHEN GRAVES: Thank you, Rich.

So our next speaker-- we thought since this conference was about academic collaboration that we might share with you the results of a collaboration between Tampere University of Technology and the Rama Research Unit and the Auto-ID Labs. And Leena Ukkonen is here to share with us some specific work in the antenna-design area that she's worked on over the course of the last year between the two institutions.

LEENA UKKONEN: So good afternoon, everyone, and it's great to be here today talking about the research on antenna designs. And we have been collaborating with the MIT IDEA Lab since 2001. And our collaboration began through the Auto-ID Center Ergonomic Alliance.

And, well, the main research focus on RFID at our resource institute in Tampere University of Technology Rama Research Unit is tag antennas. And I was here two years ago as a visiting PhD student working on tag antennas for challenging objects like objects containing metals and liquids. And this collaboration has been continuing also after when I went back to Finland, and it's been very fruitful and great to work with the MIT Auto-ID Labs.

And about today's presentation-- well, since the main research focus of our lab is tag antennas, I'm talking about omnidirectional tag antenna for passive UHF RFID of paper reels. And this has been our main research topic at Rama Research Unit in 2005.

And first I'm going to tell something about the challenges in applying passive UHF RFID in paper industry because at the moment there is an urgent need in paper industry for an identification system that would carry on the identification code throughout the whole supply chain of the reel because at the moment when all the bar-code systems are used, they are placed on the surface of the reel, on the wrapping, and all the identification is removed when the wrapping is removed. And then you cannot know anymore like the origin of the reel and that kind of things, which would be important-- for example, printing companies.

So that's why in our approach we are placing a tag on the paper reel core under the wrapped paper. And that has a lot of effects on the RFID system performance and the tag-antenna performance that have to be taken into account. And, well, of course because we are operating in the industrial environment, there is all kind of background noise that has to be taken into account, and also the environment can be kind of hard-- for example, cold environments and such. And of course there are a lot of different paper qualities and cardboard, and we would like to have a tag that would function with all of those different paper qualities and also with cardboard.

But the biggest challenge so far has been developing an omnidirectional tag antenna which is indisplaceable-- for example, in lift-truck handling. Because as you can see from here, the guy who's driving this truck, he just grabs the reel, and the identification, which is carried out using a radar unit that would be integrated into this truck, it has to be automatic so the driver doesn't have to look for any direction where the tag is. It has to be able to be read omnidirectional around the reel. And, of course, in general in paper-mill environment, if you just can identify the antenna with only one reader antenna, that would be also good anyway.

Well, next there is something about this concept of omnidirectional reading and also of the structure of this paper reel. So here you can see the vertically orientated reel. And first there is a reel core which is fabricated of hard cardboard. And then the tag is placed on the core, and then the paper is wrapped around the core.

And typically these thicknesses of the paper layer that's wrapped around the core varies between 500 and 600 millimeters. And also the length of the reel can vary, or it varies from something like 300 millimeters up to 2.5 meters.

And, well, the omnidirectional reading means that the paper reel or the tag can be identified omnidirectionally 360 degrees around the reel. So you don't have to care where the tag has been placed on this core. So you can read a tag around the reel.

And, well, in this tag-creation process, there are many steps, and I'm going to briefly describe them. So first there is modeling. This picture has been taken from the simulation software that is based on finite element method. And you can see that is a very real-life structure.

So there's the reel. The tag is placed on the core, the reel core. And then the paper is wrapped around the core. So it's like a real industrial paper reel.

And here are some radiation patterns of those tag-antenna models that we've been modeling during this project. So those pictures on the left are some earlier stages of modeling. So because we try different antenna geometries and tried changing some things and some geometries on those designs affects the radiation pattern.

And the bigger one on the left is the stage we are at the moment. So you can see that the tag antenna radiates into all directions around the reel.

And, well, then there is also, of course, measurements. And these pictures here are just some basic measurement setups with network analyzer to see how adding paper on a tag affects, for example, resonance frequency.

And, well, because our goal was to develop an omnidirectional tag antenna, we developed an omnidirectional model with which we can test the omnidirectional reading of the tags because when we go to the paper mill, we want to have as good tags as possible. So we developed this model, and we could test the omnidirectional reading from all the directions. So we have 16 measurement points and four different distances. And if the tag was identified at all the directions at all those distances, it was omnidirectional also inside a real paper reel.

And here is the omnidirectional tag antenna, which we call the C tag, because when it's wrapped around this core, it formed a shape of C. And here you can see the antenna design flat. And, well, here it is in the paper-mill environment mounted on the core before the paper is wrapped around it.

