Wireless Forever
the Future of RF Systems
that Never Plug-in

Prof. Gregory D. Durgin, Georgia Tech School of ECE
Distinguished Lecture of IEEE CRFID
IEEE CRFID

- Council within the IEEE
- Conference Series
  - IEEE RFID (April 2019 in Phoenix, US)
    http://2018.ieee-rfid.org
  - IEEE RFID-TA (Sep 2018 in Macau SER, China)
    http://2018.ieee-rfid-ta.org
- Educational outreach, distinguished lectures
- IEEE Virtual Journal on RFID
- IEEE Journal on RFID launched in 2017
- 21 member IEEE societies
Personal History

- Ph.D. at the end of 2000 from Virginia Tech (Mobile & Portable Radio Research Group)
- American researcher visiting Morinaga Laboratory (Osaka University) for 1 year
- Professor in GT School of ECE (2003-present), research program at [http://www.propagation.gatech.edu](http://www.propagation.gatech.edu)
  - Backscatter Radio
  - Wireless Channel Modeling
  - Wireless Power Transfer
  - Radiolocation
- Faculty Director of Opportunity Research Scholars (ORS) Program
- YouTube™ Channel: profdurgin
Big Questions to be Answered

*Information*: What is the Minimum Power Required for Wireless Data Exchange?

*Energy Harvesting*: How much RF power can be converted to usable electronic functions?

*Computation*: What is the minimal amount of power required to perform computation?
MINIMUM-POWER RF ENERGY HARVESTING
Trends in Electronics: UHF RFID

This trend is driving the current buzz around the Internet of Things (IoT) and related technologies.

This energy efficiency doubles every 46 months.

The 100m tag will likely occur around 2020. Or will it?

How to Rectify RF Power

Lots of different circuits, but they all have the same limitation … diodes.

Diodes must turn-on before rectification, so they have a power “overhead”

Curvature of a Schottky Diode:

Survey of RF Harvesting Efficiencies

Example RF Thermoelectric Generator

- Convert RF-heat-DC
- Converts more efficiently than diodes at low power
- Outputs much higher DC voltage than input RF

Thermal-to-DC Conversion Efficiency

\[
\eta_c = \frac{2P_C R_{DC}}{P_R (n R_S + 2R_{DC})} \left( \sqrt{1 + \frac{P_R}{P_C}} - 1 \right)^2
\]
All on the Same Graph

An Illustration of the Gap Between Theoretical Energy Harvesting Limits and Current Achievable Efficiency

- Thermodynamic Limit of a 30 MHz Bandwidth Continuous Wave RF-thermal-DC Converter @ 300 K
- Hypothetical RF Thermoelectric Generator from Durgin
- State-of-the-Art Conversion Efficiencies @ 915 MHz from Valenta
Play a Game: What to Passivize
Key Points

- Conventional chip-making has stalled RF energy harvesting
- There is still a lot of room for improvement
- Unconventional approaches are promising (tunnel diodes, MIM diodes, spin diodes, RFTGs, etc.)
- Intermediate forms of energy-conversion (thermal, acoustic, mechanical, light, etc.) can outperform Schottky diodes at low power levels
- Lots of cool applications
MINIMUM-POWER WIRELESS DATA EXCHANGE
How UHF RFID Systems Work

- Harvest an incident RF Wave
- Very low power consumption
- Power and communications channel both present

1. Generate
2. Radiate
3. Propagate
4. Harvest
5. Sense
6. Scatter
7. Receive
8. Locate

RF Reader

RF Tag
Quantum Tunneling Tag (QTT)

Use RF negative-resistance devices (like tunnel diodes) as reflection amps.

Bank energy and bias the circuitry so conservation of energy still holds.

Eliminates the need for RF signal-generator circuitry, which dominates power consumption at low transmit power levels.
Demonstration of Actual Data

- 5.8 GHz carrier
- Low-powered transmitter (-20 dBm)
- TR separation distance of 7 m
- Transmit and Receive antenna gains of 6 dBi
- 250 kbits/sec transition
- About 35 dB of reflection amplifier gain
Scattering on top of Information

- **Ambient Communications:** Like backscatter radio, except
  - Not scattering *back* to source, but to another location
  - Requires detection in the presence of massive jamming

- Remote telemetry for all sorts of sensor applications
Key Issue

- Enormous potential self-jamming
- Inability to cancel self-jamming severely limits range; need hardware pre-filtering before demod
- Key insight: use design of modulation, recording, channel, line, etc. codes
Uncoded BPSK Spectral Sketch

BPSK

1

0

Pulse Fourier Transform

real

-3R_b -2R_b -R_b 0 R_b 2R_b 3R_b

Power (log-scale)

Orange Noise

BPSK Spectrum

frequency (log-scale)
Manchester/FM0 Spectrum

Manchester Coding

1

0

Pulse Fourier Transform

-6R_b  -4R_b  -2R_b

2R_b  4R_b  6R_b

Power (log-scale)

