Intelligent Signal Processing for BackScatter Radio Communications & Networking

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Joint work with my students/colleagues at TU Crete.
Special thanks to P.N. Alevizos and G. Vougioukas

Nov. 8 2017

Agenda

1. BackScatter Radio: Tags/Reflectors
   - Intro
   - Fundamentals
2. BackScatter Radio: Derived Detectors
   - Symbol-by-Symbol
   - Sequence Detection
   - Notes on RFID/Gen2 and Embedded Receivers
3. BackScatter Radio: Networks/Apps
   - MultiStatic Networks for Extended Coverage
   - Networks/Apps

What? Where?

What/Where:

- **What**: "Ultra low-power communication by means of reflection - No amplifiers, mixers, filters or power-consuming *signal conditioning/processing* at the tag/reflector".
- **Where**: spy industry, RFIDs, medical implants, coming (really) low-power IoT!

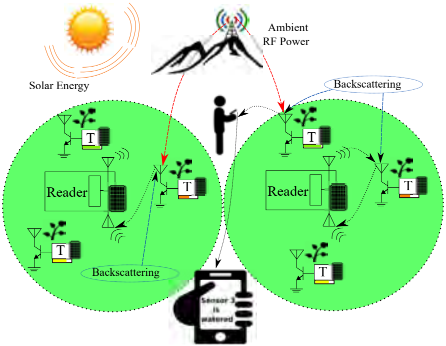
Questions for today:

- Maximum range/coverage?
- Connection to satellite/underwater communications?
- "Can you measure the water soil moisture of your favorite flower using your cellphone"?

Why?

- 1945 Theremin's "The Thing" or "Great Seal Bug" (wikipedia photos)...

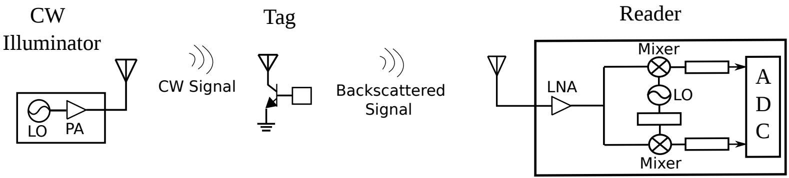
Why? Our vision...[1]



- 80-85% of total water is consumed for agriculture purposes.
- Intelligent plant irrigation: Save $\approx$ 30% of water!

[1] P. Alevizos, "Intelligent scatter radio, RF harvesting analysis, and resource allocation for ultra-low-power Internet-of-Things," Ph.D. dissertation, School of ECE, Technical University of Crete, Chania, Greece, 2017, advisor: A. Bletsas.

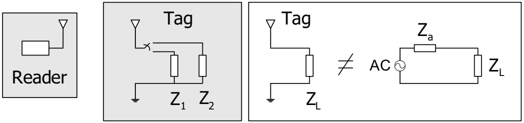
Principle: Tag Reflection



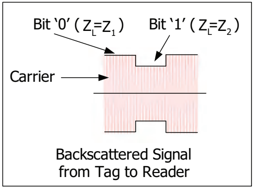
- Monostatic Architecture (RFID): illuminator + reader = same unit (common local oscillator - LO) [2], multi-antenna monostatic [3].
- Bistatic Architecture (WSNs/ambient): illuminator $\neq$ reader (distinct units).

[2] G. Vannucci, A. Bletsas, and D. Leigh, "A software-defined radio system for backscatter sensor networks", IEEE Trans. Wireless Commun., vol. 7, no. 6, pp. 2170-2179, Jun. 2008. Conf. version at IEEE PIMRC 2007, Athens, Greece.
[3] J.D. Griffin and G.D. Durgin, "Gains for RF tags using multiple antennas", IEEE Trans. Antennas Propag., vol. 56, no. 2, pp. 563-570, Feb. 2008.

