

# ***Radio Frequency Identification: Where We've Been & Where We're Going***

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# *Overview*

Five years ago I reviewed the state of the art in Radio Frequency Identification (RFID) for the joint Berkeley Wireless Research Center – WINLAB PicoRadio Networks conference.

Since then, the RFID landscape has changed, although in many ways less than we had expected. (We were too optimistic!) But there has been one very significant change: a proposed global standard for low cost RFID systems.

This talk brings the earlier overview of RFID up to date, with particular emphasis on the challenges to realizing the promise of RFID.

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## ***Overview, continued***

For those interested in the original talk, it is available on the Antiope Associates website,

`http://antiope.com/publications`

along with a review of the development of NCR's electronic price label, one of the most successful RFID-like products.

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# *Outline*

- What is RFID?
- The technology of RFID
  - Mainstream technologies
  - Exotic technologies
- The business of RFID
  - Changes over the last ten years
- The big challenges
- Conclusions

# *What is RFID?*

- Radio Frequency Identification (RFID) uses radio tags to automate logistical operations by providing a machine readable (and maybe writable) label for objects.
- It can be used as an *enhancement* of existing methods (e.g., printed bar codes).
- It can supply some *new* capabilities that printed labels lack, such as location finding, tracking and integrated sensing.

# ***What's so good about RFID?***

- Long range
- Non-line-of-sight
- Many tags can be read out at once
- More robust than printed label
- Can add additional capabilities (e.g., tracking or sensing) by upgrading tags and readers
- Cheap

# ***What's so good about RFID really?***

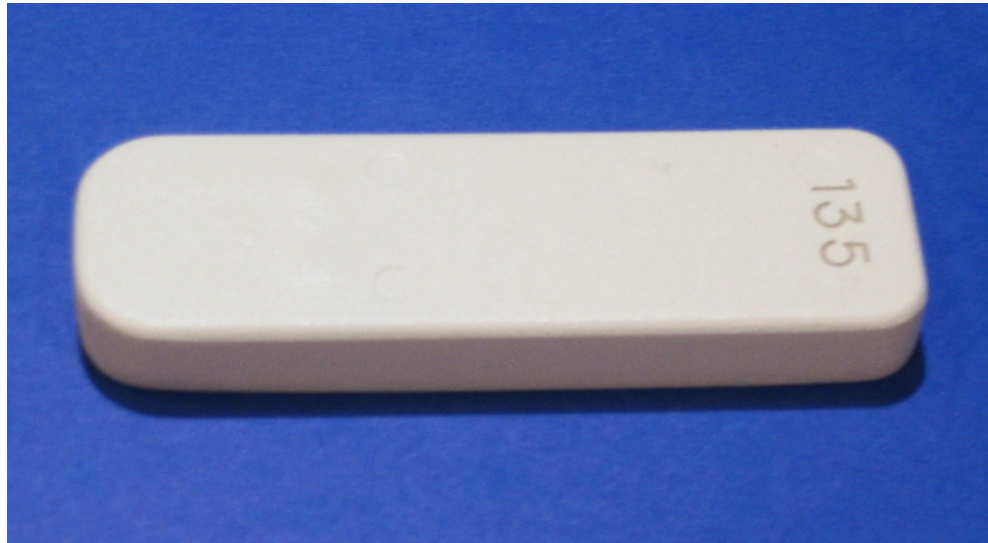
RFID is really the vision of retrieving information from tagged objects *rapidly, reliably* and at *considerable distance*.

Along with this is the assumption that the tags are *unobtrusive* (usually this means that the tags are much smaller than the tagged object).

Finally, we usually mean that the technology is cheap enough to be *ubiquitous*.

Sometimes I will refer to this as the “magic” of RFID.

## *An example*



Pictured is an RFID tag in the IATA cargo tag size. It can store several thousand bytes of data, and be read out at  $50 \text{ kbit s}^{-1}$ . The tag is about 8 cm long.

