IC1301 -WiPE

Wireless Power Transmission for Sustainable Electronics

Reinventing Wireless with Scatter Radio for the Internet of Vegetables

WIPE
COST IC1301

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European Science Foundation
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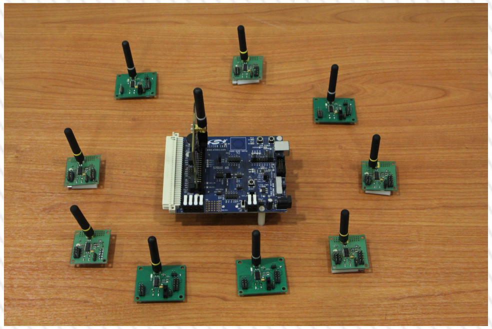
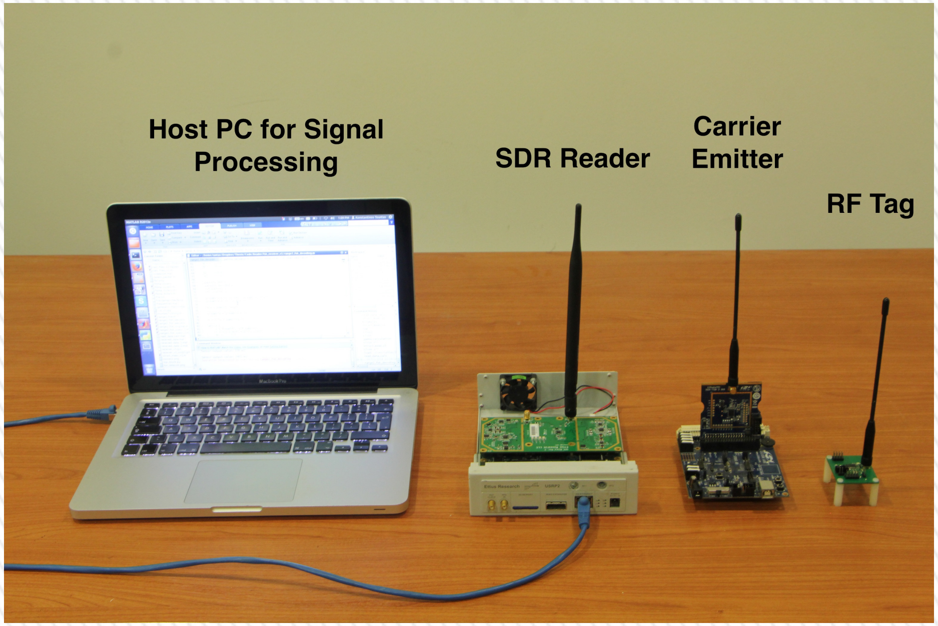
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Agenda

- » Motivation
- » Scatter Radio Advances
- » Applications
- » Conclusion





Motivation: Networking all plants in a greenhouse/ garden/field!

Why?

- Water saving:
  precise irrigation.

- Plant health monitoring:
  precision agriculture.

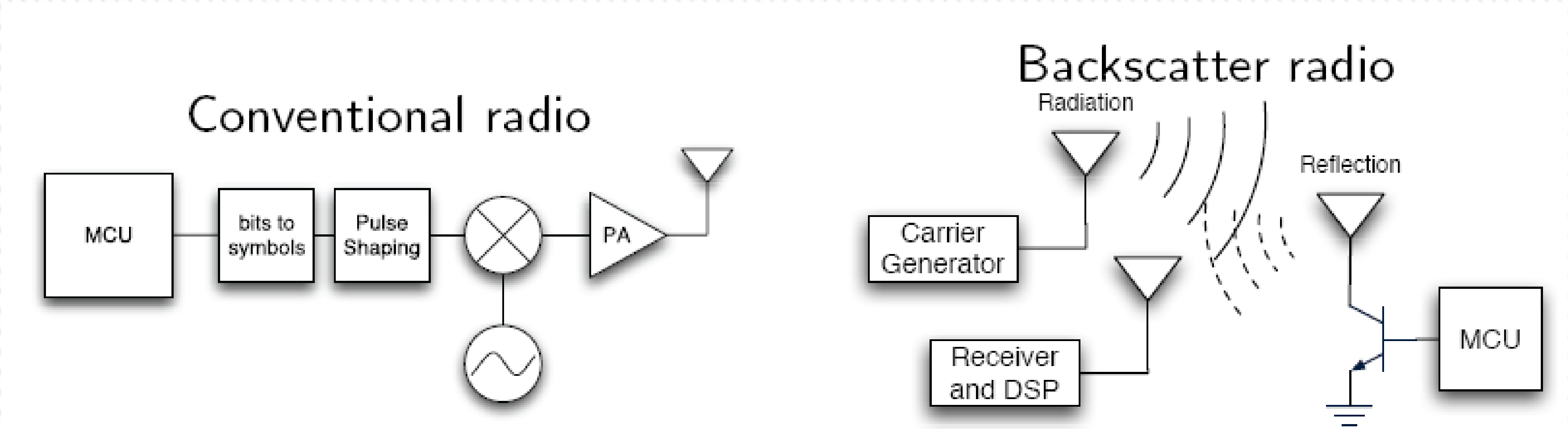
Challenge?

- Reduce cost (in $$$ and Joules) of wireless networking.

State-of-the-Art (2013) Commercial (French) Technology...

- Humidity, temperature and sunlight to mobile (Bluetooth).
- Problem: what about 10000 plants?