Simplest case: Tag Reflection with 2 Loads

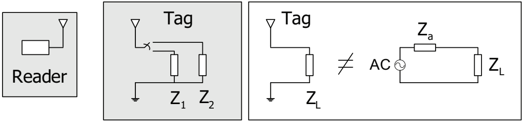


Equivalence is true only for minimum scattering antennas

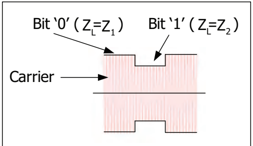


- Modified Reflection Coefficient: $\Gamma_1 = \frac{Z_2 - Z_a^*}{Z_2 + Z_a^*}$, $\Gamma_0 = \frac{Z_1 - Z_a^*}{Z_1 + Z_a^*}$, Z_a (complex) *tag antenna* characteristic impedance.
- Backscattered Tag Signal Baseband Equivalent: $A_s - \Gamma_i$, A_s (complex) load-independent tag antenna *structural* mode.

Tag Reflection with 2 Loads: OOK vs FSK

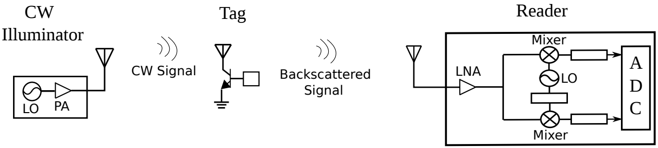


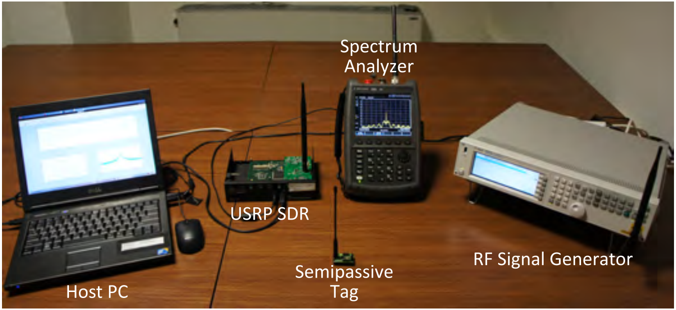
Equivalence is true only for minimum scattering antennas



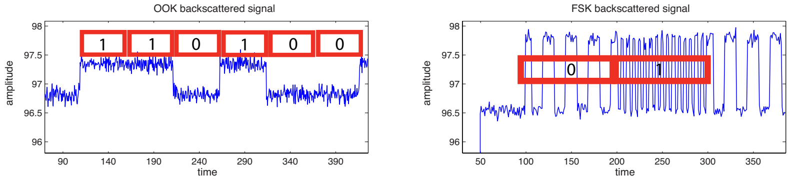
- OOK: terminate at load for whole bit duration T, i.e., Z_1 (Γ_0) for bit '0', Z_2 (Γ_1) for bit '1'.
- FSK: alternatively switch between two loads for bit duration, with switching frequency F_0 for bit '0' or F_1 for bit '1'.
  Utilize a 50% duty-cycle switching signal (with period $1/F_i$).

Tests with custom tags and SDR



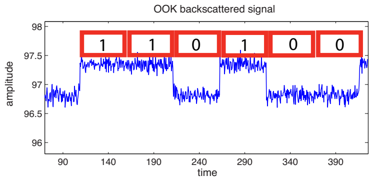


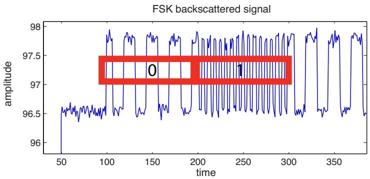
Tag Reflection with 2 Loads: OOK vs FSK



- OOK: terminate at load for whole bit duration T, i.e., Z_1 (Γ_0) for bit '0', Z_2 (Γ_1) for bit '1'.
- FSK: alternatively switch between two loads for bit duration, with switching frequency F_0 for bit '0' or F_1 for bit '1'. Utilize a 50% duty-cycle pulse-train switching signal (with period $1/F_i$).