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## *An example, II*

How does does our example stack up against the “magic” requirements?

- Rapid – yes, can dump its contents at  $50 \text{ kbit s}^{-1}$ .
- Reliable – meets the requirement of fewer than  $10^{-4}$  missed reads and fewer than  $10^{-6}$  erroneous reads at a 5 meter range while traveling  $10 \text{ m s}^{-1}$ .
- Unobtrusive – built into the rail of an airline unit load device.
- Not really cheap – but not unreasonable given the application.

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## ***An example, III***

So our example does pretty well with respect to the “magic” criteria. (And the potential customers who looked at it liked it too.)

Why wasn't it a great success? See part III of this talk.

## *Where were we?*

When I first reviewed RFID in 2000, the main feature of the RFID landscape included:

- Failure of Micron Communications' attempt to build a 2.5 GHz radio using a standard CMOS process.
- IBM's abandonment of its 2.5 GHz bar code replacement tag.
- Modest success of automobile toll tags based on 900 MHz pager technology.
- Modest success of NCR's 2.5 GHz electronic price label system.

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## *Where were we?*

Five years ago there had been some successes and some failures, but the general mood was still one of cautious optimism.

My conclusion back then:

If we can build a radio tag that encodes 40 to 100 bits, can be read at a range of 1 meter and sells for less than a dime, we'll be driving fancy cars & smoking expensive cigars.

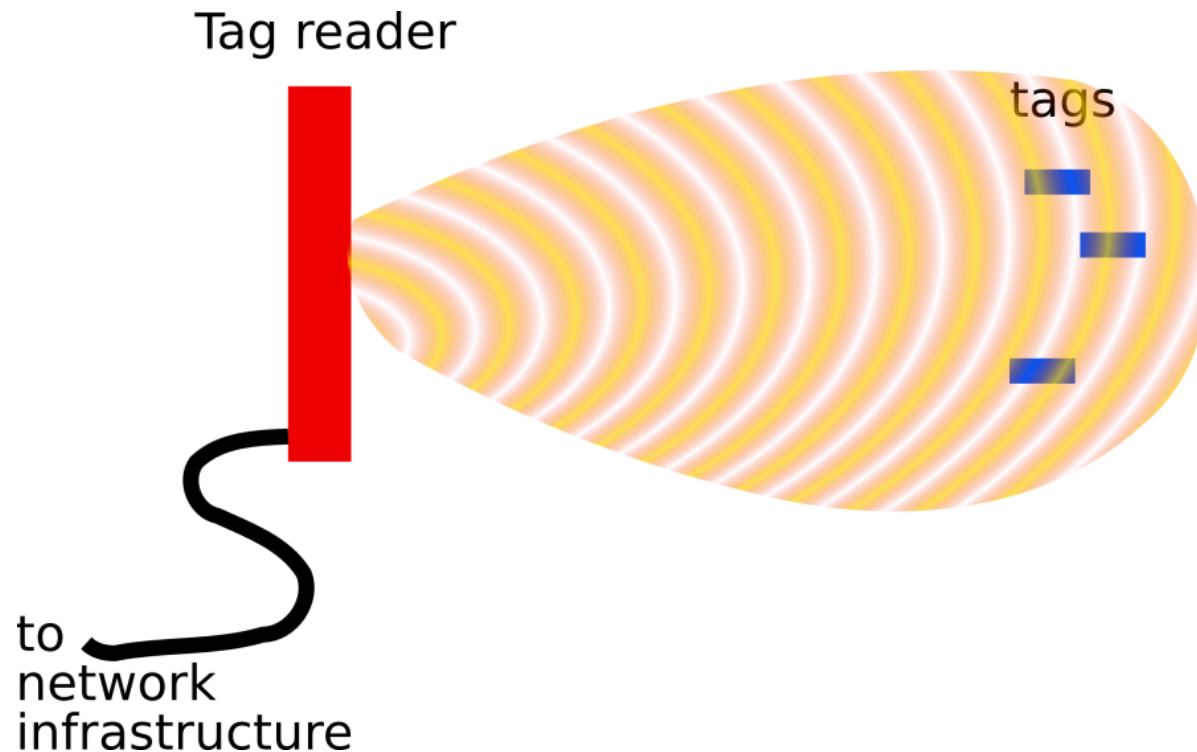
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# The Technology of RFID