Orange Noise

Manchester Spectrum

f_b

frequency (log-scale)
**Pulse Shaping with Transitions**

- Possible to design extremely deep nulls
- Each transition is a degree of freedom that can be used to deepen the null (remove $O(f^n)$ content)
- Set of $n$-transitions that maximizes DC nulls results in a “perfect” pulse

\[
\begin{align*}
1 & \quad P5 \\
0 & \\
\end{align*}
\]

\[
\left\{-\frac{1}{2}, -\frac{\sqrt{3}}{4}, -\frac{1}{4}, 0, \frac{1}{4}, \frac{\sqrt{3}}{4}, \frac{1}{2}\right\}
\]

\[\text{frequency } f/R_s\]
Pulse Shaping with Transitions

\[
\left\{ \frac{-1}{2}, \frac{-\sqrt{4+\sqrt{2}+\sqrt{2}+\sqrt{2}+\sqrt{2}+\sqrt{4-2\sqrt{2}}}}{4\sqrt{2}}, \frac{-\sqrt{2}+\sqrt{2}}{4}, \frac{-\sqrt{4+\sqrt{2}+\sqrt{2}+\sqrt{2}+\sqrt{2}+\sqrt{4-2\sqrt{2}}}}{4\sqrt{2}}, \frac{-\sqrt{2}}{4}, \frac{-\sqrt{2-2\sqrt{2}}}{4} \right\}
\]
Perfect Pulses

P2

uniform 3-sectored half-circle

time $t$

P8

uniform 9-sectored half-circle

time $t$
Modulation with Perfect Pulses

P6-BPSK

P5-8 FSK

P8 PWM
Example PP Modulation onto FM

- **Chart 1**: Amplitude vs. Frequency [Hz].
  - Plot of Amplitude vs. Frequency.
  - Two curves: 
    - Solid line: PFSK
    - Dashed line: Ambient

- **Chart 2**: Bit Error Rate vs. (Signal-to-Interference) \( \alpha \) [dB].
  - Plot of Bit Error Rate vs. \( \alpha \) [dB].
  - Two curves: 
    - Solid line: PP
    - Dashed line: SinBOC
Summary

- Emergence of long-range backscatter and ambient communications
- New paradigm for communications and networking
- Exploring the Uses of Perfect Pulses
  - Ambient/backscatter communications
  - Wireless Power Transfer (continuous power tracking)
  - Low-bit Quantizers
  - Other Signal Processing…
Helmet Shock Sensor

**System:** 5.8 GHz backscatter tags equipped with low-powered, accelerometer/gyrometer MEMs sensors that track real-time head trauma events on a sports field

**Communications:** provides more than 200 packets of 6-axis motion data per second at 30m range

**Power:** coin cell battery provides potentially months of operation

https://www.youtube.com/watch?v=_DGn6HPooRk
Wireless Motion Capture

Hybrid Microwave Inertial Reflectometry (HIMR) uses phase measurements + inertial data from sensor link to pinpoint a backscatter tag

Tests on a 5.8 GHz tag on a high-speed robotic positioning arm produce position estimates with mean and standard deviation errors of less than 2mm
Demonstration

- 5.8 GHz backscatter setup
- Tag sends 200 packets per second of 3-axis accelerometer data
- Motion track capable of moving tag up to speeds of 1.6 m/s
HIMR Estimate vs. Ground Truth

Positioner Distance Profile

- Programmed distance profile
- Distance profile using HIMR

Distance travelled in meters vs. time (sec)
Detection of Card Skimming Devices

Electromagnetic Integrity and Security Assay (ELISA) System

How ELISA Works

Sensitized microwave antenna (upper right) with load-modulated IQ signal returned to a nearby reader (lower right).

Constellation remains constant excepting temporary changes during human equipment usage.

Any dielectric components or small wires (e.g. a small foreign electronic device) placed nearby will distort the constellation.

Measured Performance

As a short, thin wire is moved away from the loop antenna, the backscatter amplitude and phase changes, as measured by “Normalized Symbol Distance”.

Highly reliable measurement, nearly impossible to spoof.

Other tamper detection applications possible.
Hope Diamond Security System

**System:** ELISA-based security system that works through ceilings, walls

**Communications:**
backscatters 5.8 GHz FSK temperature, humidity data with custom protocol

**Power:** Coin cell and passive tags designed and built

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Electro-thermal Model of an Antenna + Load

(a) thermal noise reception

\[ \mathcal{N}_A(t) \]

\[ \mathcal{N}_L(t) \]

(b) thermal noise + signal reception

\[ V_A \cos(2\pi ft) \]

\[ \mathcal{N}_L(t) \]
Thermodynamic Limit of CW RF Harvesting