Tag Reflection with 2 Loads: OOK Tag Equations [4–7]





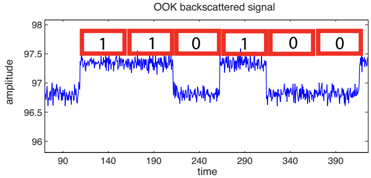
$$\text{Tag Bit n} \Rightarrow \Gamma_{\text{tag}} = \Gamma_0 \text{ for } \text{x}_\text{n} = -1, \Gamma_{\text{tag}} = \Gamma_1 \text{ for } \text{x}_\text{n} = +1 : \tag{1}$$

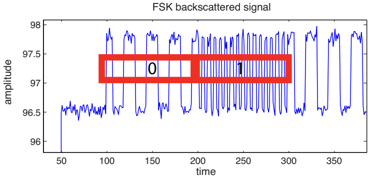
$$A_s - \Gamma_{\text{tag}} = \left(A_s - \frac{\Gamma_0 + \Gamma_1}{2}\right) + x_n \frac{\Gamma_0 - \Gamma_1}{2}, \ x_n \in \pm 1 \tag{2}$$

$$x_{Tag}(t) = \left(A_s - \frac{\Gamma_0 + \Gamma_1}{2}\right) + \frac{\Gamma_0 - \Gamma_1}{2} x_n \, \Pi_T(t - nT), \ t \in [nT, (n+1)T), \tag{3}$$

$\Pi_T(t) = 1$ for $t \in [0, T)$ and zero elsewhere.

Tag Reflection with 2 Loads: FSK Tag Equations [4–7]



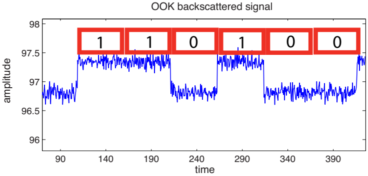


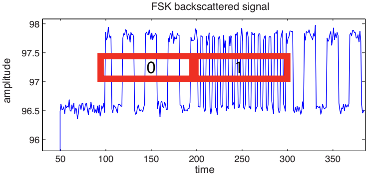
$$\mathrm{Tag\ Bit\ n} \Rightarrow \mathrm{F}^{\mathrm{sw}}_{\mathrm{tag}} \triangleq \mathrm{F}_{\mathrm{x_n}=-1} = \mathrm{F}_0, \mathrm{F}^{\mathrm{sw}}_{\mathrm{tag}} \triangleq \mathrm{F}_{\mathrm{x_n}=+1} = \mathrm{F}_1,\ \mathrm{F}_{\mathrm{x_n}} \in \{\mathrm{F}_0, \mathrm{F}_1\} \tag{4}$$

$$x_{Tag}(t) = \left(A_s - \frac{\Gamma_0 + \Gamma_1}{2}\right) + \frac{\Gamma_0 - \Gamma_1}{2}\ b_{F_{x_n}}(t - nT),\ t \in [nT, (n+1)T), \tag{5}$$

$b_F(t)$: (periodic) pulse train with fundamental frequency $F \in \{F_0, F_1\}$ and duration equal to bit duration T ($T >> \max(1/F_0, 1/F_1)$).