And we did a lot of practical testing with this antenna design, and here you can see our measurement equipment. And we used Alien Technologies European reader unit, Alien Technology straps as a microchip. And the reader was based on new ETSI regulations, and it had two-watt ERP transmitting power.

And here are some pictures from the measurements. So this is basically how the read ranges were measured in a paper mill, and we could move the reader units and the reader antenna and roll the reel on the floor so that we could measure the omnidirectional reading.

And here is some more pictures, and here you can see how the tag is placed on the core. And we didn't actually kill any tags on this process, so that was kind of good news that it went through the process.

And, well, now I'm moving on to the measurement results. So we measured in the paper mill coated printing paper with reel diameters varying from 1,200 to 1,300 millimeters. And here is the data of the read ranges that were achieved around the reel. So here you can see that it's read omnidirectionally. And the read ranges have some variation around the reel, which was also expected from the simulation results.

And, well, I'm going to briefly tell something about identification of cardboard reels. And, well, they said that it's been impossible with conventional tags. So we tested our tag also for cardboard identification. And there is some more challenges with these cardboard reels, which are larger diameter and also the more layered and inhomogeneous structure of the cardboard, which increases the boundary-length effect.

So we did some practical testing, and the tag antenna was the same that we used with the paper reel. So it was not yet optimized for the cardboard.

So the goal of the first testing was to identify the tag through the cardboard reel, which we did, as you can see here. And also, yeah, kind of the most surprising and good result was that we could identify the reel 180 degrees around it. So we achieved better results. That was like the goal of these first testing.

Well, there is still a lot of work to do on this. But to our best knowledge, this is the first omnidirectional tag antenna for passive UHF RFID paper reels that can be read omnidirectionally with standardized RFID equipment. And it has been tested with copy paper and coated printing paper, and also the cardboard has been tested with 180 degree identification around the reel.

So in the future, we will develop an omnidirectional tag antenna also for cardboard reels. And we will test and develop the antenna also for American and Asian UHF RFID bands so that we could achieve a global tag that could be used around the world.

And also longer read ranges will be achieved. So we've talked about this with industry people, and they say that a minimum of 0.5 meters from the paper surface would be required. And also the tag has to be evaluated in harsh environments-- for example, in cold temperatures.

And, well, there is some other research project also in 2006. So we'll continue also developing the tag antenna for metallic- and liquid-containing objects. So basically we will continue on the miniaturization of the [INAUDIBLE] badge-type tag.

So thank you for your attention. Thank you.

[APPLAUSE]

STEPHEN GRAVES: Thank you, Leena. And our final speaker on this panel is Dr. Alan Levesque. He's a colleague of Dr. Kaveh Pahlavan at the Center for Wireless Information Network Studies. Kaveh was, I think, a chair and an IEEE Wi-Fi committee at one point or something, but--

ALAN LEVESQUE: Yes. Actually Kaveh's been involved in wireless issues since the early days of wireless LANs. Those of you that know the business at all in the greater Boston area know that about 15 years ago-- I like that slide. Someone said hope to hype to implementation. I like that.

About 15 years ago was the hype phase of wireless LANs, and a lot of that activity was a number of startup companies actually in Massachusetts. And my colleague, Kaveh Pahlavan, was actually involved with several of those startups. So that's a good--

STEPHEN GRAVES: But in any case, they're doing some very interesting work in location-based tracking that we thought would complement this session nicely.

ALAN LEVESQUE: Exactly. Thank you, Steve. Steve's provided-- I should do that, yes.

Thank you, Steve. Steve has provided a nice introduction for me. How do we move to the next presentation? Good. Thank you. Very good. I'm painfully aware that I'm the one who's keeping us all from lunch now, so I'm going to do some real-time editing as I go along here.

Kaveh, in fact, intended to be here, but he has a commitment in Japan. So based on the weather report that Steve gave this morning about Japan, he may have swapped a snowstorm in Cambridge for a snowstorm in Japan. I'm not sure.

As Steve said, our emphasis in the last few years in the wireless center at WPI has been on location sensing. We also use the term localization. And because of some of the previous presentations and obviously the background of knowledge that many of you will have, I'll be able to skip over some of this.

We have actually been focused in recent years primarily on public safety and military applications, partly sponsored by DARPA, by NSF, and with some membership subscription-type sponsorship from member companies in the center.

I'll leave this up long enough to point out that several people made mention of the history of this technology going back 50 years to World War II, and everyone has a little bit different take on it. My take is the fact that that era introduced the use of what are called technically net broadcast radios, push-to-talk radios. The devices were so-called walkie talkies about the weight of a brick and about the volume of two or three bricks. And that was the beginning of really radio networking.