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# *An RFID system*

The components of an RFID system are tags, readers and an information infrastructure:



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# ***A classification of RFID technologies***

A useful classification of RFID tags:

- Passive (no “electronics”).
- Semi-active (powered from the incident RF, communicating via modulated backscatter).
- Active (containing a battery or other internal power source; may use modulated backscatter or an RF transmitter).

# *Mainstream technologies*

- By volume, most RFID tags today are in the “semi-active” category:
  - Conventional Si integrated circuit;
  - Powered by rectified RF;
  - The EPCglobal standard specifies a semi-active tag operating at 900 MHz.
- Active tags have had the most market success:
  - Toll tags using 900 MHz pager technology (active Tx);
  - Electronic price labels (modulated backscatter);
  - Bluetooth transceivers (active Tx).

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# *Frequencies, I*

Almost every RFID system works in one of the frequency bands designated by the FCC as an Industry, Science and Medicine (ISM) band. That means that communication uses are secondary to other uses. For example, the 2.5 GHz ISM band is shared with microwave ovens.

The ISM bands used for RFID are:

- 125 kHz;
- 13 MHz;
- 900 MHz;
- 2.5 GHz.

## ***Frequencies, II***

The low frequency bands (125 kHz, 13 MHz) are attractive because the tags are usually in the near field (no need to worry about radio propagation effects).

The higher frequency bands (900 MHz and 2.5 GHz) allow the use of directional antennas and hand-held readers. In particular, 900 MHz is a good compromise between the size of the tag antenna and the size of the reader antenna.

But 900 MHz spectrum isn't available everywhere. 2.5 GHz is available almost worldwide.

## ***Active tags, I***

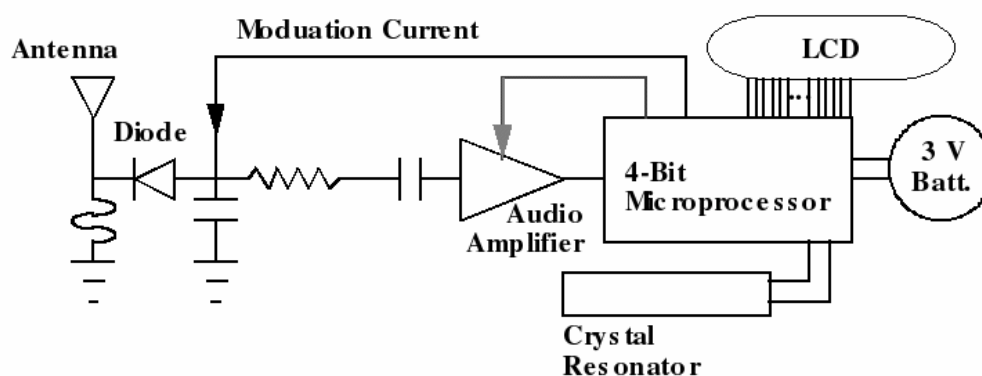
The receivers in active tags are usually just crystal radios.

To get decent range (10 to 30 meters, maybe a bit more) you need a low noise amplifier to boost the signal to levels that can be accepted by logic circuits.

Battery life is often not a problem. The NCR Electronic price label has a typical life of 7 years using only a  $\sim 500$  mAhr battery. (Average current draw of  $\sim 3 \mu\text{A}$ .)

## Active tags, II

An example of what's inside (a block-level diagram of the NCR electronic price label):



The tag communicates with a reader using modulated backscatter.