Approach: Backscatter or Scatter (Reflection) Radio



- Conventional Radio Transmitter:
  filters, mixers, amplifiers…
- ~20mA (60mW), 100m – 1km range.

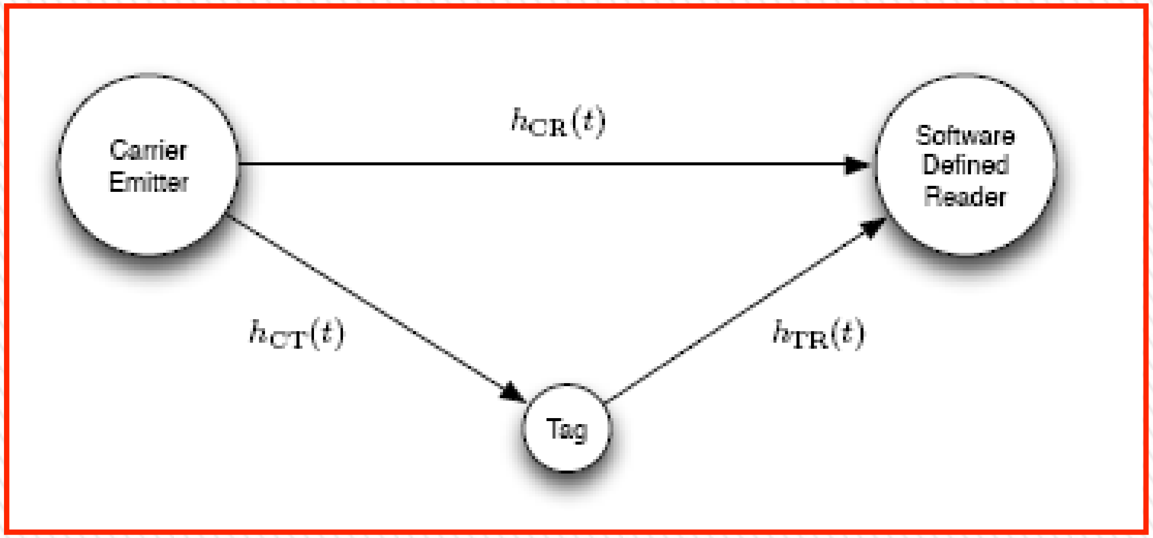
- Backscatter Radio Transmitter:
  just 1 (transistor) switch! [1]
- less than 0.6mA, range???

Scatter Radio Signal Model

- Flexible, general notation: monostatic or bistatic…

$$h_{\mathrm{CR}}(t) \triangleq a_{\mathrm{CR}}\ \delta(t-\tau_{\mathrm{CR}})$$
$$h_{\mathrm{CT}}(t) \triangleq a_{\mathrm{CT}}\ \delta(t-\tau_{\mathrm{CT}})$$
$$h_{\mathrm{TR}}(t) \triangleq a_{\mathrm{TR}}\ \delta(t-\tau_{\mathrm{TR}})$$

$$\phi_{\mathrm{CR}} \triangleq 2\pi F_c \tau_{\mathrm{CR}}$$
$$\phi_{\mathrm{CT}} \triangleq 2\pi F_c \tau_{\mathrm{CT}}$$
$$\phi_{\mathrm{TR}} \triangleq 2\pi F_c \tau_{\mathrm{TR}}$$



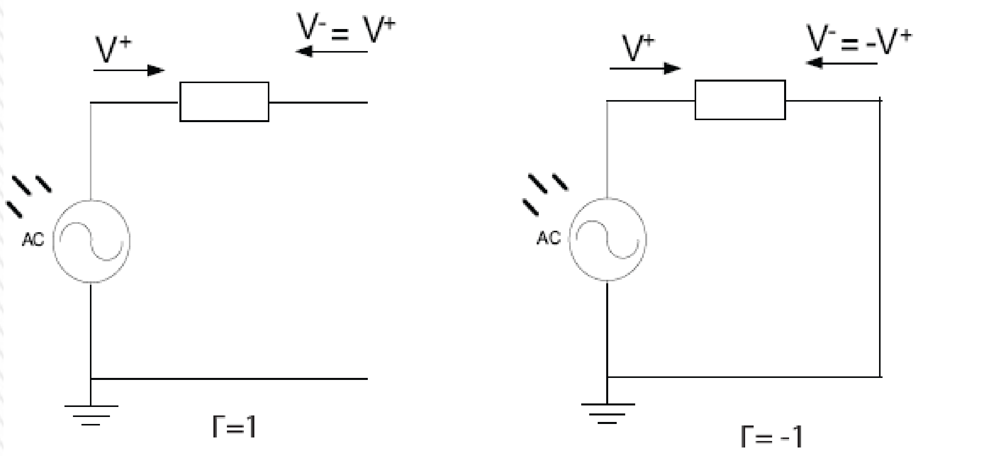
CFO ΔF ≠ 0 bistatic, ΔF = 0 monostatic

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

$$\hat{\phi}_{\mathrm{CR}} \triangleq \phi_{\mathrm{CR}} + \phi_R, \quad \hat{\phi}_{\mathrm{CTR}} \triangleq \phi_{\mathrm{CT}} + \phi_{\mathrm{TR}} + \phi_R$$