And that certainly provided efficient communications for soldiers in the field, but immediately it was recognized that that did not give you information about where the soldier was. Push-to-talk radio, the speaker gets on the net by pressing the button, and everyone else is in listen mode and hears the speaker, but we don't know where he is. All we know is that we hear his voice signal.

And those radios, just to set a historical background, used analog voice over analog frequency modulation. And those of you that work in the communications field know that analog FM has a threshold characteristic. The received voice is either very good or it's very bad. And it has a threshold characteristic, and you don't know really anything about what the received signal strength is or the received signal-to-noise ratio is. So in these 50 years, we've come a long way from that primitive technology.

I'm not going to go through all of this, but I want to-- halfway down, I want to mention the era of 1997 when the interest began in urban and indoor geolocation. DARPA had a program that was called Small Unit Operations Situational Awareness Systems. And situational awareness basically says how do you find the warfighter that is in a hostile physical situation? How do you locate him and communicate with him?

We had a piece of the research work in that project addressing specifically the radio-propagation problems in the indoor environment. And the reason I mention it is because the objectives-- the government's-- the customer's objectives for that project simply were not met. And the fundamental reason was the complexities of radio-wave propagation in the indoor environment, and that's what killed it. You could wrap all of the software that you wished around that and all the user interfaces that were all very nice, but because of the characteristics of indoor radio propagation, you could not get a precise fix on the location of a warfighter in many of those hostile-- urban fighting is the obvious scenario.

About that time there began to be some commercial developments. Pinpoint evolved into another company name. I don't quite recall. Pinpoint/Wearnet came out of the body LAN technology which was also sponsored by DoD, the concept to embed sensors and communication devices into the uniforms of service people and be able to use those as part of accomplishing the mission. We'll just skip over the rest.

Talk a little bit-- won't say very much about this because so much, obviously, has been said, and you folks are all well aware of concepts of asset tracking. Putting tracking golf balls in there, that was my idea. I figured I could save myself some money if I could find all those golf balls that I'm losing in the woods all the time. Actually someone does make a golf ball with a little radio transmitter in it, and I'm going to try it one of these-- but it doesn't have ID characteristics. So there's another research area.

OK, try to move on. Again, I think I'm preaching to the choir here, use an old slide, but everything is a terminal today. From communications networking point of view, we don't necessarily care too much about what the device does. Either it's a terminal out at the edge of the network or it's an intermediate node somewhere within the network, and perhaps it serves both functions in some situations.

This great variety of applications that keeps growing, of course, has fostered support for standardization, and other folks earlier have talked at some length about standards and the importance of standards for making an industry segment grow. And this is just our own way of characterizing some of these standards, both ultra wideband and lower-frequency technologies are being looked at for Wireless Personal Area, WPAN, one of our areas of interest, WPANs, Wireless Personal Area Networks.

And, of course, the IEEE 802.11 initiative really created the renaissance for the wireless LAN industry. Obviously value in standardization and the ubiquitous use of 802.11 devices, so-called Wi-Fi-- of course, that's just a label for a certification process. But 802, the promulgation of those devices and the economies of scale that have pushed the prices down, of course, to make that an important element to be looked at in location estimation.

Here again this kind of figure lots of folks use, and it just characterizes the different technologies, cellular technologies, wireless LAN and wireless PANs, against the dimensions of scale that are relevant to those technologies. Let me get to the areas of interest that have been motivating some of our work.

Navigation for fireman-- a professor early in the morning had a very good example, I thought, about a hypothetical case of a fire in the building. We all have tags, and he spoke about the issue. Well, suppose there's a miscount.

About seven years ago in the city of Worcester in central Massachusetts there was a very bad and deadly fire in which an unused building caught fire. And when the fire company arrived on scene, a local businessman came out and said that he saw two people running into the building.

And long story short, the fire captain on the scene sent close to 20 of his firefighters into the building, and six of them got completely lost because of the smoke in the building and the structure of the building-- several floors, a number of small rooms in the building. And six of them got lost, and they died in that fire. It was a very tragic event.

And after that was all over, it was discovered that the information was incorrect and there was no one in the building. And so six firefighters lost their lives putting out the fire in an empty building.

We at WPI actually have now a funded project from the US government through Senator Kennedy's office, and we are looking at the use of wireless technology to try to deal with the problem of tracking firefighters in such dangerous situations. One could also call to mind the recent tragedy at the Sago Mines in West Virginia, and there is already public discussion of how various technologies, including wireless technology, might have been used to say let's move on.