Tag Reflection with 2 Loads: FSK Tag Equations [4–7]





$$\mathrm{Tag\ Bit\ n} \Rightarrow \mathrm{F}^{\mathrm{sw}}_{\mathrm{tag}} \triangleq \mathrm{F}_{\mathrm{x_n}} \equiv \mathrm{F_n} \in \{\mathrm{F_0}, \mathrm{F_1}\} \tag{6}$$

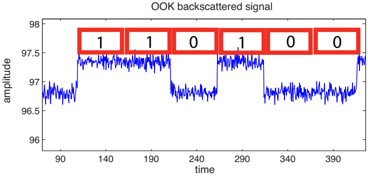
$$x_{Tag}(t) = \left(A_s - \frac{\Gamma_0 + \Gamma_1}{2}\right) + \frac{\Gamma_0 - \Gamma_1}{2}\, b_{F_n}(t - nT),\ t \in [nT, (n+1)T).$$

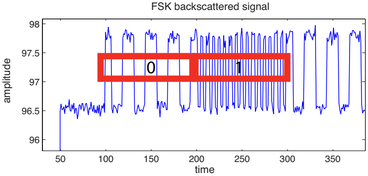
For $b_F(t)$ 50% duty-cycle, pulse train, even $b_{F_n}(t) = b_{F_n}(-t)$:

$$b_{F_n}(t) = \frac{4}{\pi} \sum_{k=0}^{+\infty} \frac{1}{2k+1} \cos\left[2\pi(2k+1)F_n t\right]. \tag{7}$$

- Only odd-order harmonics. For odd $b_F(t)$ instead, only sine terms...

Tag Reflection with 2 Loads: FSK Tag Equations [4–7]





$$\mathrm{Tag\ Bit\ n} \Rightarrow \mathrm{F}_{\mathrm{tag}}^{\mathrm{sw}} \triangleq \mathrm{F}_{\mathrm{x_n}} \equiv \mathrm{F_n} \in \{\mathrm{F_0}, \mathrm{F_1}\} \quad (8)$$

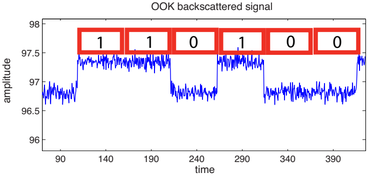
$$x_{Tag}(t) = \left(A_s - \frac{\Gamma_0 + \Gamma_1}{2}\right) + \frac{\Gamma_0 - \Gamma_1}{2}\ b_{F_n}(t - nT),\ \ t \in [nT, (n+1)T).$$

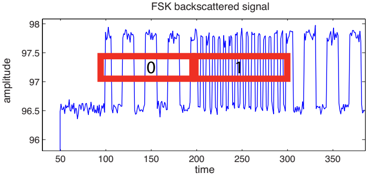
For $b_F(t)$ 50% duty-cycle, pulse train, odd $b_{F_n}(-t) = -b_{F_n}(t)$:

$$b_{F_n}(t) = \frac{4}{\pi} \sum_{k=0}^{+\infty} \frac{1}{2k+1} \sin\left[2\pi(2k+1)F_n t\right]. \quad (9)$$

- In practice, there is remaining phase Φ during tag modulation...

Tag Reflection with 2 Loads: FSK Tag Equations [4–7]





$$\text{Tag Bit n} \Rightarrow \mathrm{F}_{\mathrm{tag}}^{\mathrm{sw}} \stackrel{\triangle}{=} \mathrm{F}_{\mathrm{x_n}} \equiv \mathrm{F_n} \in \{\mathrm{F_0}, \mathrm{F_1}\} \qquad (10)$$

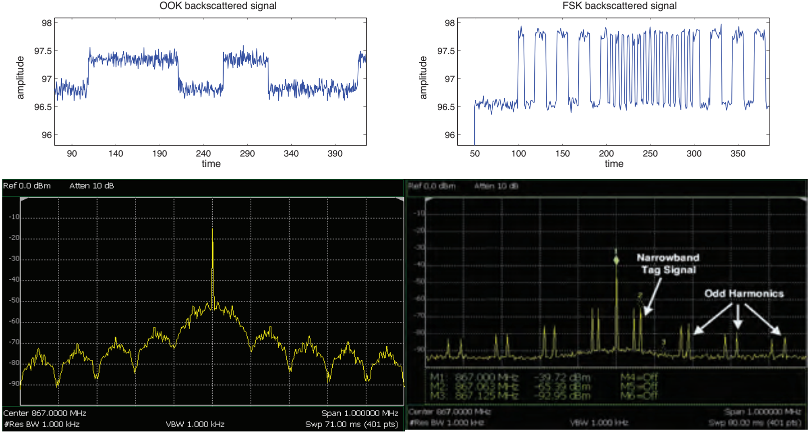
$$x_{Tag}(t) = \left(A_s - \frac{\Gamma_0 + \Gamma_1}{2}\right) + \frac{\Gamma_0 - \Gamma_1}{2}\; b_{F_n}(t - nT),\;\; t \in [nT, (n+1)T).$$