Tag Modulation with Reflection: Example

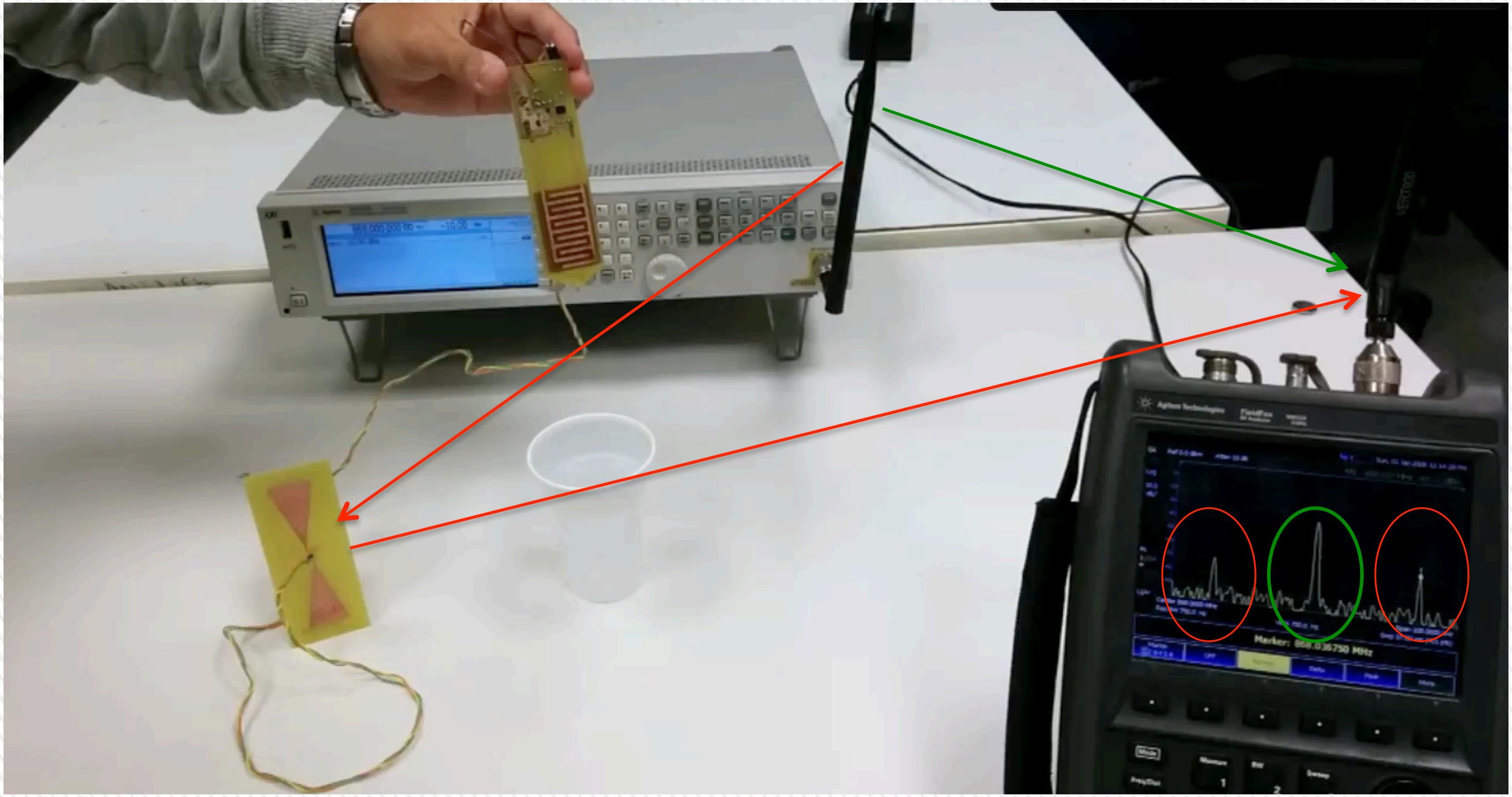
- Simplest case: open and short-circuit load.



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

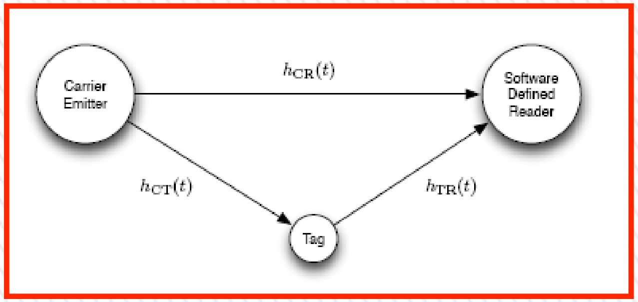
- OOK: switch and stay at each load for bit duration (Gen2).
- FSK: switch between the loads with different switching freq. per symbol.
- Different loads may offer both amplitude and phase modulation at PASSBAND (carrier) signal!

Tag Modulation with Reflection: Freq. Modulation Example



- Switch between two loads at frequency F: how many freqs are reflected?
- Answer: $F_c \pm F$ (and not just $F_c + F$ or $F_c - F$)!
- FSK: $\pm F_0$ for bit '0', $\pm F_1$ for bit '1' (need for 4 matched filters, not 2)!

