Backscatter Networks for Large-Scale Environmental Sensing

Plants as Bioelectric Wireless Sensors & Batteries with Scatter Radio and Low Cost – What we learnt!

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Agenda

- **Plants as Bioelectric Sensors & Batteries!**
- **Lesson 1 - *Scatter Radio.***
- **Lesson 2 – *Scatter Radio Sensing & Signal Processing*.**
- **Lesson 3 – *Energy Harvesting*.**
- **Conclusion**

Motivation

Dense micro-climate monitoring:

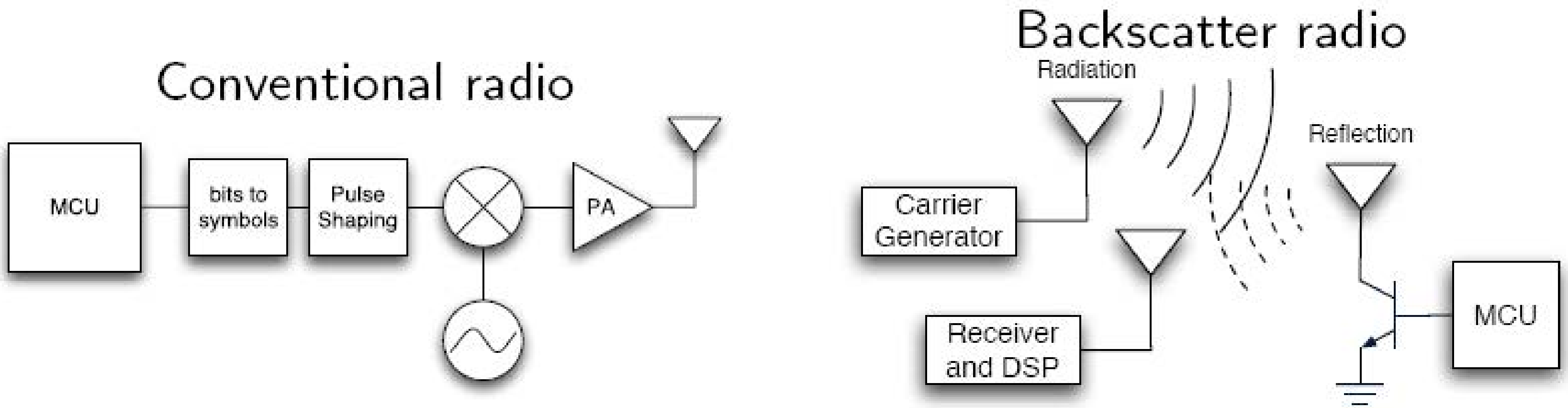
• Ultra-low cost (<1Euro per sensor)!

• Ultra-low power, battery-less!

• Appropriate for dense networks!

No existing technology for **ALL** the above.

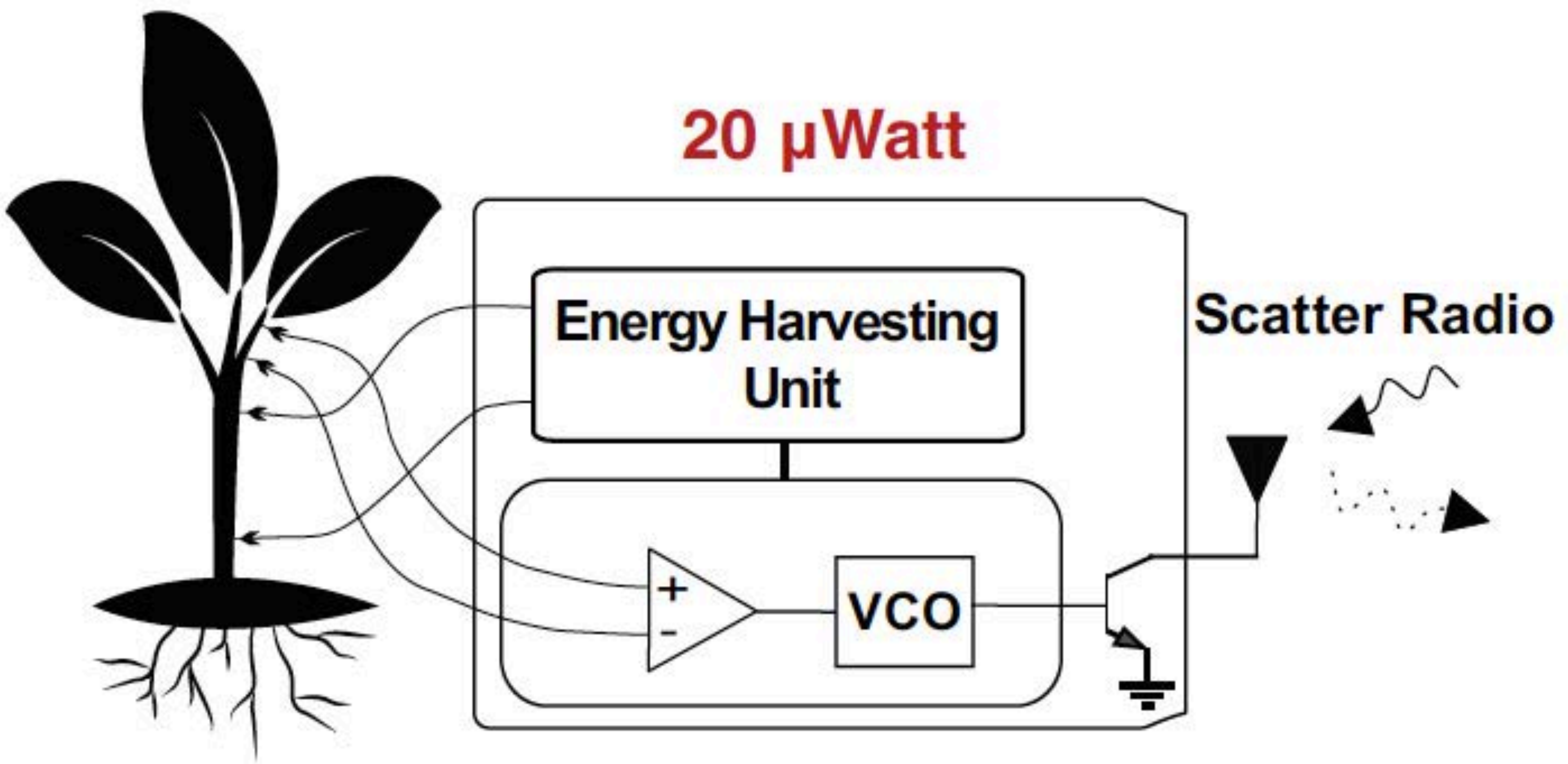
Backscatter Radio Principle



- Com by RADIATION.
- Tx current: ~ 20mA for 0dBm, $2.4 - 500$kbps, 100m $\sim 5 - 10\$$

- Com by **REFLECTION**!
- Tx current: ~ 0.6mA for 1MHz clock at the MCU, $\sim 0.1 - 1\$$, Range?

Plants as Bioelectric Sensors & Batteries!



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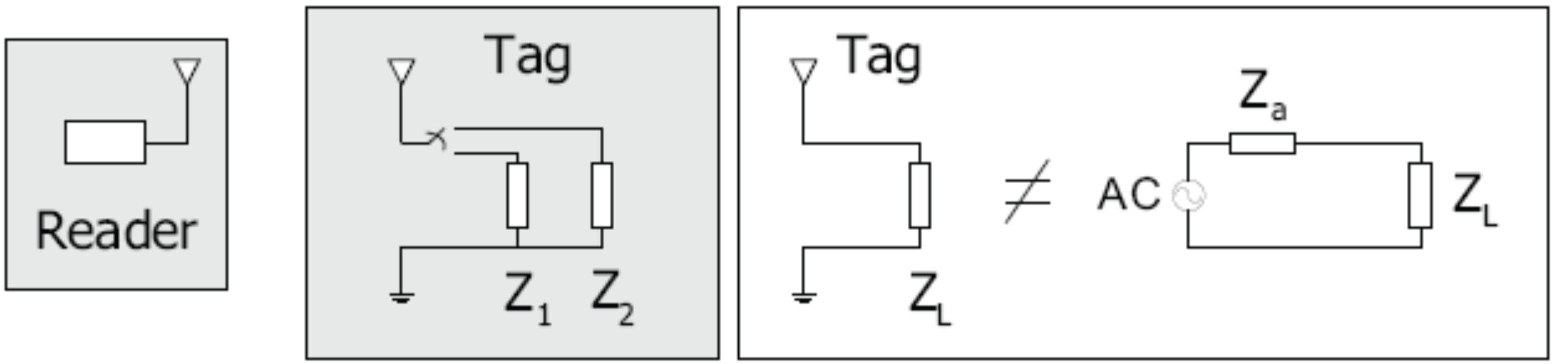
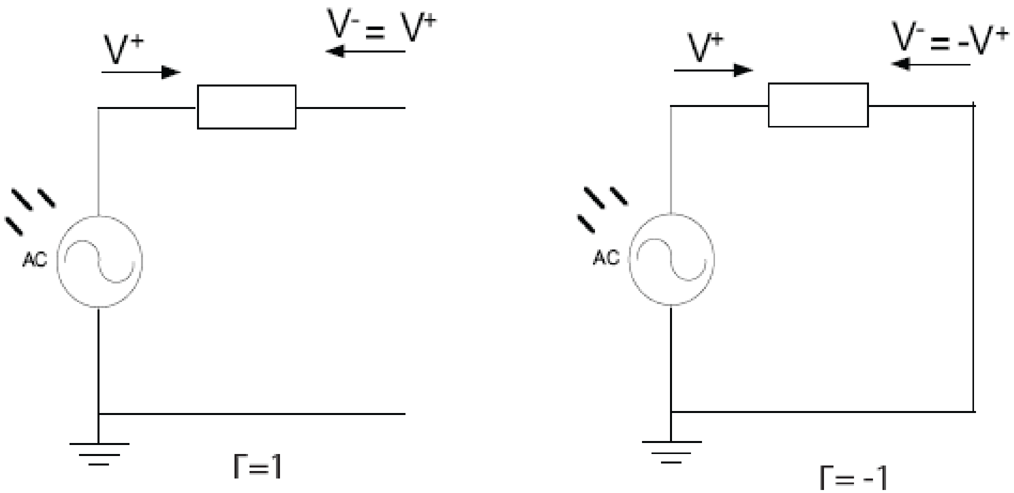
Backscatter Radio Principle



Equivalence is true only for minimum scattering antennas

- Communication by means of reflection.
- Binary backscatter: terminate tag antenna at two different loads!
- Simplest case: open and short-circuit load.