Total RF subsystem cost: under \$1

Total tag cost  $\sim$  \$3 (depends on the size of the LCD).

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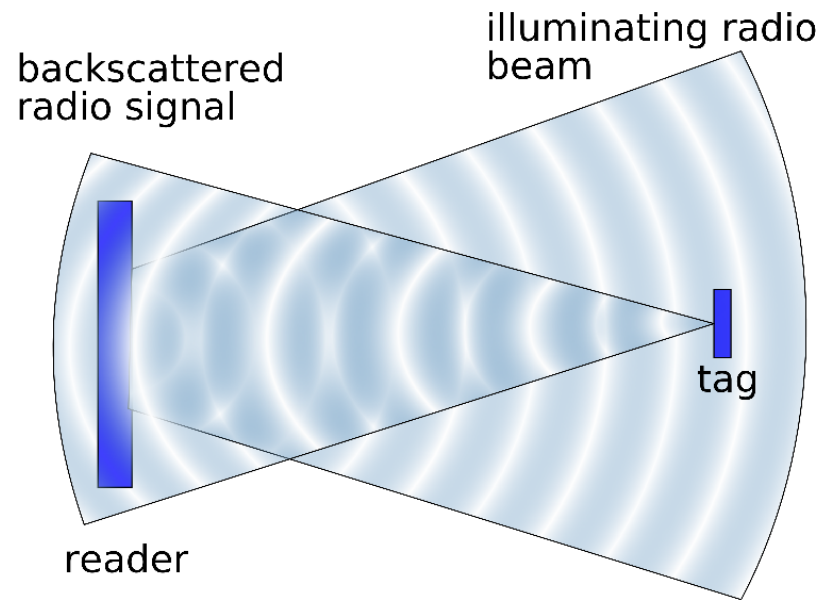
## ***Semi-active tags***

These are almost the same as active tags that use modulated backscatter, but they extract their power from the RF field instead of using a battery.

The need to get power from the RF significantly reduces the range of the tag, but also makes it a good deal cheaper.

Without a battery the tag can usually be safely discarded without special precautions.

# *Modulated backscatter, I*

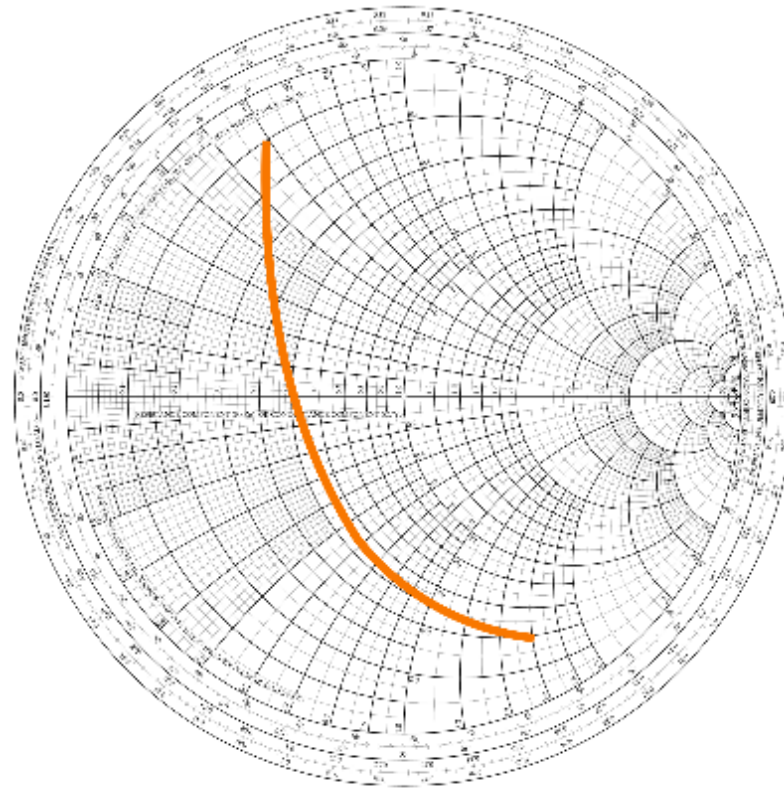


Modulated backscatter saves us the expense and power consumption of a transmitter on the tag. The incident RF is reflected by the tag antenna, which is terminated in a time varying impedance. As the impedance varies, the phase and amplitude of the reflected signal changes.