Tag Modulation with Reflection Models



CFO due to bistatic

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

OOK

$$x(t) = (A_s - \frac{\Gamma_0 + \Gamma_1}{2}) + \frac{\Gamma_0 - \Gamma_1}{2} \sum_{n=0}^{N-1} x_n\ \Pi(t - nT)$$

$x_n \in \{-1, +1\}$

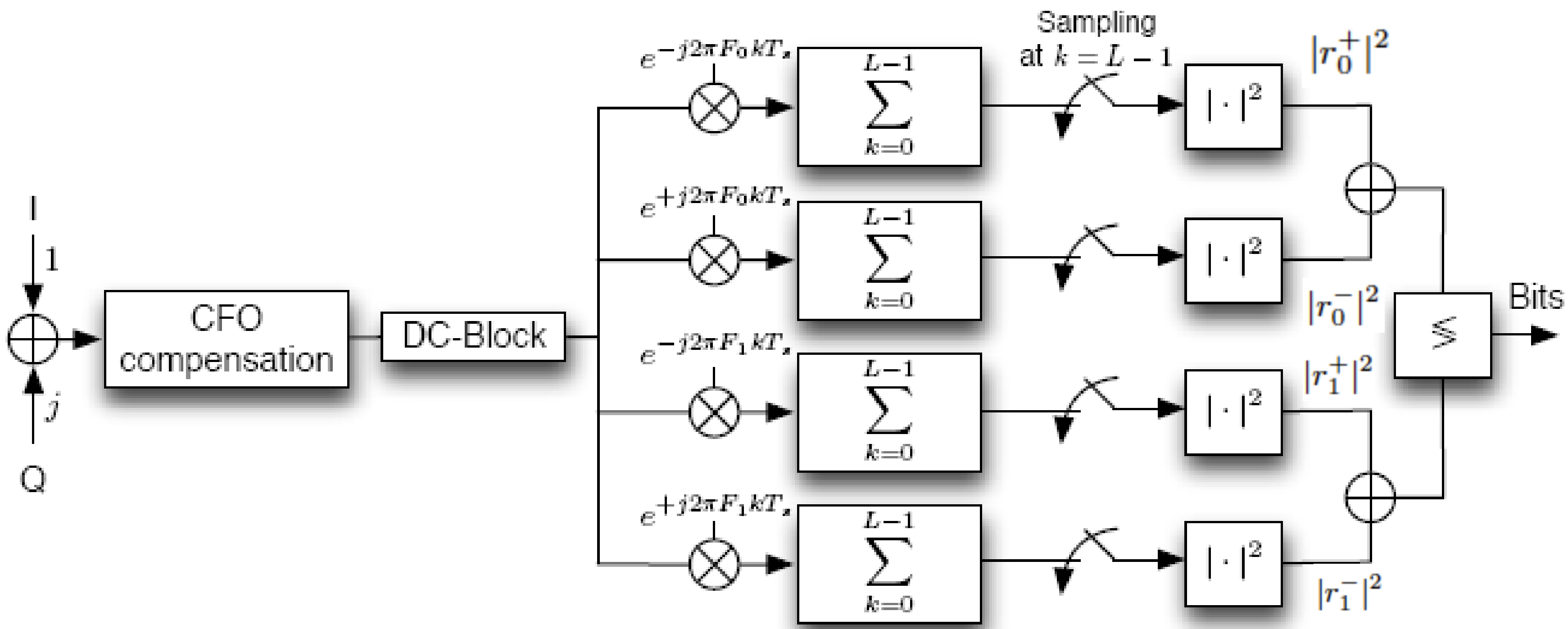
FSK

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

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

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]

Non-coherent sequence (FEC-coded) BFSK scatter radio reception

- 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]:

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

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

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

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

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

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

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

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

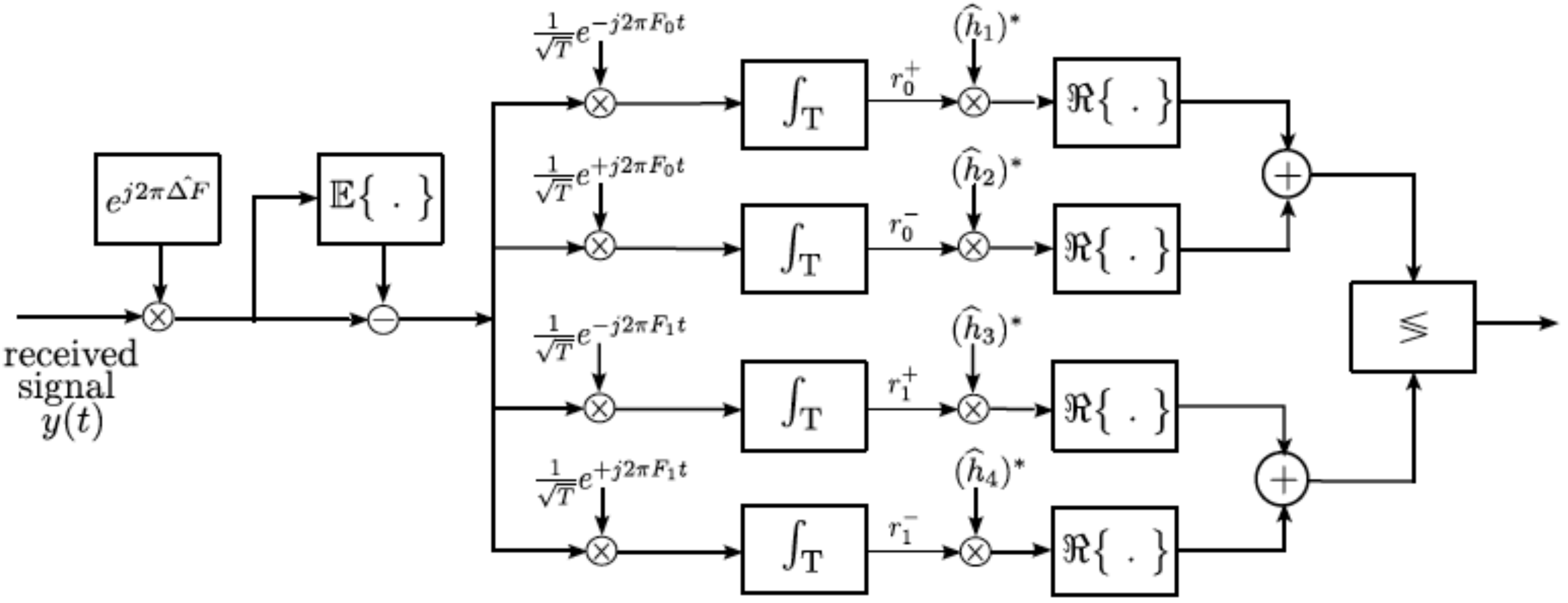
- YES! All unknowns can be squeezed under mild assumptions in a single 4x1 complex vector **h** [26] [9] that can be estimated with LS technique!