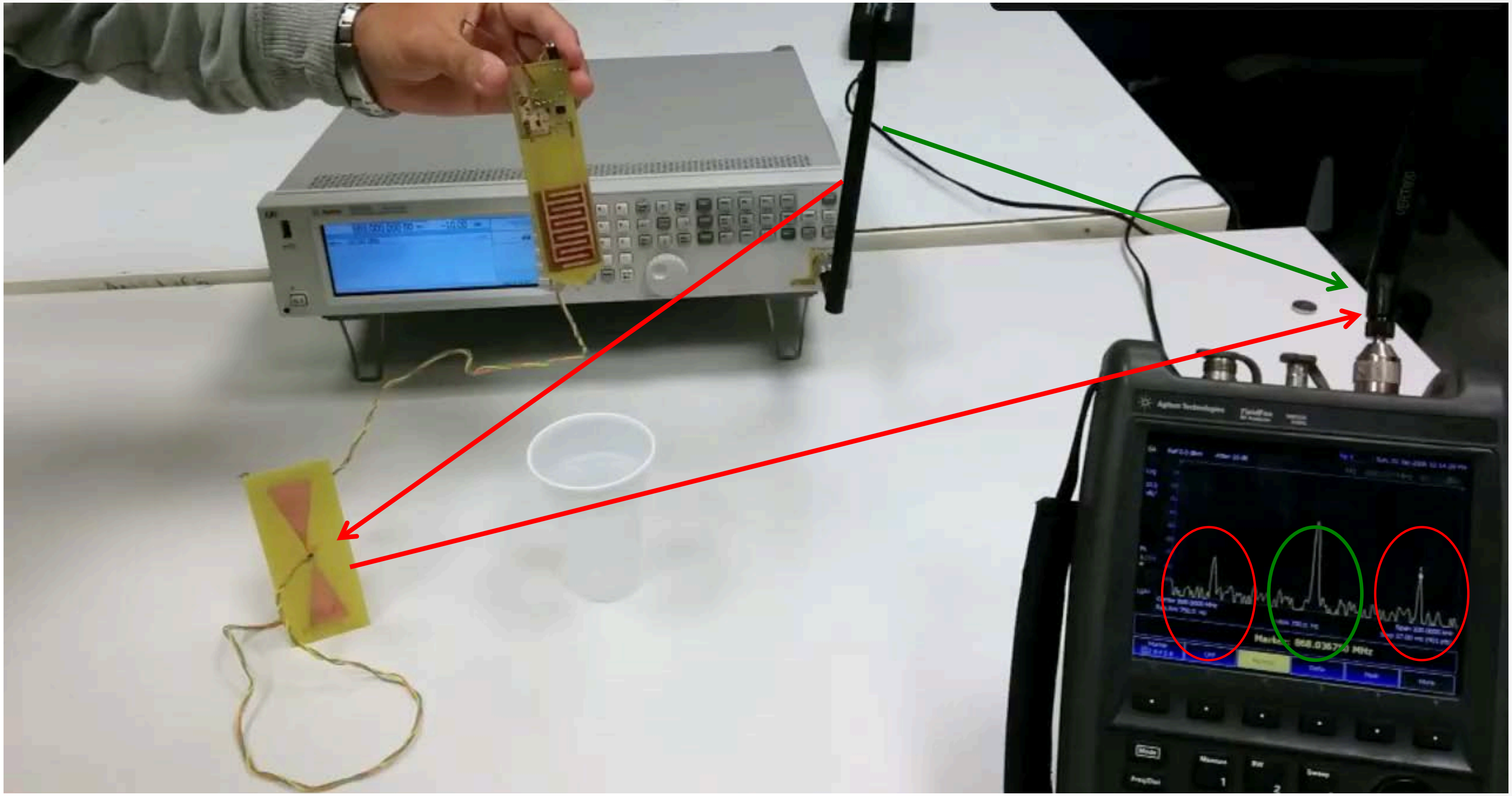
Backscatter Radio Principle



$$\Gamma = 1 : y(t) = +A\cos(2\pi f_c t + \phi_0) = A\cos(2\pi f_c t + \phi_0 + 2\pi),$$
$$\Gamma = -1 : y(t) = -A\cos(2\pi f_c t + \phi_0) = A\cos(2\pi f_c t + \phi_0 + \pi),$$
$$\Rightarrow y(t) = A\cos(2\pi f_c t + \phi_0 + m(t))$$

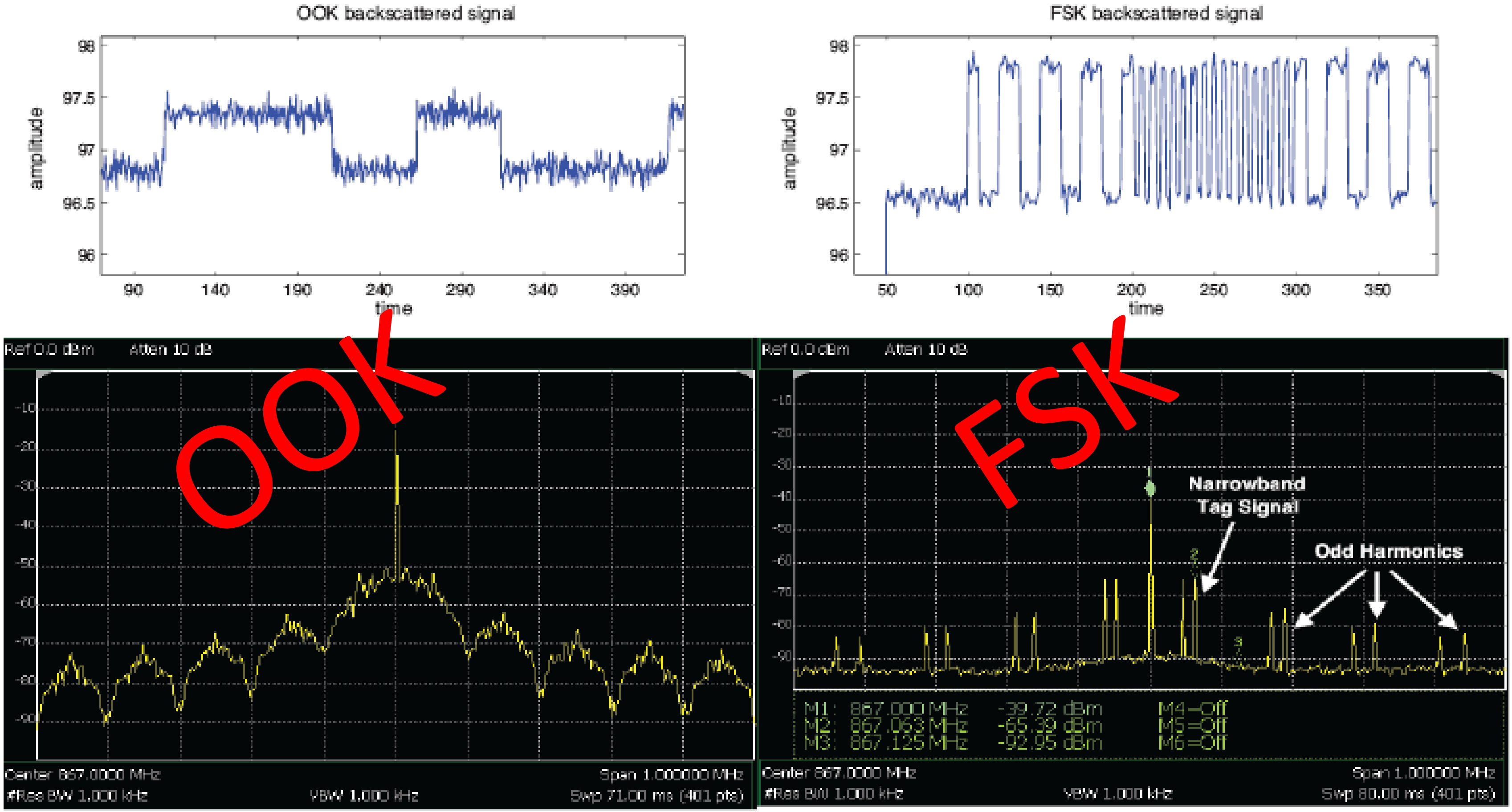
- OOK: switch and stay at each load for bit duration (Gen2).
- FSK: switch between the loads with different switching freq. per symbol.

Lesson: Extended range is possible with APPROPRIATE physical layer and signal processing!



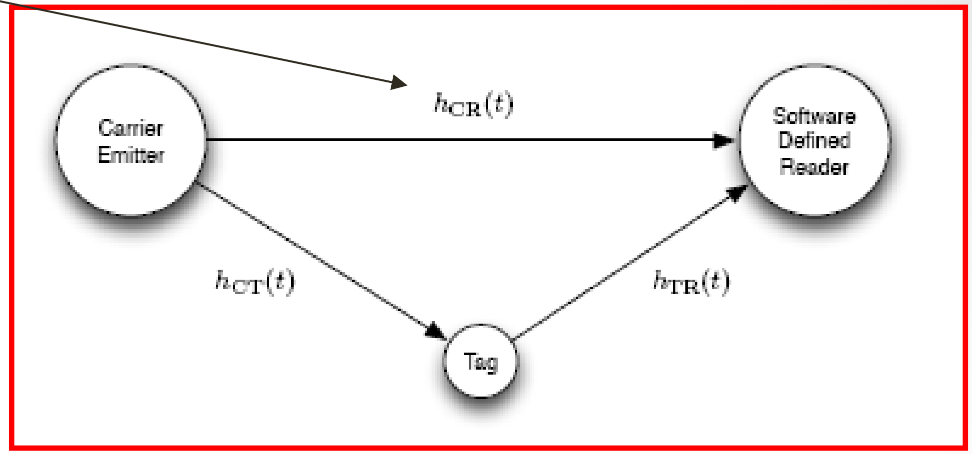
- Baseband signal model of scatter radio is significantly different than Marconi radio – appropriate signal processing is needed!
- Example: Switch tag loads with frequency F. how many freqs are reflected?
- Answer: $F_c \pm F$ (and not just $F_c + F$ or F_c - F)!

Experimental Backscatter OOK, FSK (time & freq domain)



TX to RX leakage in monostatic (or bistatic)

Scatter Radio General Signal Model



$$y(t) \triangleq I(t) + jQ(t)$$
$$= \frac{A}{2}\left[a_{CR}\, e^{-j\hat{\phi}_{CR}} + a_{CT} a_{TR}\, s\, x(t-\tau_{TR})\, e^{-j\hat{\phi}_{CTR}}\right] e^{-j2\pi \Delta F t} + n(t)$$

CFO in bistatic

OOK $x(t) \triangleq A_s - \Gamma_0$ or $x(t) \triangleq A_s - \Gamma_1$

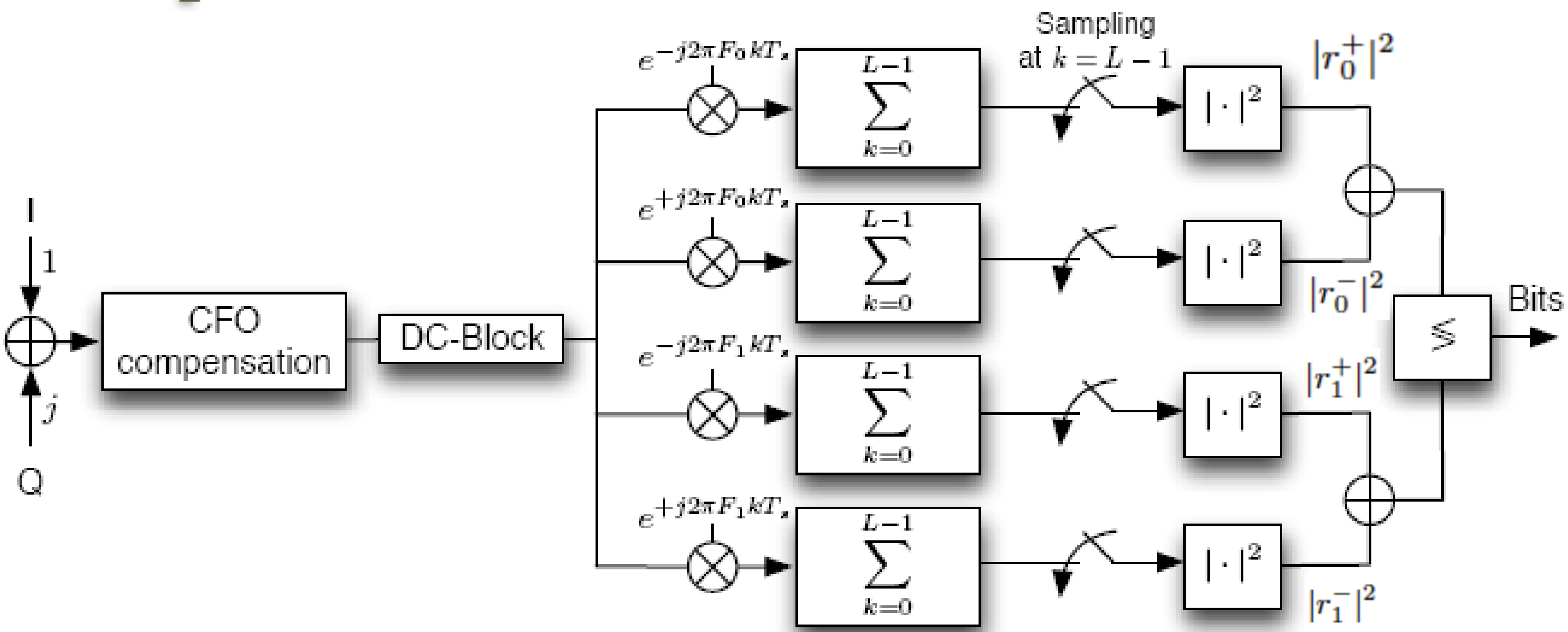
FSK

$$x(t) = \left(A_s - \frac{\Gamma_0 + \Gamma_1}{2}\right) + \frac{\Gamma_0 - \Gamma_1}{2}\, b_i(t), \;\; i = 0, 1$$

$$b_i(t) = \frac{4}{\pi} \sum_{k=0}^{+\infty} \frac{1}{2k+1} \cos[(2k+1)(2\pi F_i t + \Phi)]$$

cosine models ± switching freqs. (±F_0 for bit ‘0’, ±F_1 for bit ‘1’)