For $b_F(t)$ 50% duty-cycle, pulse train, even $b_{F_n}(t) = b_{F_n}(-t)$:

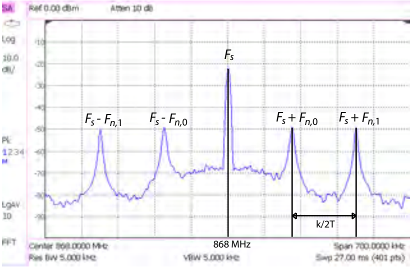
$$b_{F_n}(t) = \frac{4}{\pi} \sum_{k=0}^{+\infty} \frac{1}{2k+1} \cos\left[2\pi(2k+1)F_n t + \Phi\right]. \qquad (11)$$

- Tag (remaining) phase Φ, due to imperfect tag modulation, matters!
- Simplify notation: $b_{F_n}(t) \equiv b_n(t), n \in \{0, 1\}$.

Tag Reflection with 2 Loads: OOK vs FSK



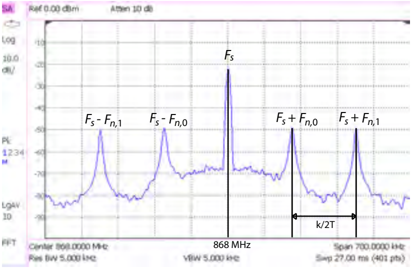
Tag Reflection with 2 Loads: OOK or FSK?



$$\{F_{\nu,0}, F_{\nu,1}\}, \nu = 1, 2, \ldots N \text{ Tags...}$$

- OOK: RFID industry (GEN2) (+), clutter around carrier freq. (-), need for receiver at Tag for CSMA (framed Aloha) (-)...

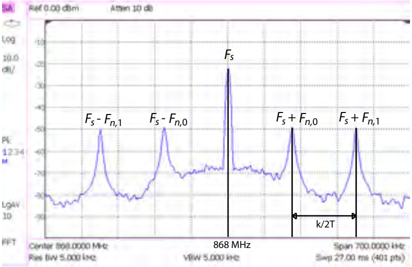
Tag Reflection with 2 Loads: OOK or FSK?



$$\{F_{\nu,0}, F_{\nu,1}\}, \nu = 1, 2, \ldots N \text{ Tags...}$$

- FSK: power-limited regime (+), easy, Tag receiver-less networking (FDMA with common carrier freq.) (+), ideal for low bitrate (bandwidth) sensors (+), non-ideal for high bitrate sensors (-)...

Tag Reflection with 2 Loads: OOK or FSK?



$$\{F_{\nu,0}, F_{\nu,1}\}, \nu = 1, 2, \ldots N \text{ Tags...}$$

- FSK: what about odd harmonics? Don't you need pulse shaping with multiple loads?

Tag Reflection and Pulse Shaping: 2 vs multiple Loads

- Answer: **NO**!

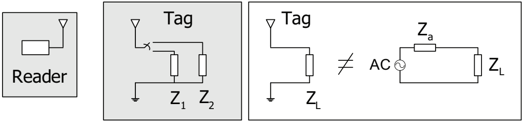
Lemma

Pulse shaping in FSK with only two loads is possible - see MSK work with backscatter radio, circa 2007 – 2008 [2]!