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

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

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

Coherent Binary FSK scatter radio reception

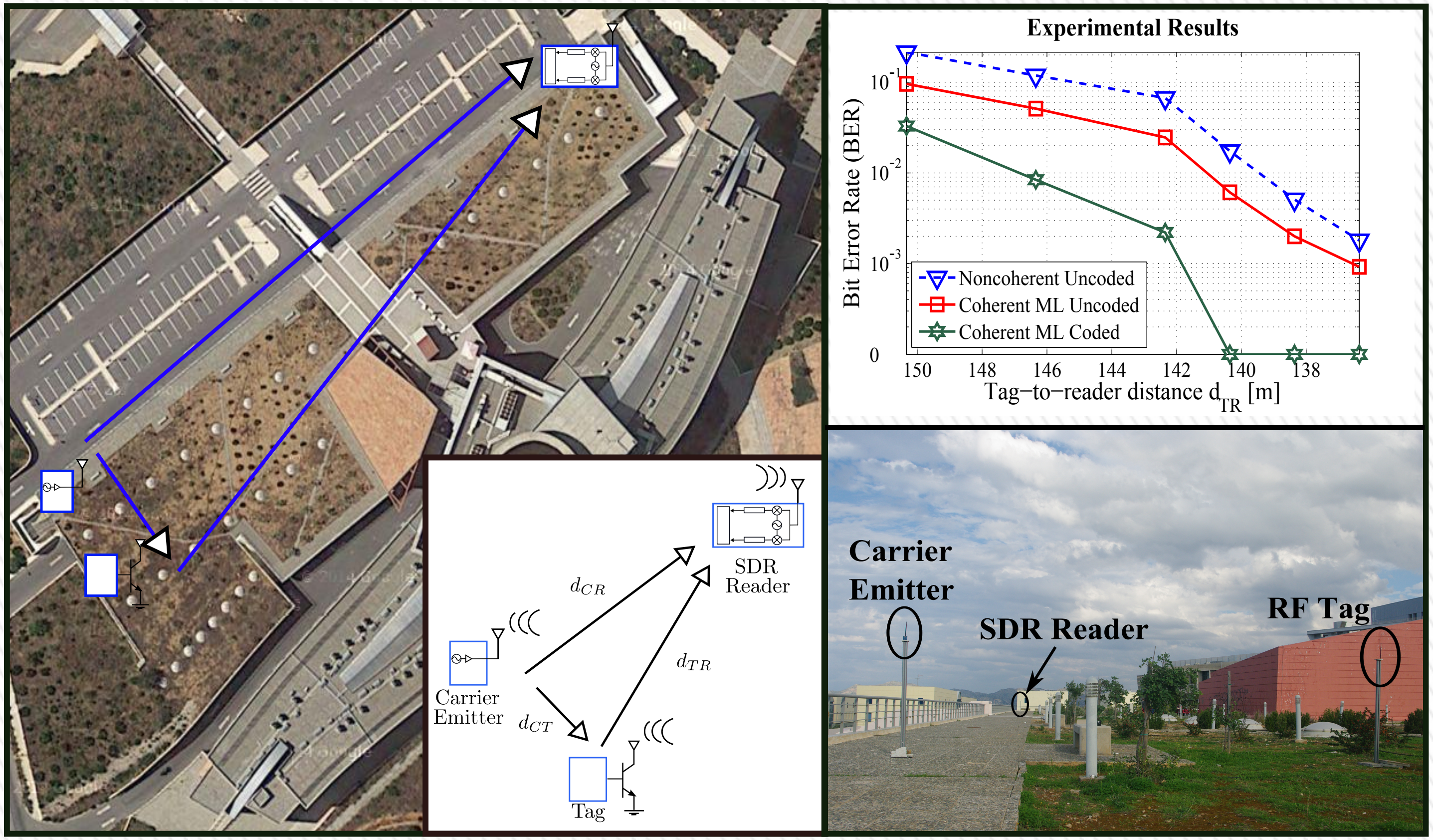


$$b_i^{\mathrm{ML}} = \underset{b_i \in \{0,1\}}{\operatorname{argmax}} \ \exp\left\{ -\frac{2}{N_0} \left\| \mathbf{r} - \hat{\mathbf{h}} \odot \mathbf{s}_{b_i} \right\|_2^2 \right\}$$