Non-coherent Binary FSK scatter radio reception



$$z_0 \triangleq |r_0^+|^2 + |r_0^-|^2 \overset{\text{bit } 0}{\geq} |r_1^+|^2 + |r_1^-|^2 \triangleq z_1$$

- Non-coherent design, tailored to backscatter signal model...
- no 3dB loss compared to classic radio binary FSK (BFSK) receivers [1], [5], [26]

Is <u>coherent</u> scatter radio (coded or not) BFSK reception possible?

$$\underbrace{\begin{bmatrix} r_0^+ \\ r_0^- \\ r_1^+ \\ r_1^- \end{bmatrix}}_{\mathbf{r}} = \underbrace{\begin{bmatrix} \frac{\sqrt{T}h_{\text{CTR}}}{2}e^{+j\Phi_0} \\ \frac{\sqrt{T}h_{\text{CTR}}}{2}e^{-j\Phi_0} \\ \frac{\sqrt{T}h_{\text{CTR}}}{2}e^{+j\Phi_1} \\ \frac{\sqrt{T}h_{\text{CTR}}}{2}e^{-j\Phi_1} \end{bmatrix}}_{\mathbf{h}} \odot \underbrace{\begin{bmatrix} (1-b_i) \\ (1-b_i) \\ b_i \\ b_i \end{bmatrix}}_{\mathbf{s}_{b_i}} + \underbrace{\begin{bmatrix} n_0^+ \\ n_0^- \\ n_1^+ \\ n_1^- \end{bmatrix}}_{\mathbf{n}}$$

$$\Leftrightarrow \mathbf{r} = \mathbf{h} \odot \mathbf{s}_{b_i} + \mathbf{n}$$

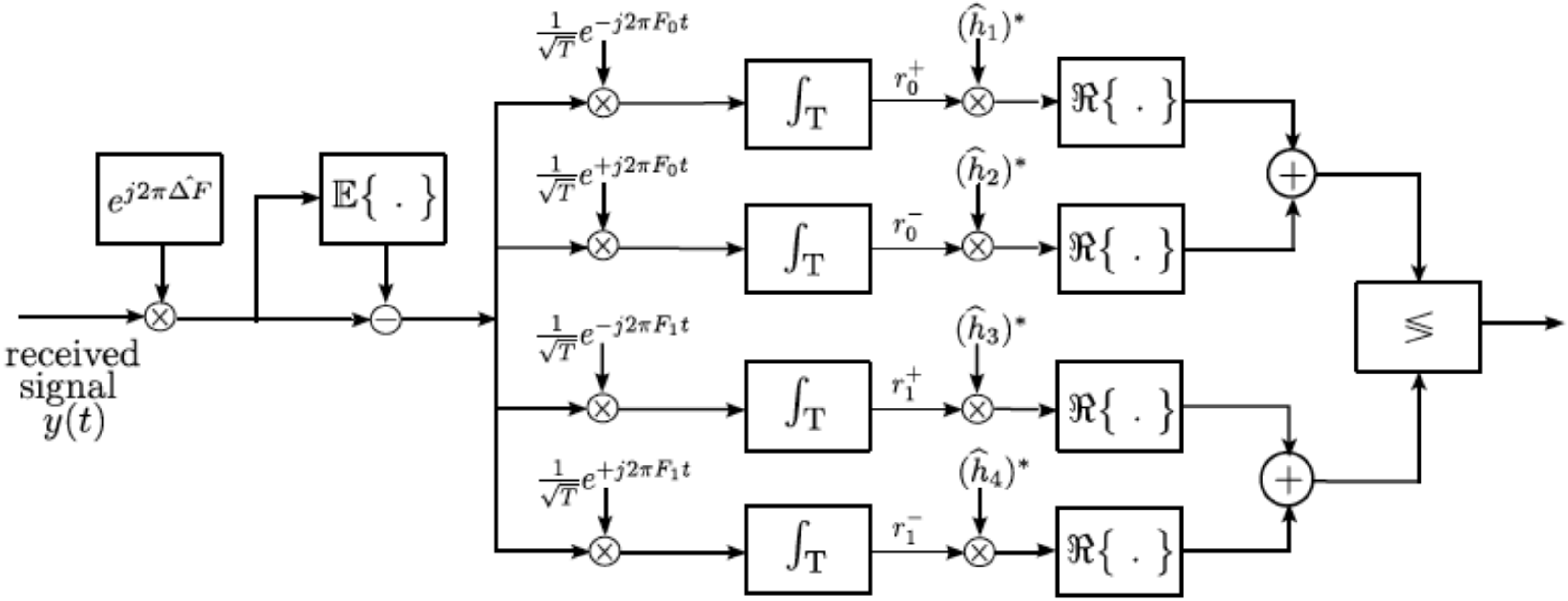
- YES! All unknowns can be squeezed under mild assumptions in a single 4x1 complex vector **h** [26] [9] that can be estimated with LS technique!

$$\mathbf{h} = [h_1 \; h_2 \; h_3 \; h_4]^T \qquad \mathbf{n} = [n_0^+ \; n_0^- \; n_1^+ \; n_1^-]^\top \sim \mathcal{CN}\left(\mathbf{0}_4, \frac{N_0}{2}\mathbf{I}_4\right)$$

$$h_{\text{CTR}} = m_{\text{CTR}} e^{-j\phi_{\text{CTR}}},$$

$$m_{\text{CTR}} = \frac{2\sqrt{2P_c}}{\pi} \; s \; |\Gamma_0 - \Gamma_1| \; a_{\text{CT}} \; a_{\text{TR}}, \;\; \phi_{\text{CTR}} = \phi_{\text{CT}} + \phi_{\text{TR}} + \phi_R + \angle(\Gamma_0 - \Gamma_1).$$

Coherent Binary FSK scatter radio reception



$$b_i^{\mathrm{ML}} = \underset{b_i \in \{0,1\}}{\operatorname{argmax}} \exp\left\{-\frac{2}{N_0}\left\|\mathbf{r} - \hat{\mathbf{h}} \odot \mathbf{s}_{b_i}\right\|_2^2\right\}$$

$$\Leftrightarrow \Re\left((\hat{h}_1)^*\, r_0^+ + (\hat{h}_2)^*\, r_0^-\right) \overset{\text{bit } 0}{\geq} \Re\left((\hat{h}_3)^*\, r_1^+ + (\hat{h}_4)^*\, r_1^-\right)$$

- Estimation of **h** with preambles and Least Squares.
- Minimum distance receiver has been extended to coded (sequence) setups [26] [9]!

Non-coherent sequence BFSK scatter radio reception with or without short channel (FEC) codes

- Could small-block length forward error correction (FEC) improve performance? …need for sequence **c** detection!

$$\widehat{\mathbf{c}} = \arg\max_{\mathbf{c}\in\mathcal{C}} \mathop{\mathbb{E}}_{\Phi_0,\Phi_1}\left[\max_{\mathbf{h}\in\mathbb{C}^N} \ln\left(f_{\mathbf{r}_{1:N}|\mathbf{c},\mathbf{h},\Phi_0,\Phi_1}(\mathbf{r}_{1:N}|\mathbf{c},\mathbf{h},\Phi_0,\Phi_1)\right)\right]$$

- Composite Hypothesis Testing above, can be simplified under mild assumptions, to the problem below [10]:

$$\widehat{\mathbf{c}} = \arg\max_{\mathbf{c}\in\mathcal{C}} \mathbf{w}\mathbf{c}^\top$$

$$\mathbf{w} = [w(1)\ w(2)\ \ldots\ w(N)] \triangleq \{z_1(n) - z_0(n)\}_{n=1}^{N},\ z_i(n) \triangleq |r_i^+(n)|^2 + |r_i^-(n)|^2, i \in \mathbb{B}$$

- Soft-decision metrics **w** is the key; other solutions tested in [8] :

$$\{w(i)\}_{i=1}^{N_{\text{TOT}}} \triangleq \left\{\ln\left(\frac{z_0(i)}{z_1(i)}\right)\right\}_{i=1}^{N_{\text{TOT}}}$$

Non-coherent sequence BFSK scatter radio reception with or without short channel (FEC) codes

- GLRT-optimal loglinear complexity sequence detection in flat fading for orthogonal signals was presented in [11].

$$\underbrace{\begin{bmatrix} r_1 \\ r_2 \\ \vdots \\ r_M \end{bmatrix}}_{\mathbf{r}} = \sqrt{P} h \mathbf{e}_x + \underbrace{\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_M \end{bmatrix}}_{\mathbf{n}} \qquad \mathbf{y} \triangleq \begin{bmatrix} \mathbf{y}_1 \\ \vdots \\ \mathbf{y}_N \end{bmatrix} = \sqrt{P} h \underbrace{\begin{bmatrix} \mathbf{e}_{x_1} \\ \vdots \\ \mathbf{e}_{x_N} \end{bmatrix}}_{\mathbf{s}} + \mathbf{w}$$

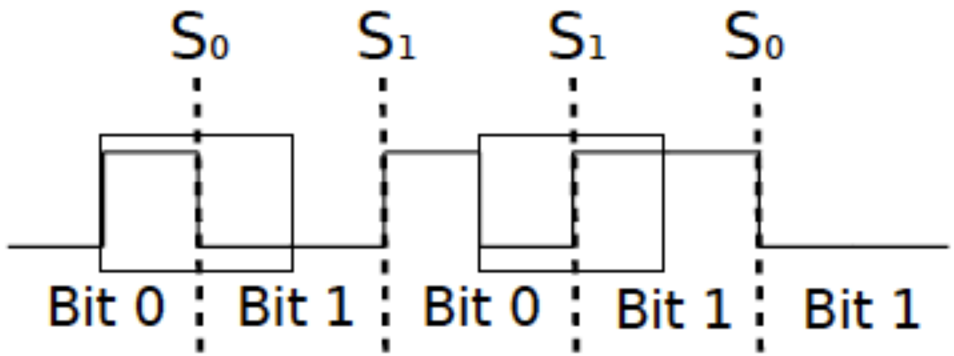
where $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \sigma_w^2 \mathbf{I}_M)$ and $\qquad \mathbf{w} \sim \mathcal{CN}(\mathbf{0}, \sigma_w^2 \mathbf{I}_{MN})$

$$x = 1, 2, \ldots, M \qquad \mathbf{e}_x = [\underbrace{0 \ \ldots \ 0}_{x-1} \ 1 \ \underbrace{0 \ \ldots \ 0}_{M-x}]^T$$

- For sequence of N symbols, GLRT-optimal detector was found with NlogN complexity and zero knowledge of (constant) *h* [11].
- FM0 line coding in Gen2 RFID standard boils down to this…

Non-coherent sequence BFSK scatter radio reception with or without short channel (FEC) codes

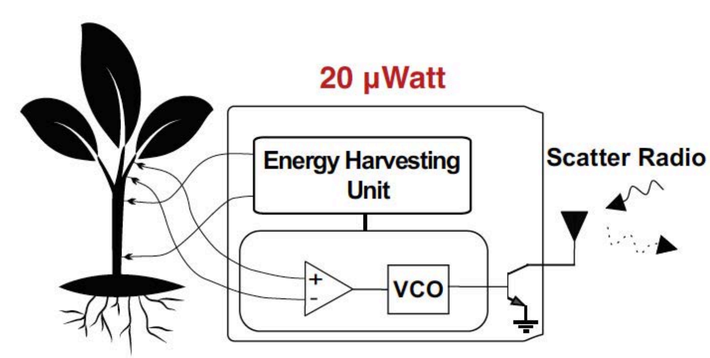
$$\mathbf{y} \triangleq \begin{bmatrix} \mathbf{y}_1 \\ \vdots \\ \mathbf{y}_N \end{bmatrix} = \sqrt{P}h \underbrace{\begin{bmatrix} \mathbf{e}_{x_1} \\ \vdots \\ \mathbf{e}_{x_N} \end{bmatrix}}_{\mathbf{s}} + \mathbf{w},$$



$$\hat{\mathbf{s}}^{\mathrm{GLRT}} = \arg\min_{\mathbf{s}\in\mathcal{I}_M^N} \left\{ \min_{h\in\mathbb{C}} \left\| \mathbf{y} - \sqrt{P}h\mathbf{s} \right\|^2 \right\} = \arg\max_{\mathbf{s}\in\mathcal{I}_M^N} \left| \mathbf{s}^T \mathbf{y} \right|$$

- FM0 line coding in Gen2 RFID standard boils down to this…
- …solved with NlogN, instead of 2^N complexity...