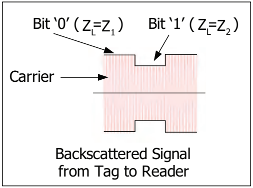
- Minimum Shift Keying (MSK): FSK without discontinuities at bit boundaries, PSD drops with fourth power of frequency - see PLL implementation in the paper above.
- Pulse shaping in FSK with multiple loads: rotating phasor that shifts tag signal spectrum at left or right of the illuminating carrier frequency [8].

[2] G. Vannucci, A. Bletsas, and D. Leigh, "A software-defined radio system for backscatter sensor networks", IEEE Trans. Wireless Commun., vol. 7, no. 6, pp. 2170-2179, Jun. 2008. Conf. version at IEEE PIMRC 2007, Athens, Greece.
[8] V. Iyer, V. Talla, B. Kellogg, S. Gollakota, and J. Smith, "Inter-technology backscatter: Towards internet connectivity for implanted devices", in Proceedings of the 2016 ACM SIGCOMM, Florianopolis, Brazil.

Tag Reflection with 2 Loads: things to remember...



Equivalence is true only for minimum scattering antennas



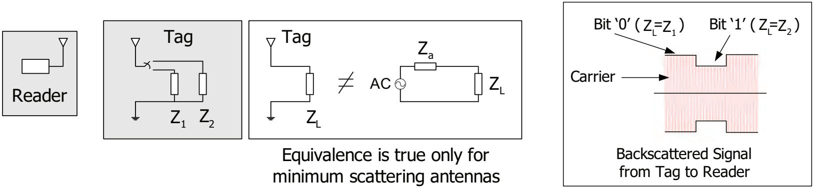
Current mindset for backscattering:

- for minimum scattering antennas only $|\Gamma_0 - \Gamma_1|$ matters!
- for *coherent* (i.e., minimum distance) detection, $|(A_s - \Gamma_0) - (A_s - \Gamma_1)| = |\Gamma_1 - \Gamma_0|$ matters!

However,

- For non-minimum scattering antennas [9] or certain house keeping tasks *before* detection, A_s matters... controls the carrier...
- ...think of bistatic setups, where emitter-to-reader link is blocked... CFO estimation?

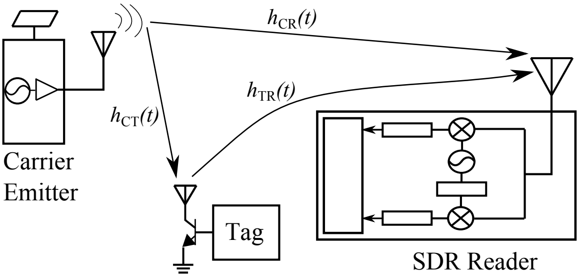
Tag Reflection with 2 Loads: things to remember...



- Measurement method for A_s estimation can be found in [9].

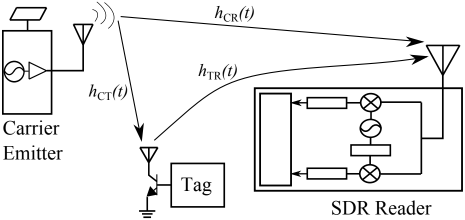
[9] A. Bletsas, A. G. Dimitriou, and J. Sahalos, "Improving backscatter radio tag efficiency", IEEE Trans. Microw. Theory Techn., vol. 58, no. 6, pp. 1502 - 1509, Jun. 2010.