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# ***Modulated backscatter, II***

The efficiency of modulated backscatter depends on how far across the Smith chart the effective terminating impedance can go.



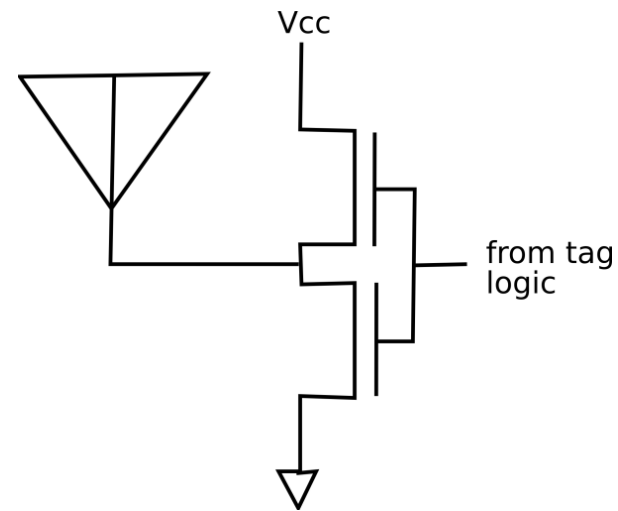
impedance variation with detector diode bias current change

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## *Modulated backscatter, III*

With care, you can design a modulator circuit integrated with the receiver diode that gets 70% or more of the optimum modulation.

But even a a dead simple circuit can provide reasonable (30% of optimal) modulation:



(US patent 6,243,012). And this circuit costs nothing.

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## ***Modulated backscatter, IV***

Homodyne detection works wonderfully for receiving modulated backscatter signals. Homodyne mixing cancels most of the phase noise of the LO, so the modulated scatter need only be shifted by about a kHz.

See Skolnik (ed.), The Radar Handbook (chapter on FM-CW radar) for a good explanation of how this works.

One thing that was unexpected: there are a lot of modulated scatterers around, especially indoors. Fluorescent light ballast circuit are surprisingly good modulators at 2.5 GHz.

# ***Power from the RF field***

Extracting power from the RF field is a simple extension of the basic crystal radio.

The problem is to get enough voltage to turn on a diode (often a Si Schottky diode with about 0.2 V forward drop).

CMOS logic in fine geometry process has no problem running at 150 mV, and the tag logic usually draws very little current.

Typically, we are limited by the need to generate enough voltage to overcome a diode drop, rather than the power we can absorb from the RF field.

## ***Multiple access methods***

To read out many tags at once, we need a multiple access scheme. Tags almost always use a time division scheme, repeating their messages with random, tag dependent delays.

More sophisticated tags, like the cargo tag used as an example, synchronize to a frame signal sent by the reader. (In the cargo tag case, the frame signal was a short interruption of the RF illumination.)

Since modulated backscatter precludes power control, CDMA type multiplexing is hard.

# ***Exotic technologies***

Some of these ideas are based on common anti-theft tags:

- Diode-based harmonic generator (Checkpoint Systems).
- Magnetic-acoustic resonance in a magnetostrictive material (Sensormatic, now Tyco).

These have proven effective at encoding a single bit, but have resisted cost-effective extension to tens of bits.

One of the most interesting attempts at a purely passive tag came from Xcyte, which made a  $\text{LiNbO}_3$  surface acoustic wave device that allowed a completely passive modulated backscatter system. The cost of the  $\text{LiNbO}_3$  made the tag expensive, though.