Power-limited Regime Telecom



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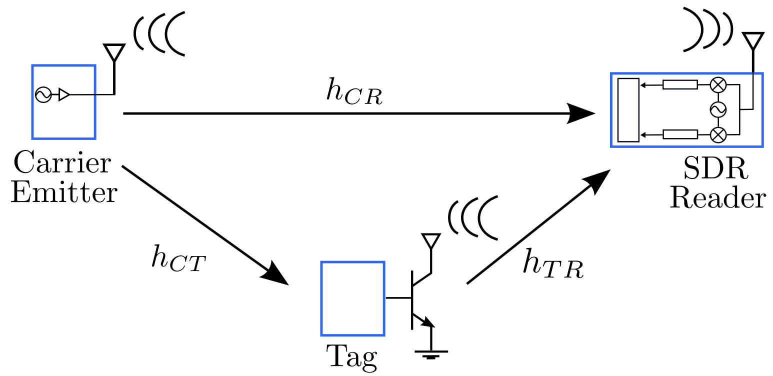
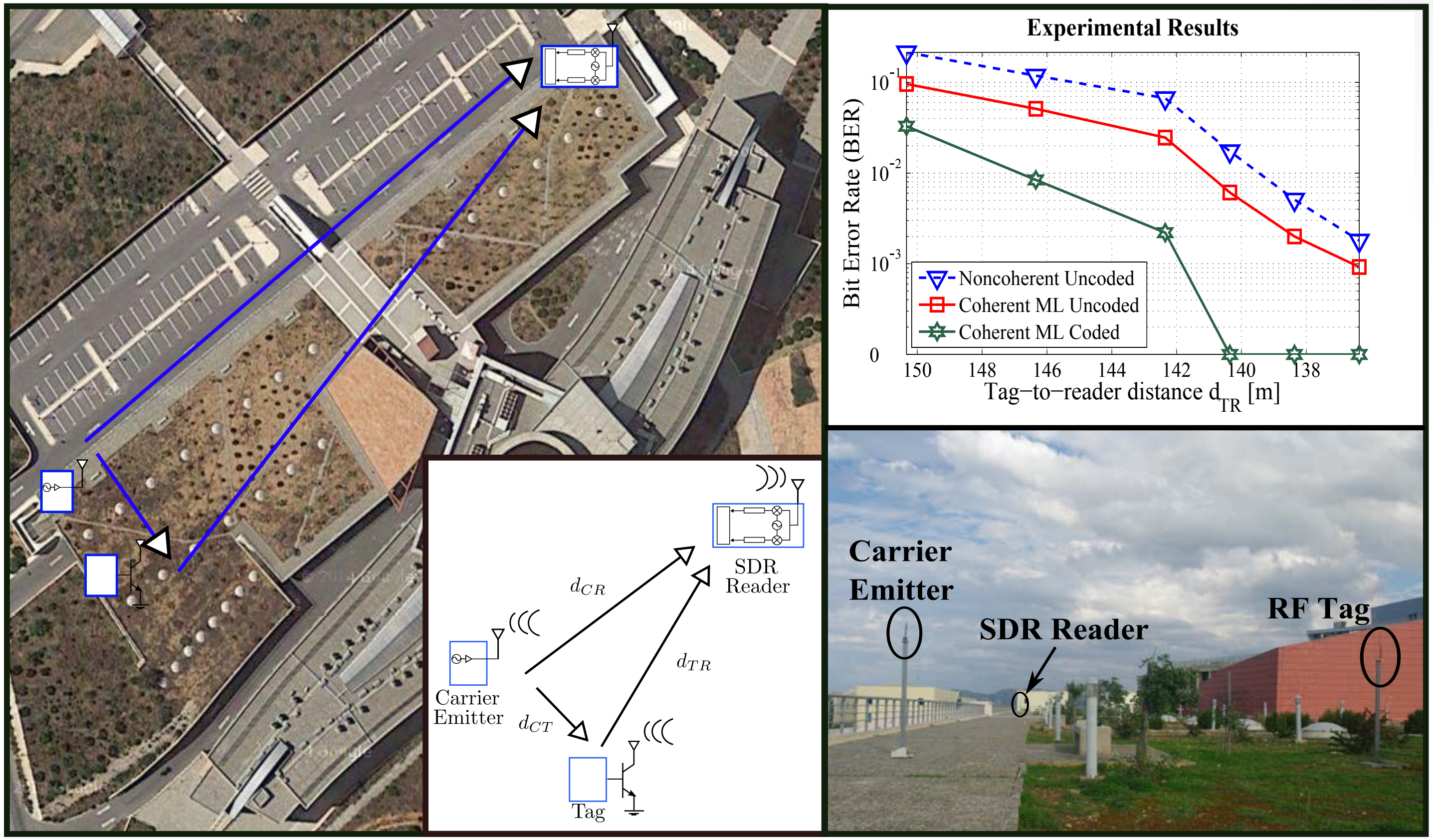
Scatter Radio Receiver Advances



- Uncoded (no FEC), non-coherent receivers for bistatic setup (OOK or FSK), SDR demo [KBS12], [KBS12b], [KBS13], [KBS14].
- Coded (with FEC), non-coherent receivers, with various soft-decision metrics, SDR demo [AFT14], [AB15], [TATB15].
- Coded (with FEC), coherent receivers, SDR demo [FAB15], [FAB15b].
- Coded (with line coding), coherent RFID/Gen2 receivers, code available online [KMB15].
- Uncoded (no FEC), GLRT-optimal non-coherent receivers, in flat fading for orthogonal signals, relevant to other apps, as well [AFK15], [AFK16].
- Uncoded (no FEC) *suboptimal* reception with 3-Euro, FSK conventional module – see our 270m range paper (at 13dBm Tx power), WPTC 16 paper! [VDB16]

Lesson: Scatter Radio Range is not an issue…

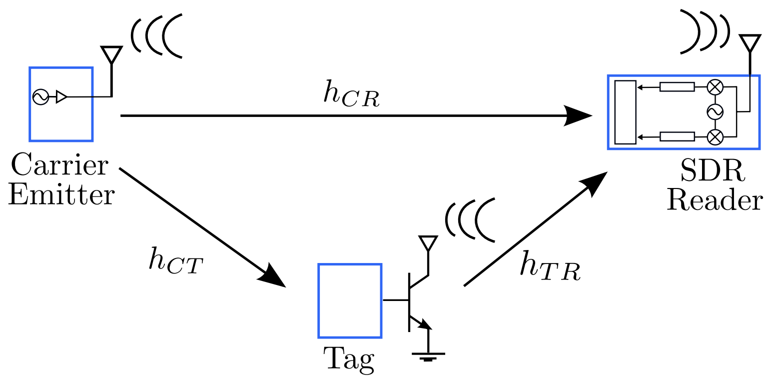


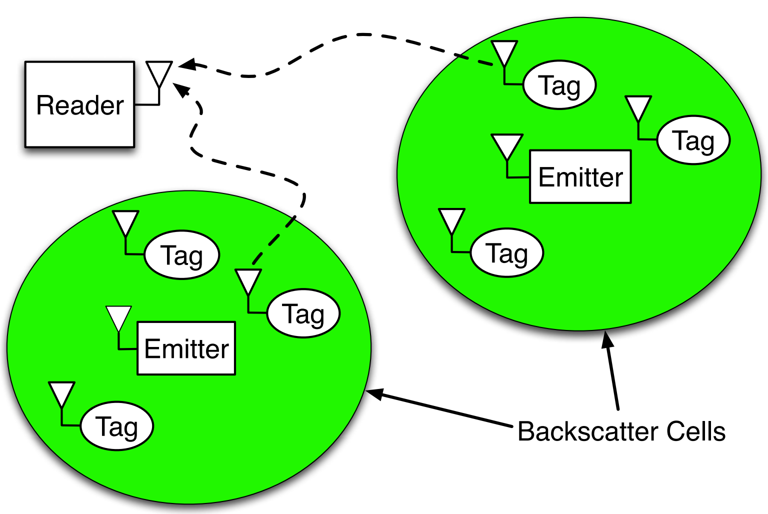
- Analog & MCU-based Digital tags, with/without FEC, coherent/non-coherent scatter radio – Tesla, Marconi, Gallagher and Proakis should be very proud! *(emitter at photo is at -13dBm, receiver is commodity low-cost SDR with increased NF>>7dB)*

Awards & Distinctions: Paper Awards

- **IEEE RFID-TA,** September 2017, Warsaw, Poland, Conference-wide best student paper award.
- **IEEE ICASSP**, April 2015, Brisbane, Australia, Conference-wide best student paper award and best student paper award in Communications and Networks track.
- **IEEE Sensors**, November 2013, Baltimore, USA. Selected among the best papers of the conference (and invited for submission to IEEE Sensors Journal).
- **IEEE RFID-TA,** September 2011, Sitges, Spain, Conference-wide best student paper award.

Scatter Radio Networking Approach





Decouple…

- …scatter radio from RF energy harvesting (semi-passive tag/sensors).
- …illuminating emitter from reader (flexible multi-static architectures, general signal model).
- …energy Harvesting from RF Energy Harvesting!

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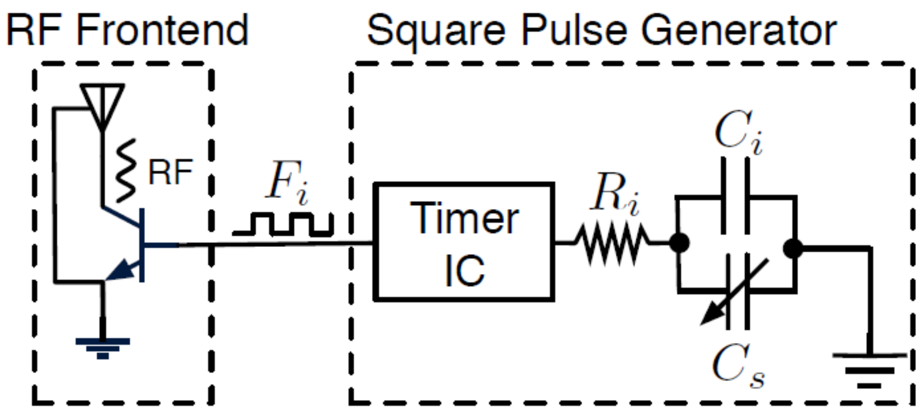
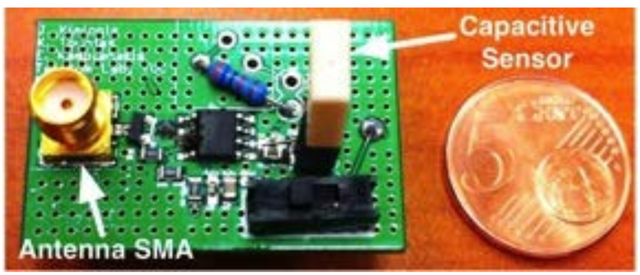
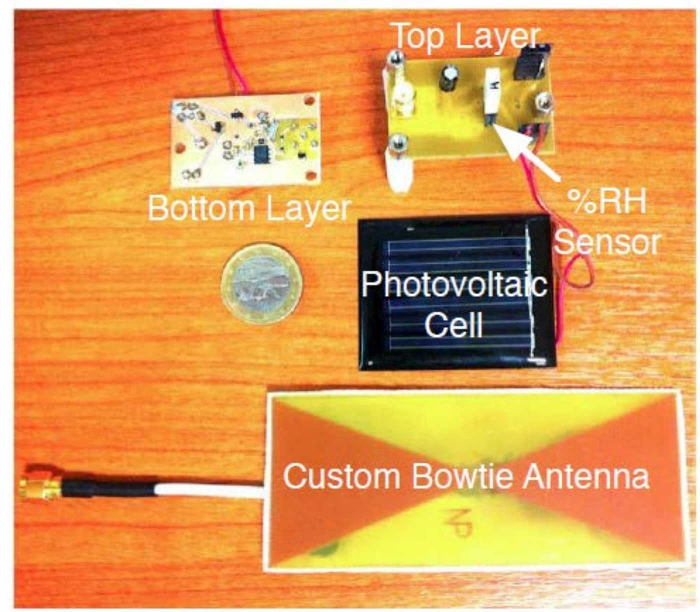
Example 1: Analog Environmental Humidity Sensing