Wireless Model



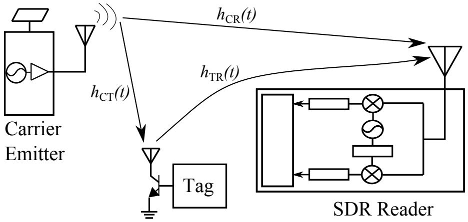
- Flat fading: $h_{\mathrm{m}}(t) = h_{\mathrm{m}},\ \mathrm{m} \in \{\mathrm{CR}, \mathrm{CT}, \mathrm{TR}\}$.
- $h_{\mathrm{m}}(t) = a_{\mathrm{m}}\delta(t - \tau_{\mathrm{m}})$, modeling channel amplitude and phase...
- This work can model asymmetric scenarios (as in *ambient*)...

Wireless Fading Models Assumed



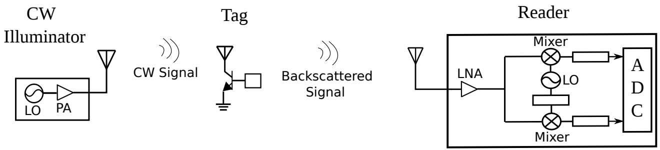
- Flat Rician fading: $h_{\mathrm{m}}(t) = h_{\mathrm{m}} \sim \mathcal{CN}\left(\sqrt{\frac{\kappa_{\mathrm{m}}}{\kappa_{\mathrm{m}}+1}}\sigma_{\mathrm{m}}, \frac{\sigma_{\mathrm{m}}^2}{\kappa_{\mathrm{m}}+1}\right)$, $\mathrm{m} \in \{\mathrm{CR}, \mathrm{CT}, \mathrm{TR}\}$.
- Similarly, flat Nakagami fading will be also assumed...
- This work can model asymmetric scenarios (as in *ambient*)...

Wireless Model



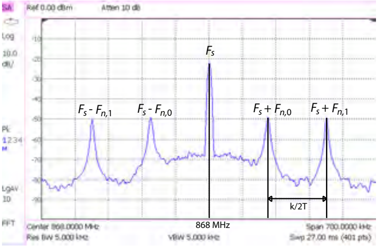
- Carrier emitter: $\mathrm{c}(t) = \sqrt{2P_{\mathrm{C}}}\, \mathrm{e}^{-\mathrm{j}(2\pi\Delta F t + \Delta\phi)}$, modeling CFO ($\Delta F = 0$ for monostatic).
- Tag backscatters:
$x^{i}_{\mathrm{Tag}}(t) = \left(\left(A_s - \frac{\Gamma_0+\Gamma_1}{2}\right) + \frac{\Gamma_0-\Gamma_1}{2}\,\mathrm{b}_i(t)\right)\,\mathrm{s}\, a_{\mathrm{CT}}\, \mathrm{e}^{-\mathrm{j}\phi_{\mathrm{CT}}}\mathrm{c}(t),\ \ i \in \mathbb{B}.$
- Reader receives:
$\mathrm{y}(t) = a_{\mathrm{CR}}\, \mathrm{e}^{-\mathrm{j}\phi_{\mathrm{CR}}}\, \mathrm{c}(t) + a_{\mathrm{TR}}\, \mathrm{e}^{-\mathrm{j}\phi_{\mathrm{TR}}}\, x^{i}_{\mathrm{Tag}}(t) + \mathrm{n}(t).$

RFID/Backscatter Radio Inherent Problems



- Inherent problems:
  - Large path-loss attenuation $\Longrightarrow$ Limited range.
  - Passive tags $\Longrightarrow$ Powering issues $\Longrightarrow$ Limited range.
  - High bitrate $\Longrightarrow$ Reduced energy per bit $\Longrightarrow$ Limited range.
- This work:
  - Short-packet communication.
  - Optimal receiver design for scatter radio signals.