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# ***Multiple access?***

Exotic technologies usually have no multiple access scheme.

You just have to tailor the system so that tags appear in the field of the reader one at a time.

# The Business of RFID

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# ***EPCglobal***

The biggest change in RFID in the last decade is the adoption of a proposed global standard.

The organization behind this is called EPCglobal for “Electronic Product Code”. It is modelled on the Universal Product Code (UPC) effort that gave use bar coded products in supermarkets.

## ***EPCglobal, II***

- RF powered tags at 900 MHz (longer range operation than at 2.5 GHz — up to 3 meters).
- Backed mostly by systems integrators and middleware vendors.
- Only a couple of tag producers.
- Driven strongly by the largest retailer: Wal-Mart.

# ***EPCglobal, III***

Still some problems:

- The middleware vendors complain that the tags good read rate is too low. The tag vendors are claiming read rates in the high 90s, but middleware vendors say that they're only seeing 80 to 90% good reads.
- There are a lot of patent claims on pieces of this technology, and one tag vendor (Intermec) is suing the other tag vendor (Matrics, now Symbol).

The low read rate might be a real killer. It violates the implied promise that RFID is “magic”. Magic has to work more than 85% of the time.

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## ***EPCglobal, IV***

It's not hard to understand what the problem is:

- A simple antenna at 900 MHz is sensitive to the RF characteristics of whatever is within  $\sim 20$  cm.
- Can't afford a patch antenna (which would provide some isolation from the immediate environment).
- So anything you attach the tag to becomes part of the antenna matching circuit, only often it doesn't match.

Our 2.5 GHz cargo tag used an expensive high dielectric constant substrate just for this reason.

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# *The numbers you need to know, I*

Potential markets:

- Aircraft cargo containers (unit load devices)  $5 \times 10^5$  of all types;
- Railcars  $5 \times 10^5$  in service in the US;
- Ship cargo containers  $\sim 2 \times 10^6$  twenty foot equivalents (TEUs) in service worldwide;
- Truck trailers  $2.2 \times 10^6$  in service in the US.

If you think carefully about the markets represented by these numbers, they're not that big.

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# *The numbers you need to know, II*

Perhaps more promising markets:

- airline luggage tags: 1 to  $2 \times 10^9$  per year;
- express parcel tags: 2 to  $5 \times 10^9$  per year;
- RF postage stamp: around  $10^{10}$  per year;
- RF bar code: around  $10^{11}$  per year.

The key to addressing any of these markets is a product that is dirt cheap.

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## *The numbers you need to know, III*

Maybe the military will pay a premium for a very capable system. But the quantities that the military purchase are usually far too low to reap the benefits of real high-volume production:

- A typical “smart bomb”, e.g., the Sensor Fused Munition or the Wind Corrected Munitions Dispenser, is purchased a few thousand at a time, with total product runs of a few  $\times 10^4$ .

Military markets for disposable sensors based on RFID may not be much bigger than this.

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# *The numbers you need to know, IV*

Other important numbers:

- Standard digital CMOS silicon processing: \$2 to \$10  $\text{cm}^{-2}$ ;
- Cost of attaching a single bond wire:  $\sim$  \$ 0.01;
- Cost of a drop of epoxy resin to encapsulate a small IC:  $\sim$  \$ 0.01;
- Cost of FR-4 circuit board material:  $\sim$  \$ 0.02 to \$ 0.04  $\text{cm}^{-2}$ .

# *Numbers you need to know, V*

Not to mention...

- Time to test (and perhaps serialize) an RFID chip:  
~ 1 to 5 seconds;
- Cost of an IC tester: ~ \$  $10^6$ ;
- Number of seconds in a year:  $3.15 \times 10^7$ .

For comparison,

- Cost of consumables to print a airline luggage tag:  
~ \$ 0.15.