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

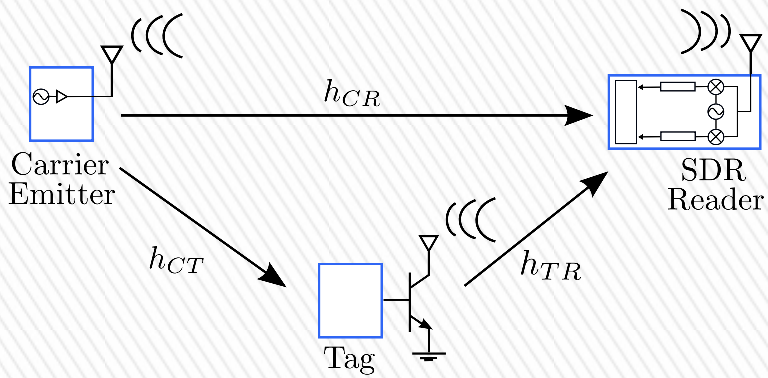
- Estimation of **h** with preambles and Least Squares.
- Minimum distance receiver has been extended to coded (sequence) setups [26] [9]!

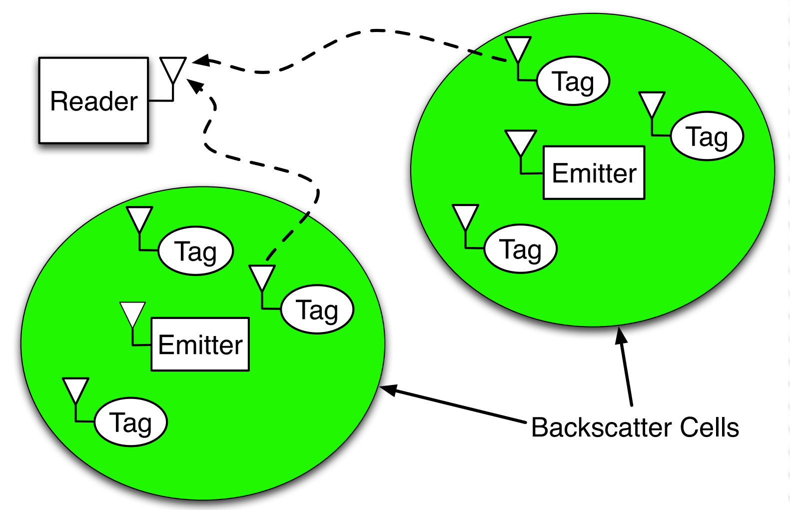
State-of-the-art Scatter Radio Technology: Range is not an issue!



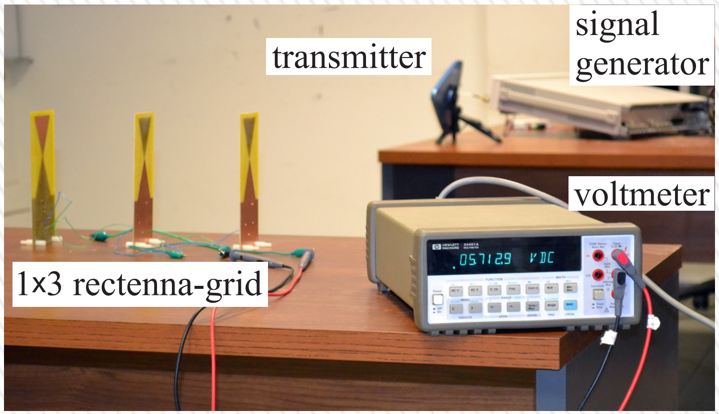
- Analog & Digital tags, with or without FEC, coherent or non-coherent scatter radio – Tesla, Marconi, Gallagher and Proakis should be very proud!