This is the kind of concept that the warfighters or the firefighters would like to have. They would like to have a display-- we call it a tactical display that would present some kind of representation of a building, for example, and be able to locate firefighters or warfighters within that building.

This refers to small unit. I spoke about that, the situational awareness that DARPA was interested in.

This I think is important. The current DoD interest is in using signals of opportunity to be able to accomplish-- to take advantage of whatever is out there in the ether, whatever frequency bands are available. And so that is a current area of interest for us as well.

Other interesting research problems, location-based handoff, location-based routing, and ad hoc networks. And, of course, on that earlier list there is at least one company-- Newberry, I believe-- that is in the business of location-based authentication and security technology. There's been a lot of discussion about security issues earlier.

So I'll finish up by talking about the two categories of approaches for doing location estimation, and one is received signal strength, of course, which is used in cellular networks. The second-generation CDMA networks, for example, already use received signal strength estimation.

Advantage-- the hardware is simple, and that approach is not particularly sensitive. I should say the accuracy is not sensitive to the multipath and/or bandwidth. It does not require synchronization because it's incoherent. It's incoherent signal processing.

However, it, in most cases, will not provide the accuracy that's required, for example, for some of these public-safety applications. Suppose, for example, you could achieve a location accuracy of one foot, and you're trying to locate a firefighter inside a smoke-filled building. Well, you may have spotted his location to within one foot, but you don't know if he's on this side of the wall or this side of the wall. So if your algorithm says he's over here and he's really over here and you have some kind of a system that supports this to try to help him find his way out of the building, he's in the wrong room. So one foot of accuracy may seem very precise, but in that kind of an application, it's not precise enough. Just an example.

To achieve greater accuracy, you can resort to time-of-arrival techniques. And fundamental time-of-arrival techniques are not particularly new, but making them work in a multipath environment is a very difficult problem. An advantage is that if you can do it, you can accomplish rather accurate positioning with only a few reference points, and it also doesn't need training.

The problem is that while it doesn't need training, what it does need is synchronous operation. So in communications terms, you have to build a coherent signal processing system. That adds to complexity. And you also need a synchronization process to do that.

Let's move along. Just say briefly two general classes of time-of-arrival algorithms. One is distance-based localization with a few reference points. And the other, perhaps a more general way of thinking about it, is a pattern-recognition approach where you deploy many reference points on a regular grid, and then you can use a variety of pattern-recognition techniques to be able to get an accurate estimate.

Getting to the end here-- a good technique in the pattern-recognition branch-- let me call it that-- is the nearest-neighbor algorithm. And I should mention Ekahau that is in the RF tag-- ID tag business. And they also have a very now highly developed software product which the Ekahau positioning algorithm, and that's very recent. And so that represents the state of the art with that approach.

Our work in the center has been focused on developing an extensive laboratory test bed with instrumentation-- measurement instrumentation, channel simulation, instrumentation, and focusing on the evaluation. This gives us the capability to evaluate a variety of localisation algorithms under a wide range of realistic propagation in environments.

I'll just move ahead. Coverage, of course, and range reading is a topic that's been discussed by a few speakers already.

Bandwidth-- it's a common belief that increasing the bandwidth steadily increases the resolution, and therefore ultra wideband is the right solution. The problem is if you go up in bandwidth, you reduce the coverage. So there's a trade-off issue there, and we don't see ultra wideband as the optimal solution.

The last topic is very important one. UDP refers to Undirected Direct Path. It sounds like an oxymoron, but you visualize a transmitter, a receiver. You're inside a building. And in many instances, the line of sight path from the transmitter to the receiver is not detectable, and all of your energy is coming from the multipath components.

And what we're finding at this point that is very often the Achilles heel for time of arrival based positioning estimation system. And that, in fact, was the central problem that caused the failure to meet the objectives in the [INAUDIBLE] program several years back.

So we continue to focus our research now on algorithms that will allow us to operate in a condition of undetected direct path, and that very often means making use most of the time of the multipath components. And we're looking at techniques like tracking, which works fine if the transmitter is mobile. However, that doesn't work if the transmitter is not mobile. If it's mobile, you can do tracking, and you can work with the multipath components and the direct path, which will occasionally appear in a time record of measurements. We're also looking at use of diversity techniques. And some of that is being done in cooperation with Draper Lab.

And I realize we're running out of time. So just beating the drum and saying that localization is still an important research area, and we regard it as an unsolved problem. Thank you very much.

[APPLAUSE]