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# ***Bad ideas***

One especially bad idea (that gets repeated over and over) is to try to sell an RFID system that costs too much on the basis of the new “features” that it will allow. (A typical suggestion is to make the data in the tag writable.)

This ploy killed the early Philips, Hughes and Daimler-Chrysler Aerospace airline bag tags. There was no solid cost justification for the new features (and in some cases the proposed “features” were a step backward from bar codes).

Never forget that for high volume applications, the competition is a technology that has been refined for half a millennium: printing.

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## ***Our example, revisited***

As I mentioned earlier, our cargo container product meet the customer's specifications and could be built at a reasonable cost. Why didn't it succeed as a product?

- The market wasn't big enough. If we were to capture 100% of the market the total revenue would only be about \$7 – \$10 million a year. That will support a company of about 30 to 40 people.
- The prospect of a couple of years of little revenue as the product worked its way into the customer's systems. Even if we could get \$10 million a year revenue someday, in the short run we still had to eat.

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# The Big Challenges

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## ***Remember the magic of RFID?***

The one *big* challenge is living up to customer expectations for RFID.

Over the years, many wonderful things have been promised from RFID, but only now are there one or two systems that live up to the hype.

(For instance, you can finally use a toll tag while driving at speed on the New Jersey turnpike.)

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# ***Can ultrawideband help?***

Most ultrawideband (UWB) proposals are pure snake oil.

However, if we could get regulatory changes to allow much higher *peak* power we might be able to power RF tags at longer range. (Remember, the a tag powered from the RF field is usually limited by generating a high enough voltage to turn on its circuits, not by the total power it could extract from the RF.)

- Requires looking more carefully at circuits that start up quickly, especially if we want to use integrated capacitors.

# ***Polymer electronics?***

Polymer electronics seem ideal for RFID (they're going to cost next to nothing, right?)

At the moment, even state of the art polymer transistors don't have enough performance to build radios

- Require  $\sim 10$  volts to operate;
- $f_T \sim 10^6$  Hz (that's Hz, not kHz or MHz!).

## ***Innovative assembly techniques?***

Since assembly costs are such a significant factor in the total RFID product cost, are there cheaper ways to put them together?

Alien Technologies ([www.alientechnology.com](http://www.alientechnology.com)) originally claimed to have a “fluidic self-assembly” process, but it’s not clear that they actually use it in their products.

Hard to tell what opportunities are here. But new assembly techniques could be very lucrative, if applied to the larger field of low cost electronic assembly.

## ***Cheap passive tags?***

Is there a way to build a passive (or nearly passive) tag that is easy to encode and is incredibly cheap?

People have tried but the results have been disappointing. (For example, ink loaded with semiconductor dust has been tried. When illuminated by a strong RF field, harmonics are generated by rectified currents flowing in the ink. But it needed kilowatts of RF power to work at distances of 1 meter and could only encode a few bits.)

Is there a good idea just waiting to be found?

# Conclusions

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## ***Where are we now?***

The big change is the EPCglobal standard. It is important to realize that this is a huge gamble for RFID.

- If it succeeds, it will open up many new fields of application.
- However, up to now the system performance falls well short of a “magic” RFID system and may disappoint customers.
- If it fails, it may poison the well for years.

## ***Where are we now?***

There may be an opportunity to build a more capable RFID system as a building block for many applications.

- Some companies are repackaging Bluetooth radios for this purpose, but this might be too expensive.
- Ballpark specs:
  - 100 kB data capacity;
  - Read at 20 meters;
  - 10 kb s<sup>-1</sup> read rate;
  - Tag cost less than \$5, including battery.

## ***Where are we now?***

Alas, we're not all that far from where we were in 2000.

The EPCglobal effort has produced an expectation that RFID will have a range a bit more than a meter, so the new conclusion is

If we can build a radio tag that encodes 40 to 100 bits, can be read at a range of 2 meters and sells for less than a dime, we'll be driving fancy cars & smoking expensive cigars.

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