Scatter Radio Sensor Networking Advances

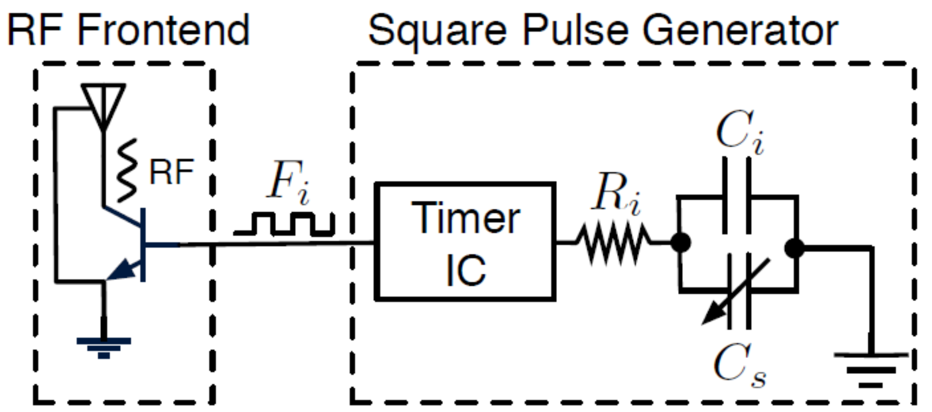


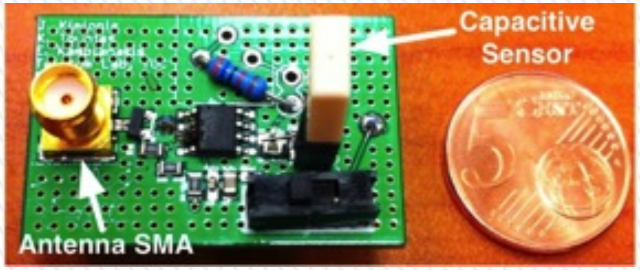


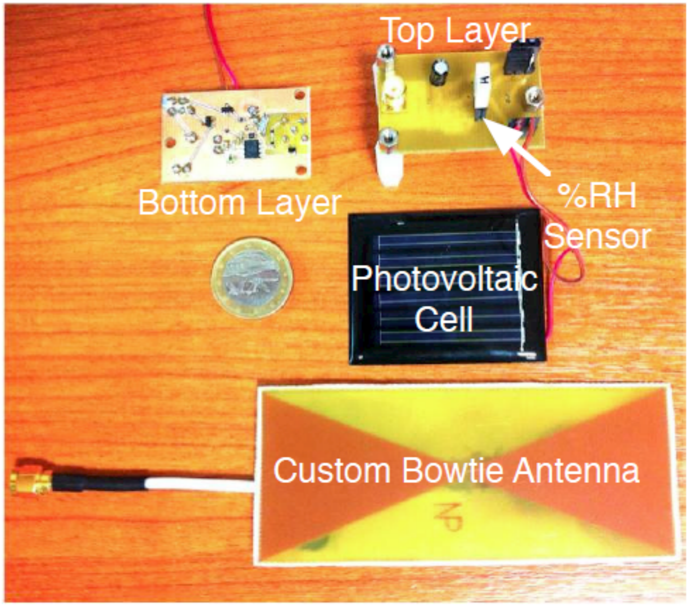
- Network advances [2]-[5]
- Detection and FEC advances (digital tags) [5]-[11], [26]
- Joint radio & sensor design (analog tags) [9]-[15]
- RF/Microwave scatter radio advances [16]-[20]
- RF harvesting advances [21]-[22]
- Energy harvesting advances (biologic batteries)
- Sensing advances [13]-[15]



Application Example 1: Analog Environmental Humidity Sensing

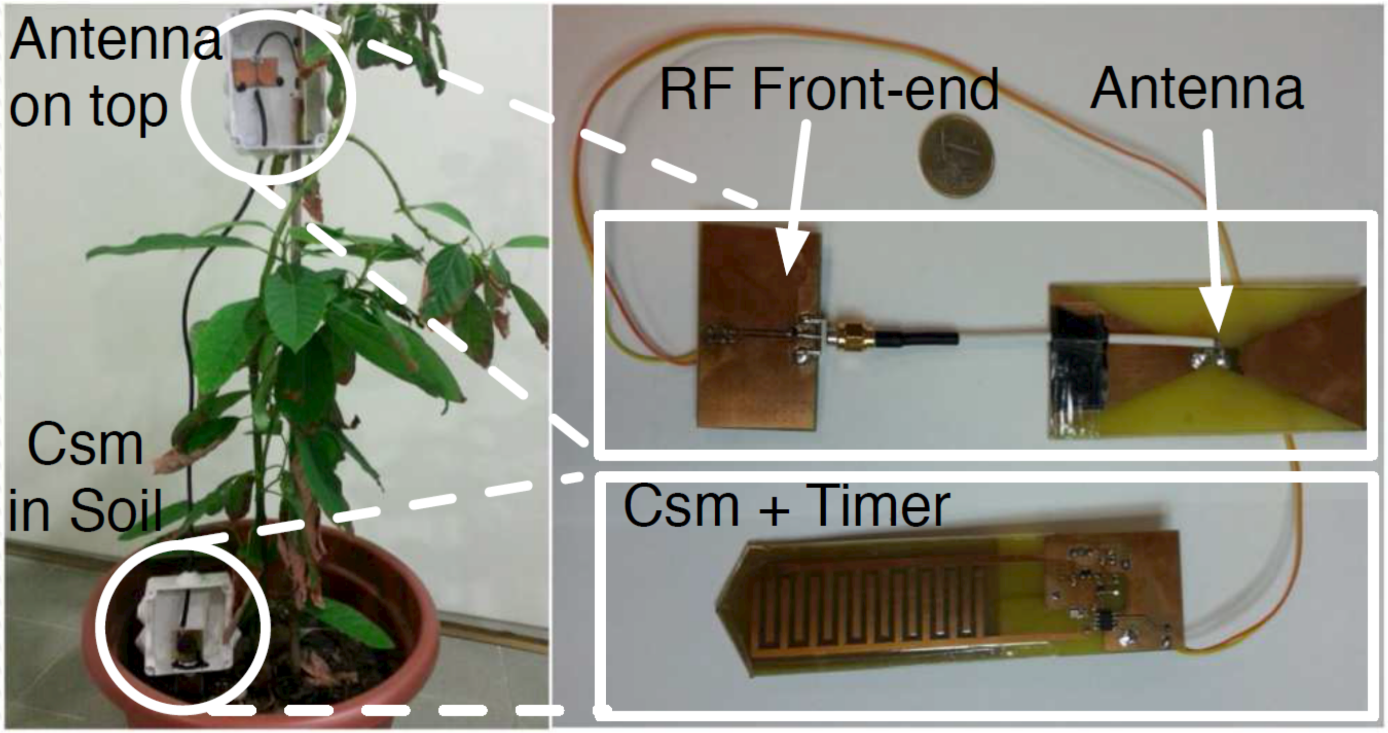






- Principle: convert capacitor changes to backscattered freq [12], [14]!
- Cost ~3€ (quantity of 1), Power 220μWatt, RMS 1-2% RH.
- Simple Networking (FDMA).