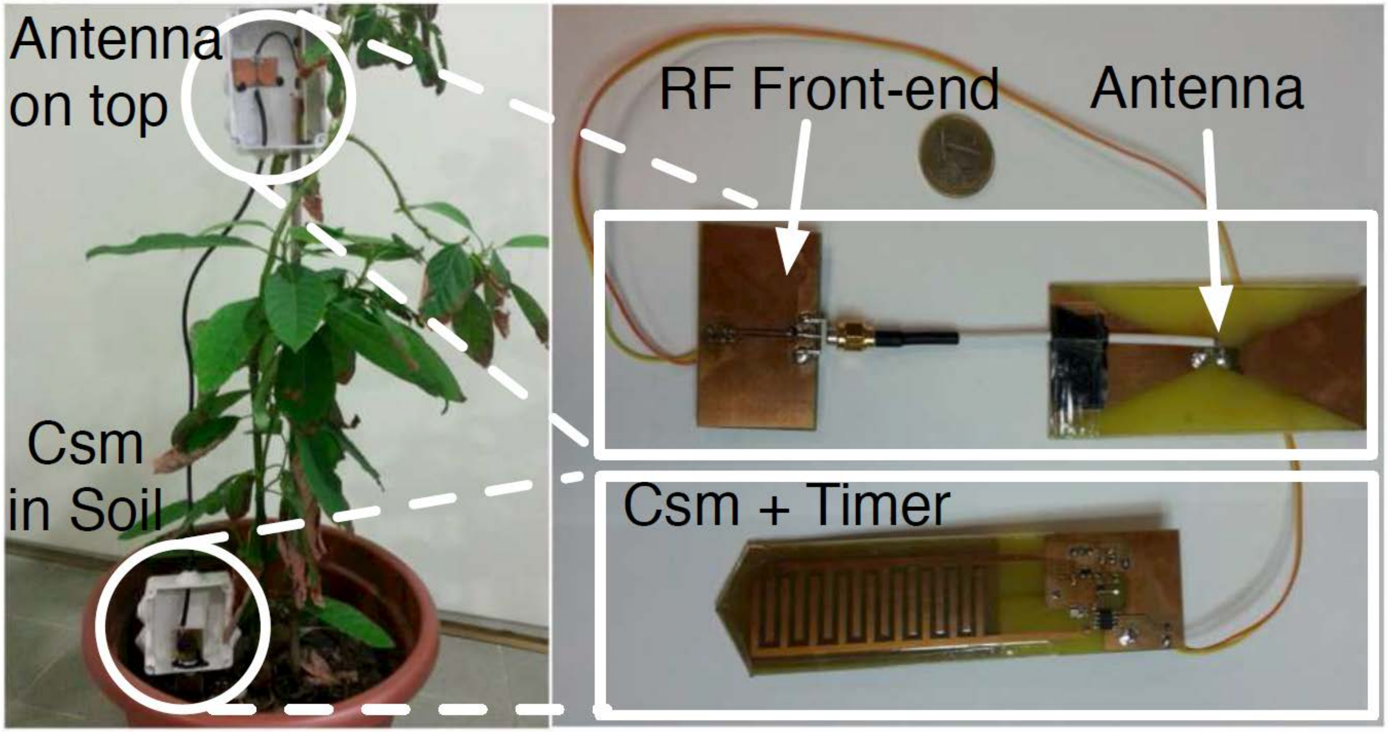






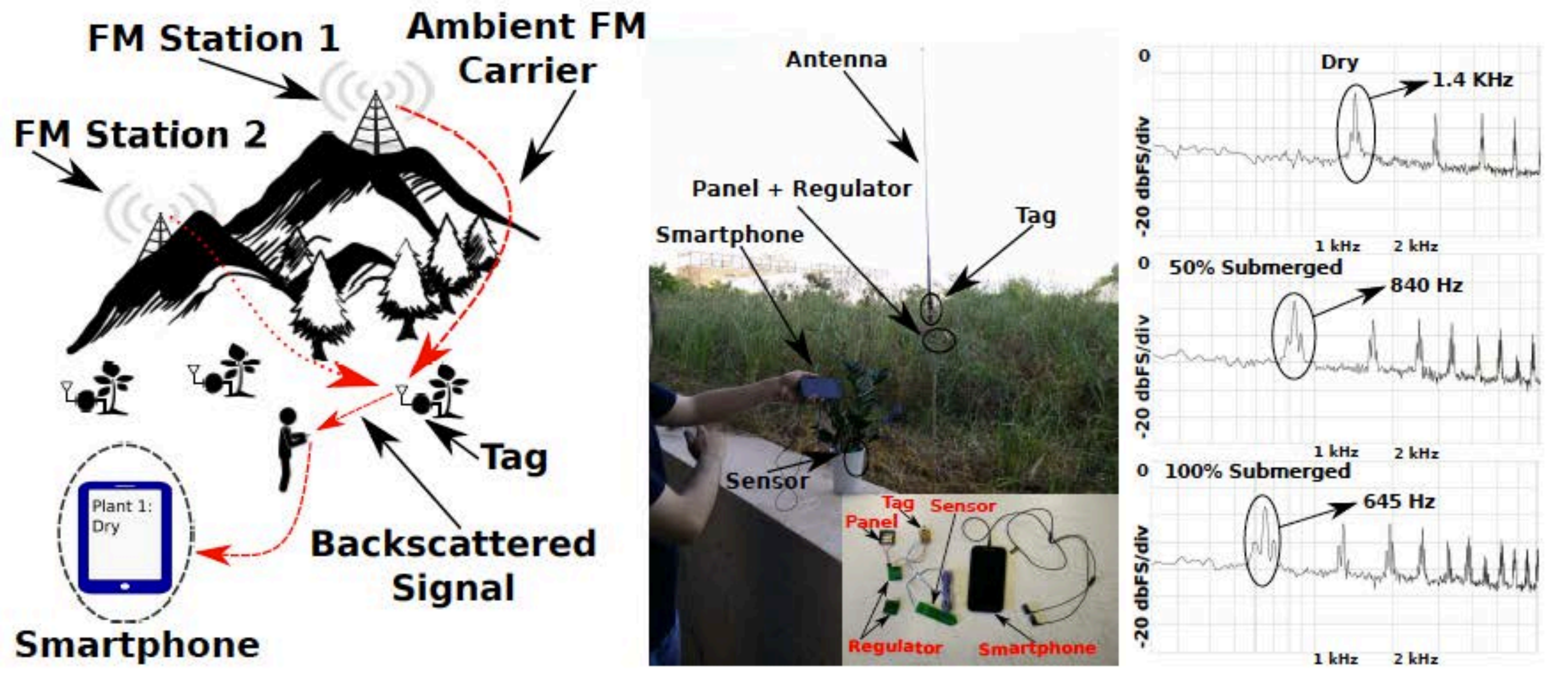
- Principle: convert capacitor changes to backscattered freq [12], [14]!
- Cost ~3€ (quantity of 1), Power 220μWatt, RMS 1-2% RH.
- Simple Networking (FDMA).

Example 2: Soil Moisture Sensing



- Principle: convert capacitor changes to backscattered freq [15]!
- Cost ~5€ (quantity of 1), Power ~100μWatt, RMS 1.9% SM.
- Simple Networking (FDMA).

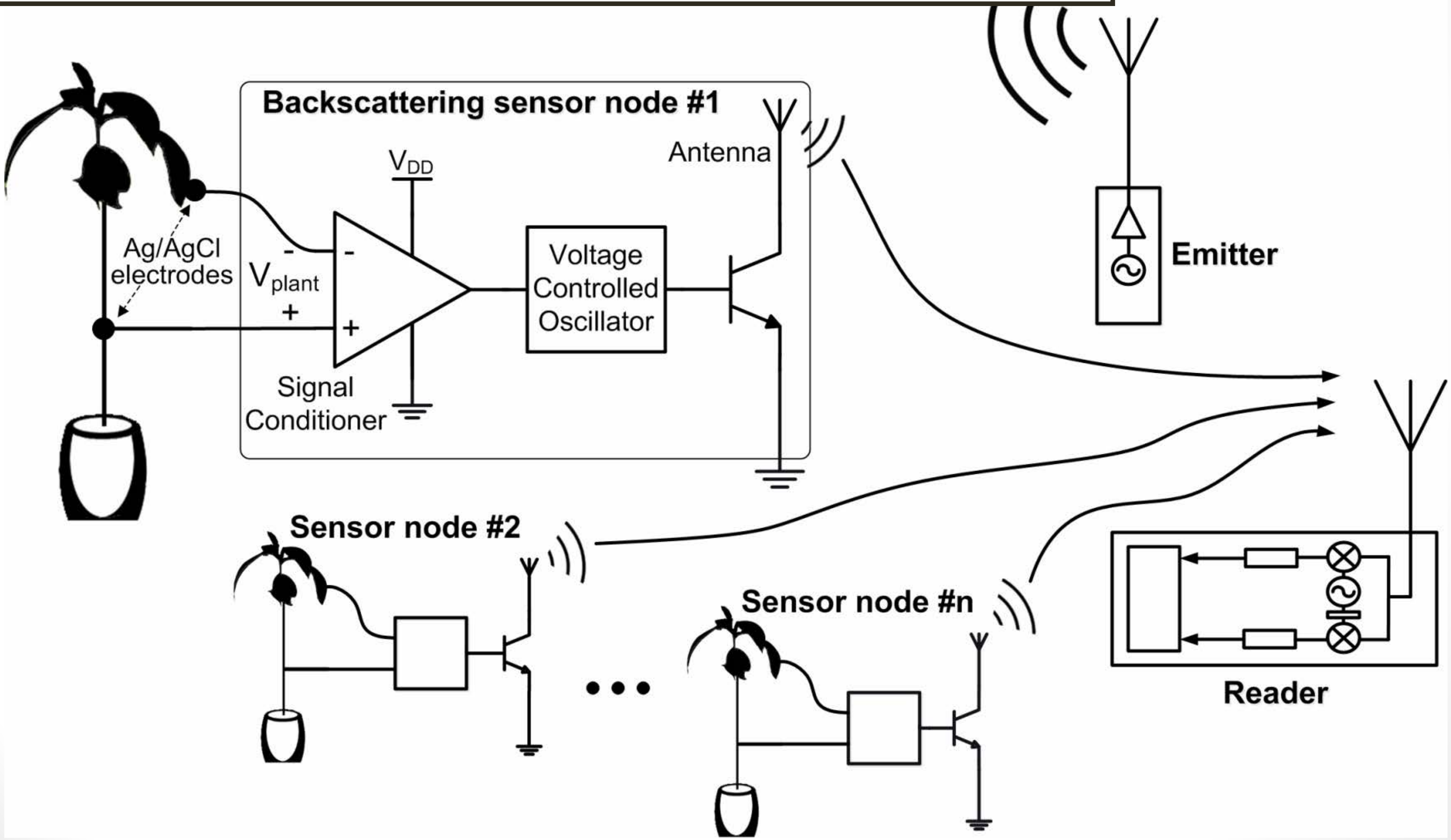
Example 3: Smartphone Moisture Sensing with FMs!



- Principle: measure capacitance or resistance on top of Ambient FM.
- Receiver = Smartphone, emitter = Ambient FM.
- Exploit Transmit Diversity!

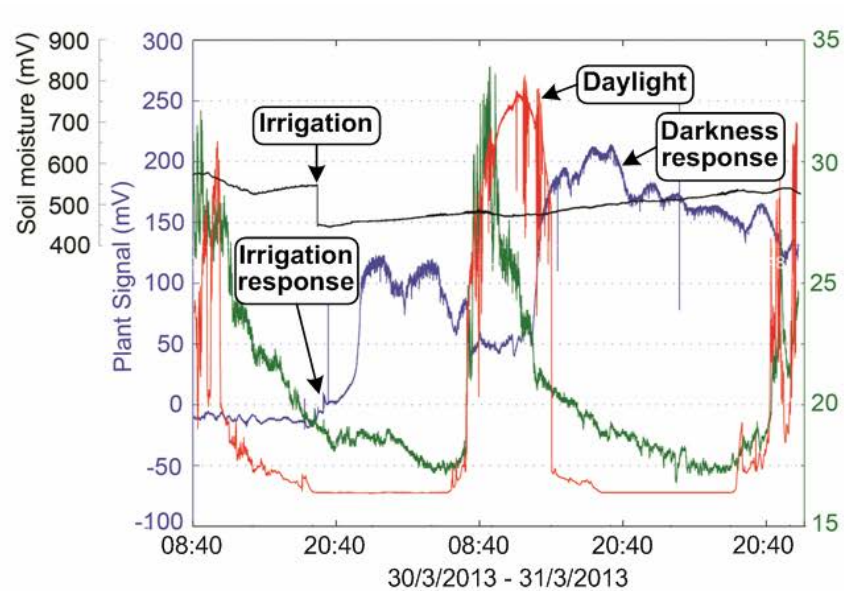
Example 4: Plant is the sensor, i.e. transmit the plant electric potential (EP)!

- *Replace capacitor/timer circuit with a low-power VCO!*

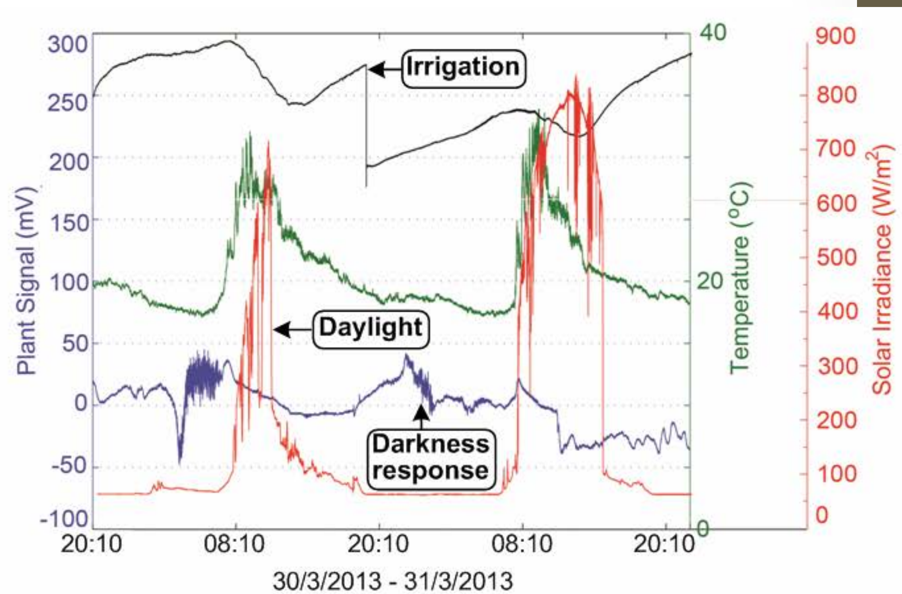


Plant = Sensor!

Avocado tree

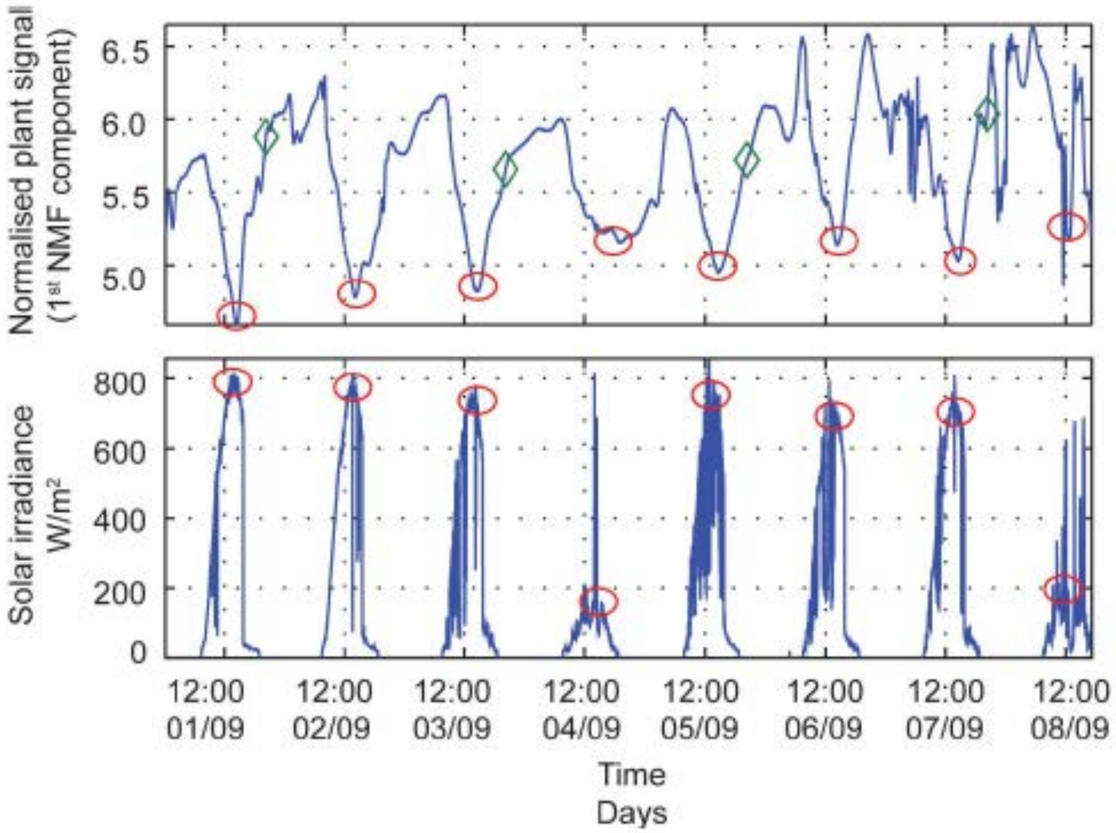


Orange tree



➢ Plant Electric Potential (EP): A LOT OF INFO [KKK13]!

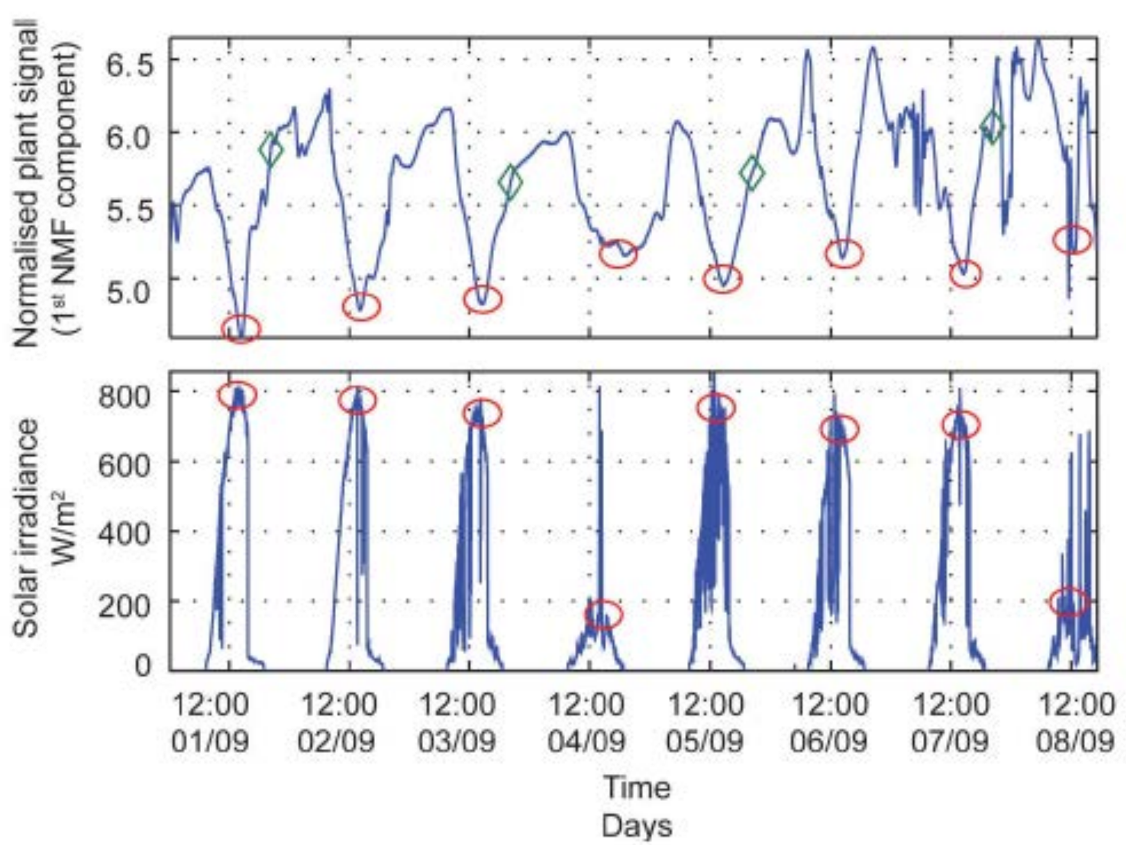
NMF-based Signal Processing



X = **W V**, **X**: N x T, **W** weights, **V** NMF components.

- NMF method: alternating LS [KKM16].

Plant = Sensor!



- ➢ EP signal correlated with solar irradiance [KKM16]!
- ➢ EP slope change correlated with plant watering [KKK13], [KKM16]!

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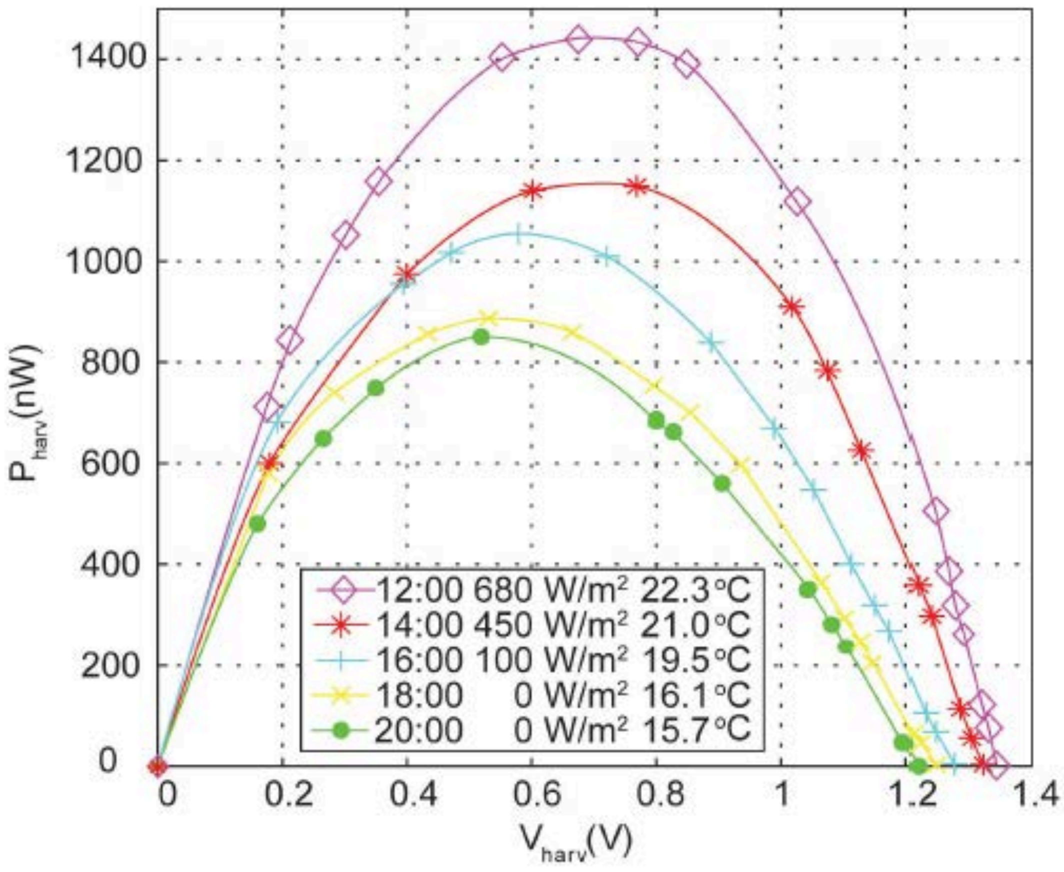
Ambient Energy Densities!