Application Example 2: Soil Moisture Sensing

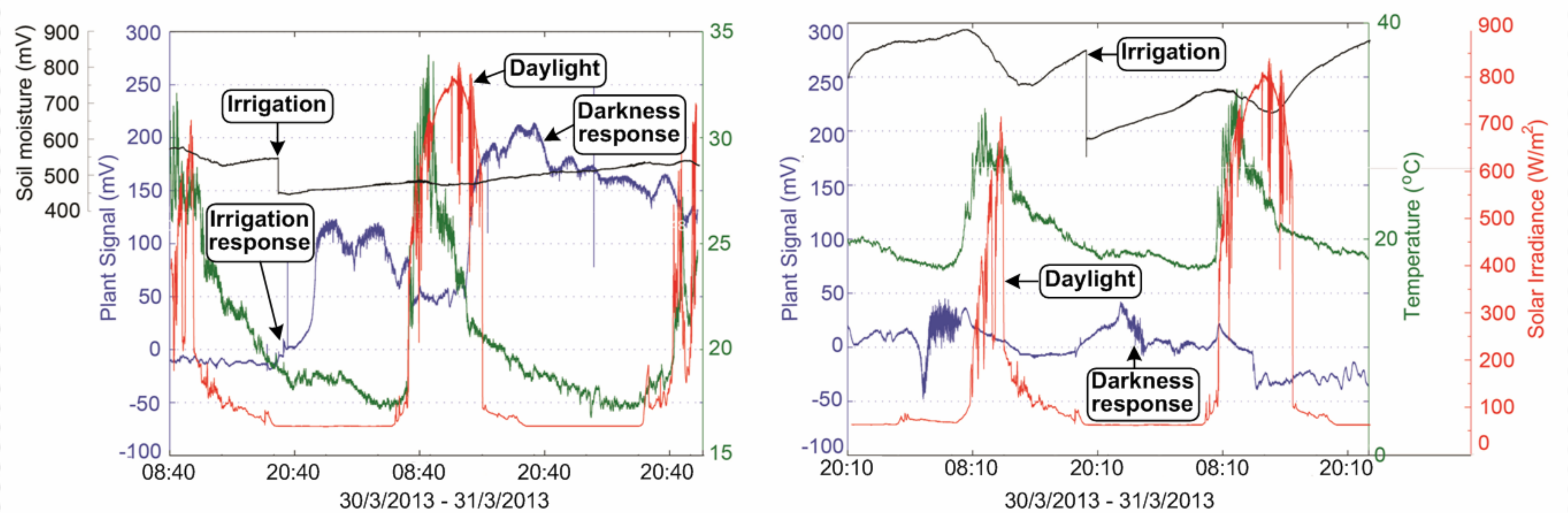


- Principle: convert capacitor changes to backscattered freq [15]!
- Cost ~5€ (quantity of 1), Power ~100μWatt, RMS 1.9% SM.
- Simple Networking (FDMA).

Application Example 3: Plant is the Sensor!

Avocado tree

Orange tree



➢ Plant Electric Potential (EP): A LOT OF INFO [13]!

Conclusion

- Extended-range Scatter Radio Sensor Networking (even for Internet of Vegetables) is FEASIBLE!
- Scatter radio modulation at PASSBAND requires careful redesign of receivers.
- Both coherent and non-coherent reception (coded or uncoded) is possible.
- Comparison of coded non-coherent vs coherent is available [10].
- Problems appeared in scatter radio helped us solve sequence detection problems in conventional radio (useful in sat and underwater com).
- Experimental scatter radio networks are already a reality.

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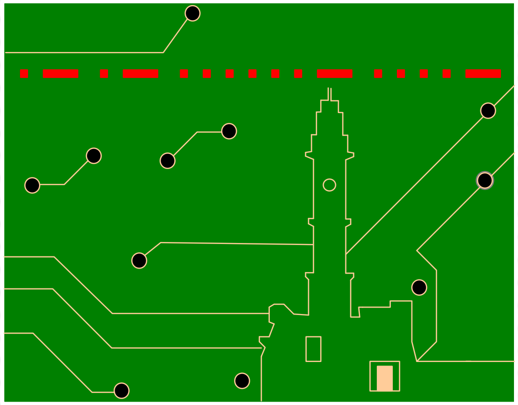

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Big THANK YOU
to my students and colleagues!

Backscatter Networks for Large-Scale Environmental Sensing

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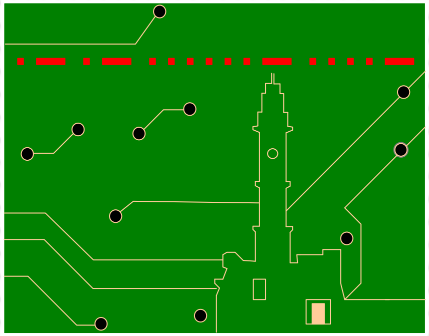

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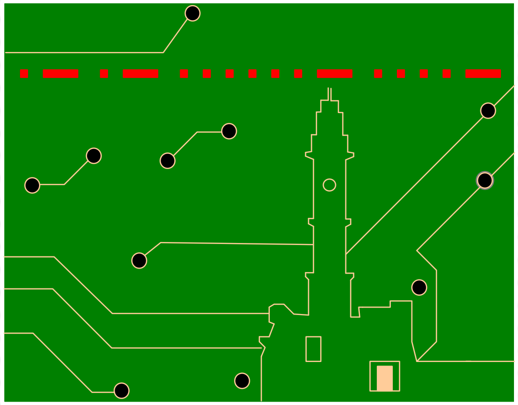

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Time for a small DEMO Video of a digital scatter radio network!