	Energy Source	Ambient Energy Availability	Current-Technology Offered Electric Power (after conversion, incorporating efficiency)
1	Light/ Solar	35mWatt/cm^2	**135mWatt** (Polycrystalline Blue Solar Cell 5.4cm x 4.3cm, efficiency 16.5%) [FUT15]
2	Kinetic/ Vibration		**20mWatt** (PMG FSH Electromagnetic transducer) [PER15]
3	Thermal		**1mWatt** (Thermoelectric Generator, 25° C @ 200Ωhm load) [MPE15]
4	Chemical/ Biologic	Voltage from an Avocado plant (*persea americana*) 60 cm tall	**1.15μWatt** @ 21° C, 12.00 pm **1.05μWatt** @ 19.5° C, 16.00 pm [KKM16]
5	RF	0.1μWatt/cm^2 (GSM band) [TEX10]	**0.88μWatt** (efficiency 6%, dipole antenna)
6	RF	-40dBm/FM station (FM band) [Fig. 2]	**0.018μWatt** (efficiency 3%, harvesting from six FM stations)
7	RF	-40dBm/FM station (FM band) [Fig. 2]	**0.003μWatt** (efficiency 3%, harvesting from one FM station)

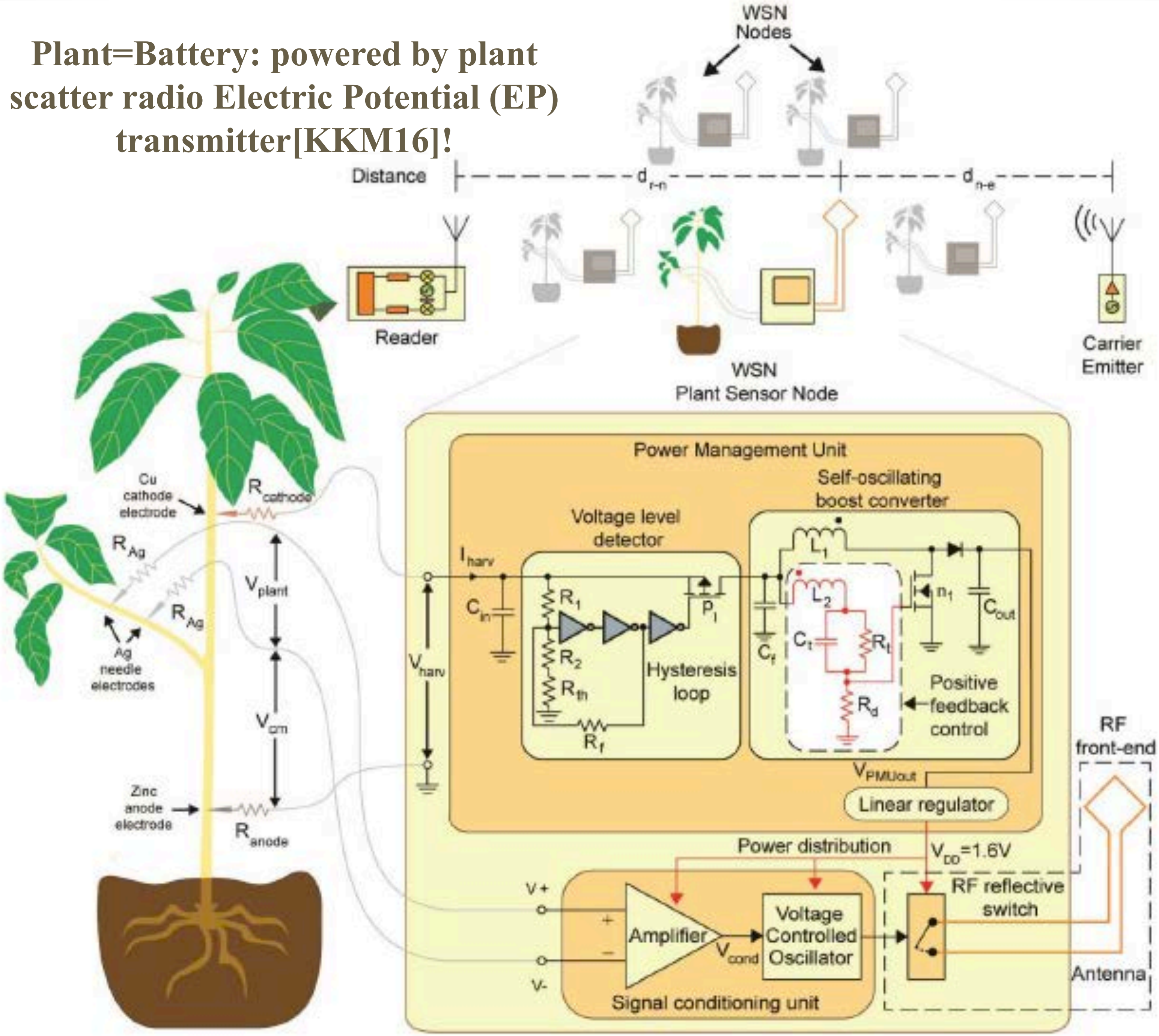
Disruptive Environmental Energy Harvesting: Plants [KKM16]!



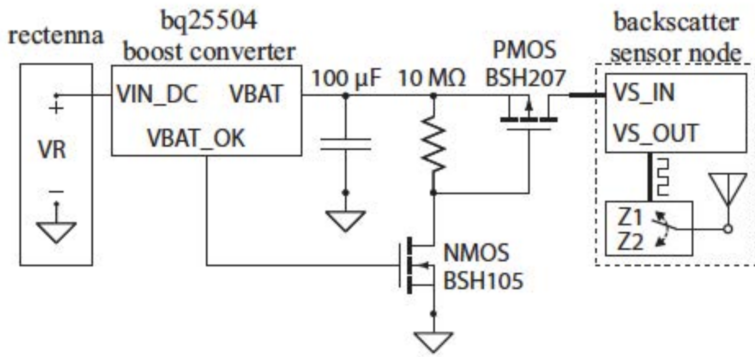
- Plants can offer ORDERS OF MAGNITUDE larger (than RF) power densities at specific times of day!

(measurements from a persea americana (avocado) about a half-a-meter tall)

Plant=Battery: powered by plant scatter radio Electric Potential (EP) transmitter[KKM16]!

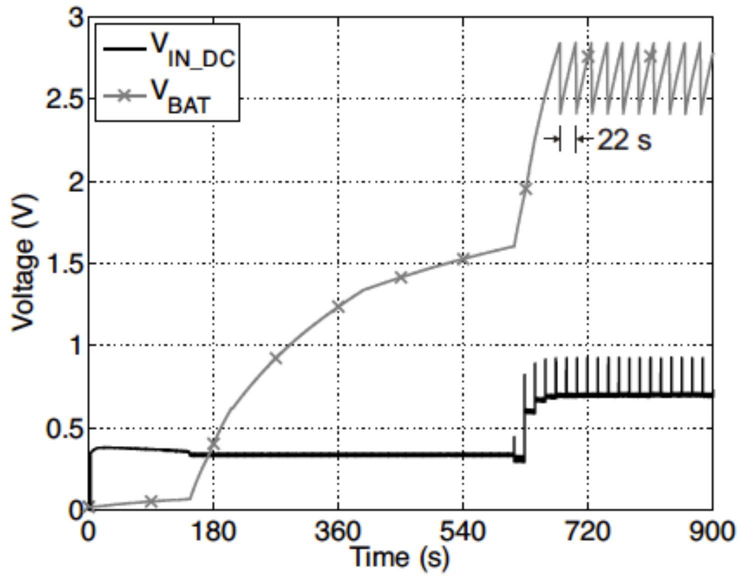


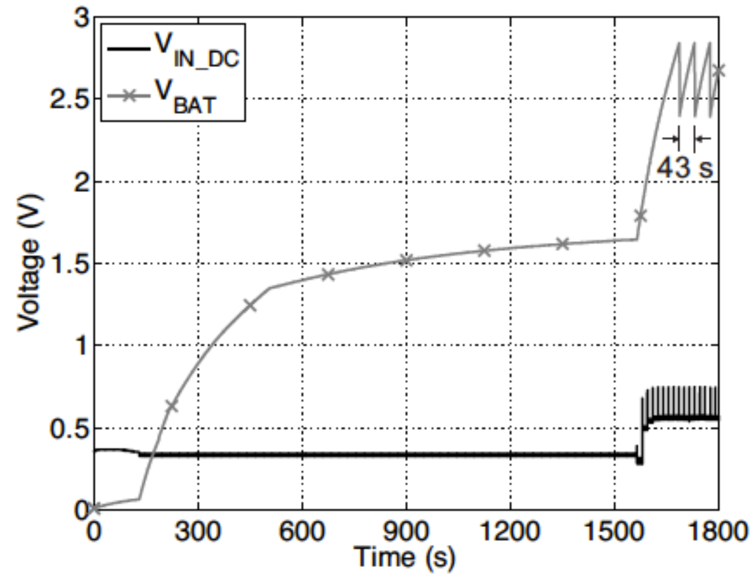
Common problems with RF Energy Harvesting!
(Boost Converter is the hard part) [ADB16]!



-20dBm

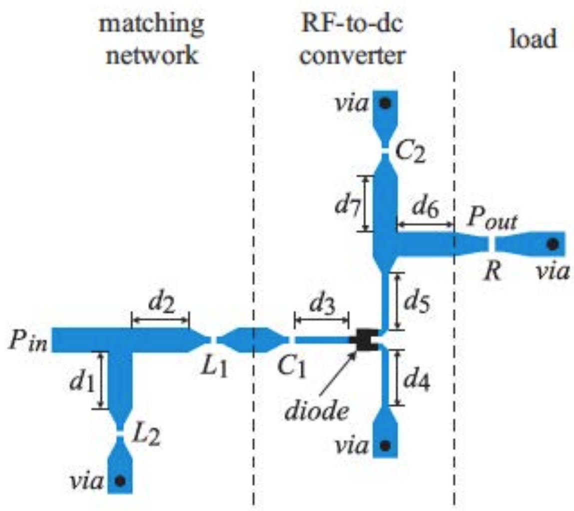
-22dBm

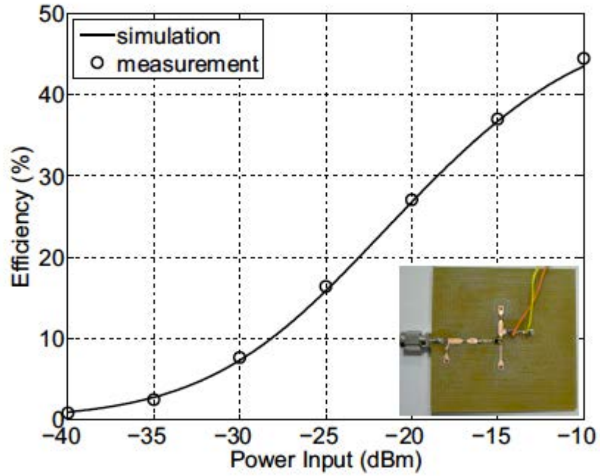


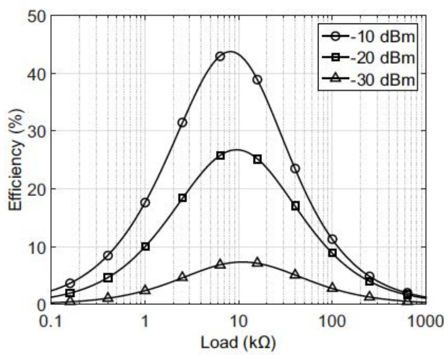


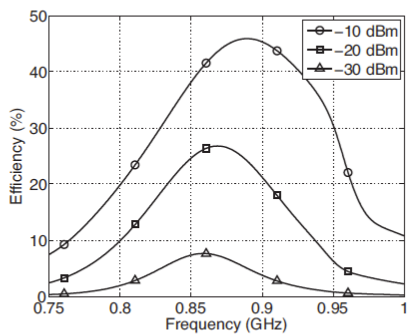
- Trade operation at lower input power (sensitivity) with smaller duty cycle!
- …we did NOT use the application note of the boost converter!

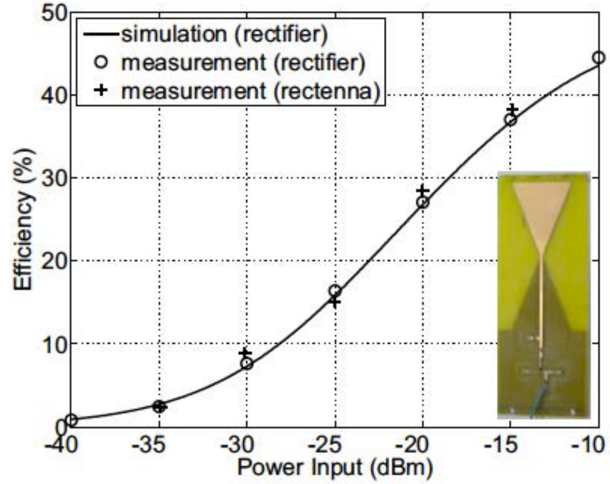
Single Rectenna optimization: include trace dimensions on (lossy) FR4





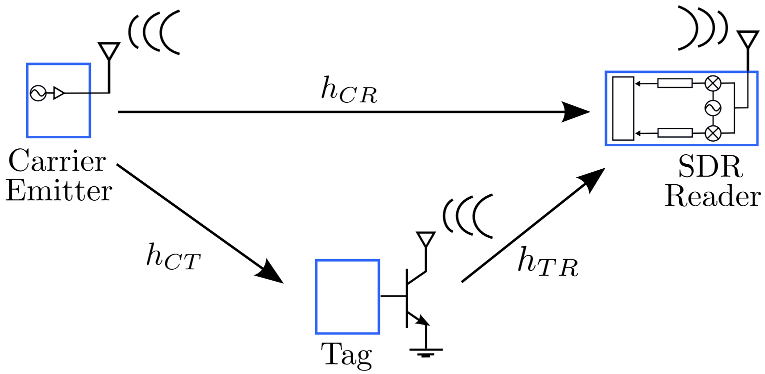


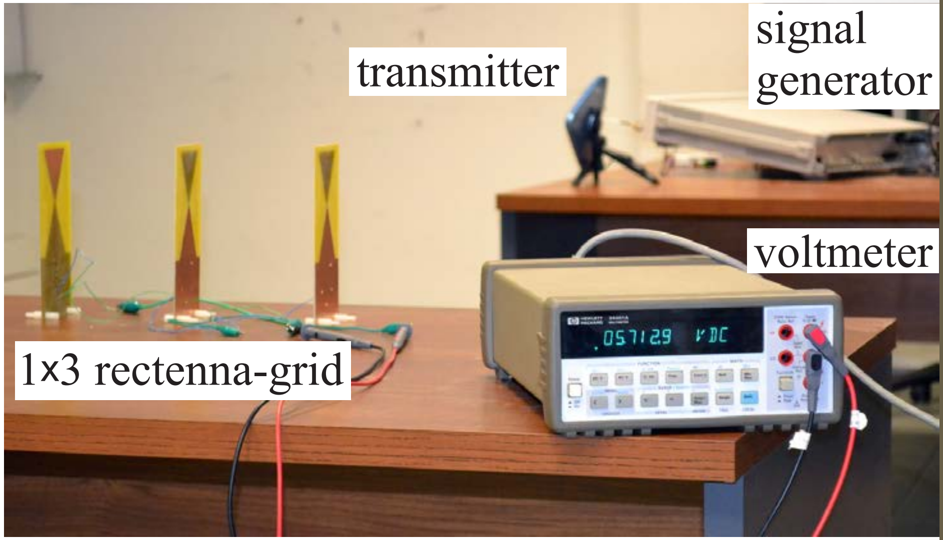




- Minimum reflection coefficient and maximum efficiency, study optimum load, operational BW (around 868MHz) [ASB14], [ADB14], [ADB16].

RF Rectenna Grids, Duty-cycled Operation: Improved Sensitivity

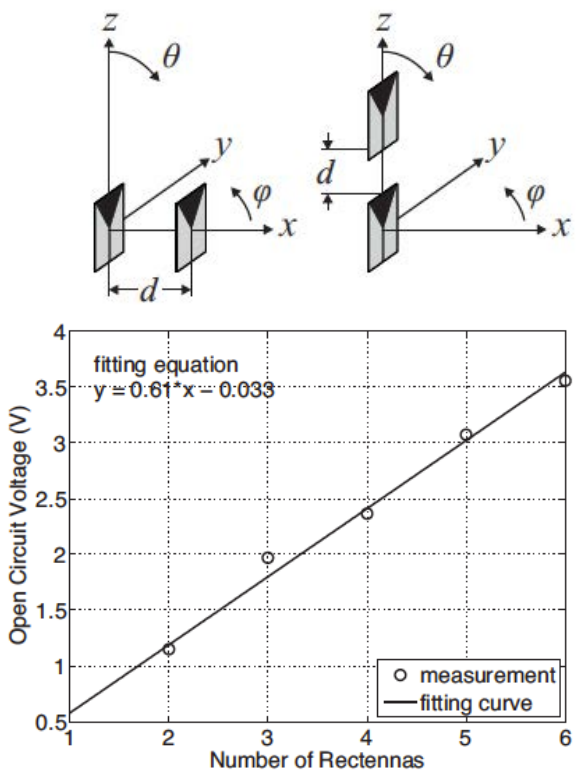


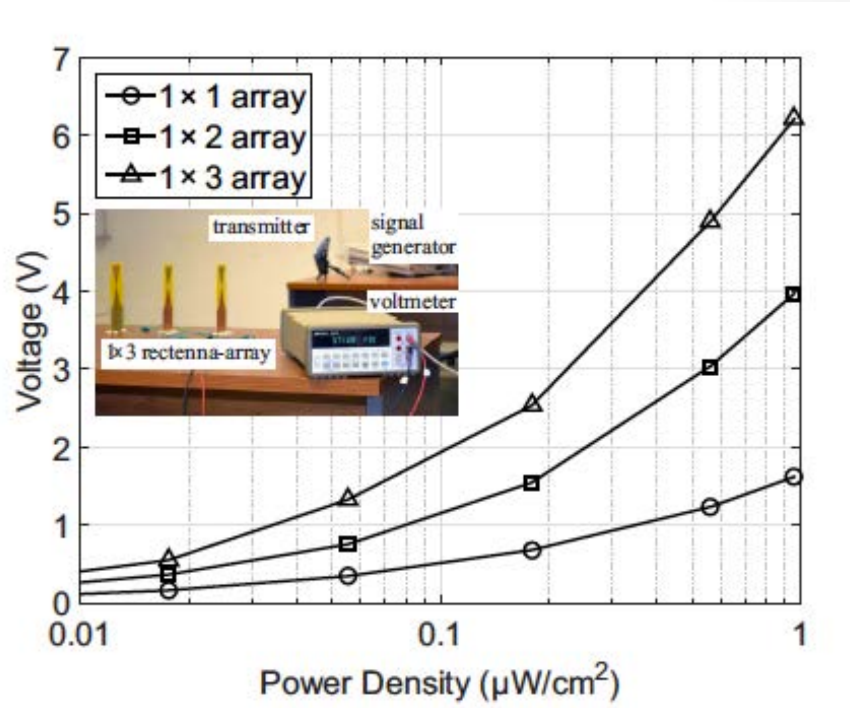


- Rectenna efficiency hits limiting walls at lower input power (<-30dBm).
- Sensors operate in low duty-cycle…
- ...need for RF harvesters operating below -30 dBm.
- …need for complete RF harvesting supplies, not just rectennas!
- <u>…willing to trade lower duty cycle for higher sensitivity</u>

  (i.e., able to operate at smaller input power levels)!

Rectenna Grids [ADB16]



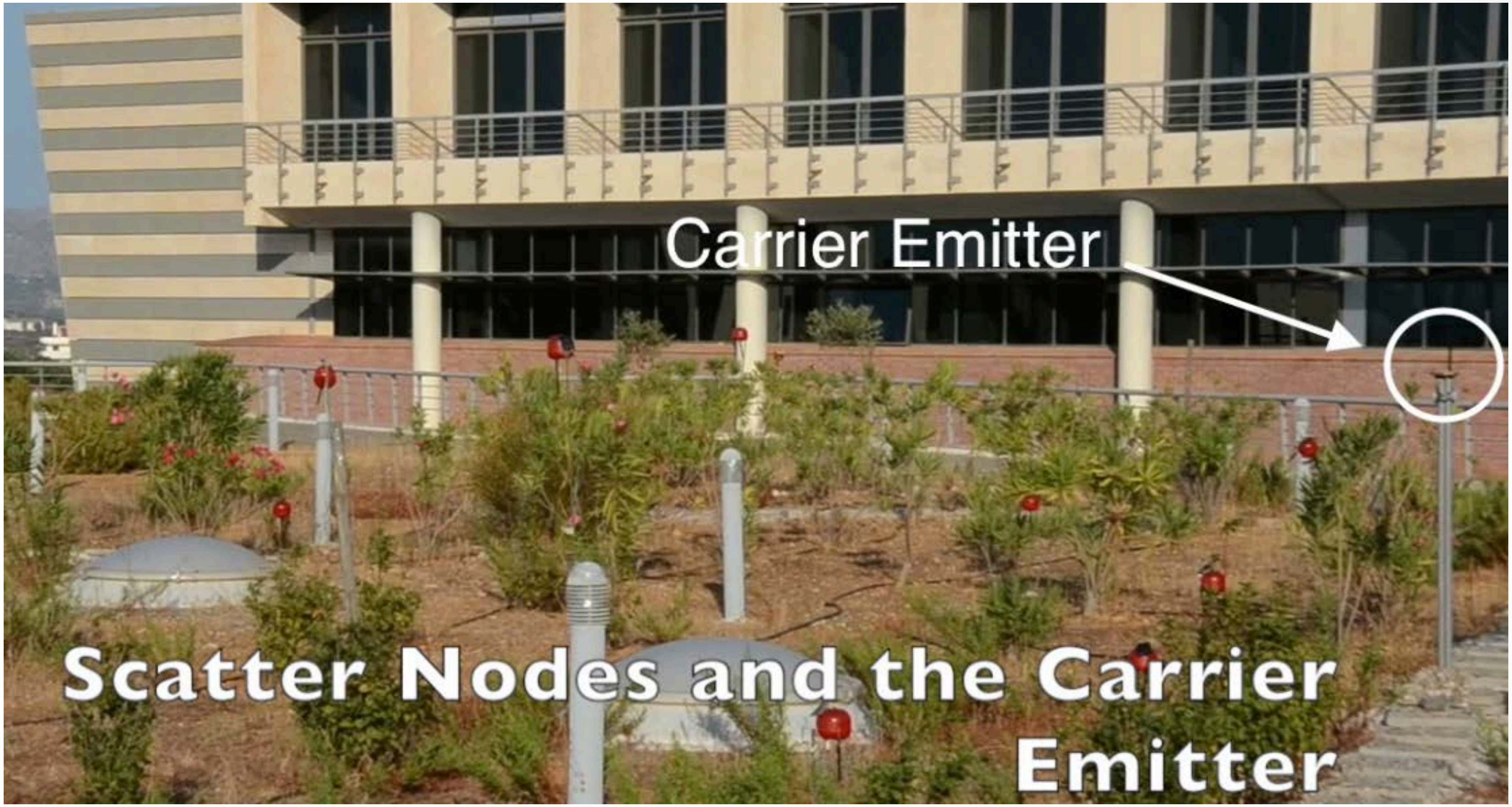


- Connect rectenna voltage output in series.
- Output (almost) linear with number of rectennas.
- Able to operate at fraction of 0.1μWatt/cm^2.

Agenda

- **Plants as Bioelectric Sensors & Batteries!**
- **Lesson 1 - *Scatter Radio.***
- **Lesson 2 – *Scatter Radio Sensing & Signal Processing*.**
- **Lesson 3 – *Energy Harvesting*.**
- **Conclusion**

Network Demos



- Digital Backscatter Sensor Network for Environmental Sensing!

Conclusion

- Scatter radio is tricky – need for careful signal processing.
- Disruptive energy harvesting sources (e.g., plants) typically offer much more than (insensitive) RF.
- Plants are wonderful Bioelectric Sensors!
- ...fertile area for further ECE research and innovation!

http://blase.tuc.gr

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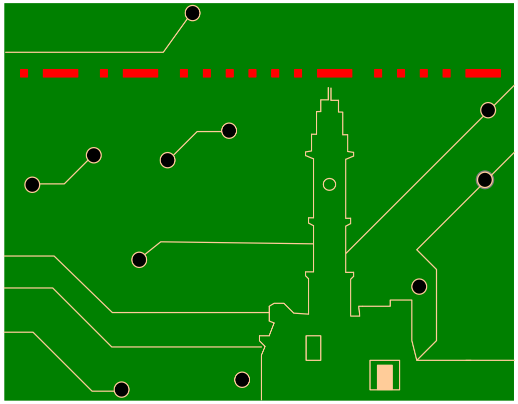

Big THANK YOU
to my students and colleagues!

Backscatter Networks for Large-Scale Environmental Sensing

Collaborators in the "Plants-as-Sensors-and-Batteries": Prof. Koutroulis, Prof. Mitianoudis, Dr. Dimitriou, Mr. Konstantopoulos, Mr. Kampianakis.

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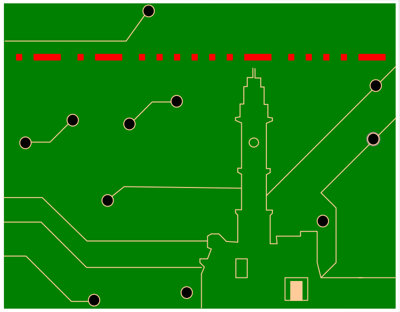

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