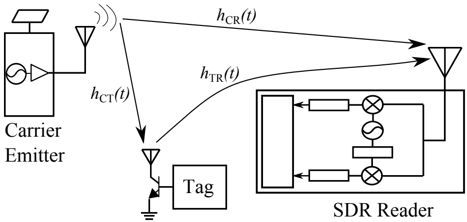
2-load Tag Reflection Principles Reminder!



$$\{F_{\nu,0}, F_{\nu,1}\}, \nu = 1, 2, \ldots N \text{ Tags...} \tag{12}$$

- Switching between two loads with rate $F_i, i \in \{0, 1\}$ results to $F_c \pm F_i$...
- 4 instead of 2 peaks $\Rightarrow$ 4 matched filters!
- Coherent detection: $|F_0 - F_1| = k/(2T)$,
  Noncoherent detection: $|F_0 - F_1| = k/T, k \in \mathcal{Z}$.

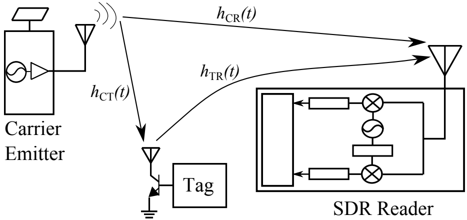
Noncoherent Bistatic FSK Symbol-by-Symbol Detector



- Decouple Emitter (illuminator) from Reader, work with (simpler) FSK [4–7].
- Caveat: no phase continuity/PSD compared to MSK [2]...

[4] J. Kimionis, A. Bletsas, and J. N. Sahalos, "Design and implementation of RFID systems with software-defined radio", in Proc. IEEE European Conf. on Antennas and Propagation (EuCAP), Prague, Czech Republic, Mar. 2012, pp. 3464-3468.
[5] —, "Bistatic backscatter radio for tag read-range extension", in Proc. IEEE RFID Techn. and Applications (RFID-TA), Nice, France, Nov. 2012.
[7] —, "Increased range bistatic scatter radio", IEEE Trans. Commun., vol. 62, no. 3, pp. 1091-1104, Mar. 2014.

Noncoherent Bistatic FSK Symbol-by-Symbol Detector



- Decouple Emitter (illuminator) from Reader, work with (simpler) FSK [4–7].
- *Ambient backscatter* (SIGCOMM Aug. 2013 [10]) is a bistatic architecture!

[4] J. Kimionis, A. Bletsas, and J. N. Sahalos, "Design and implementation of RFID systems with software-defined radio", in Proc. IEEE European Conf. on Antennas and Propagation (EuCAP), Prague, Czech Republic, Mar. 2012, pp. 3464-3468.
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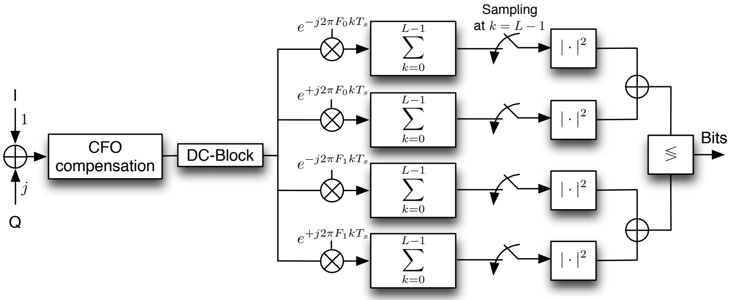
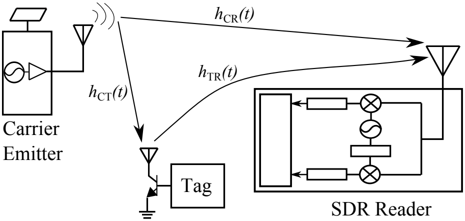
Noncoherent Symbol-by-Symbol Bistatic FSK [4–7]



- Housekeeping: periodogram-based CFO compensation, DC block...
- Detection: $|r_0^+|^2 + |r_0^-|^2$ vs $|r_1^+|^2 + |r_1^-|^2$
- Why not $|r_0^+| + |r_0^-|$ vs $|r_1^+| + |r_1^-|$???

Coherent Symbol-by-Symbol/Sequence Bistatic FSK



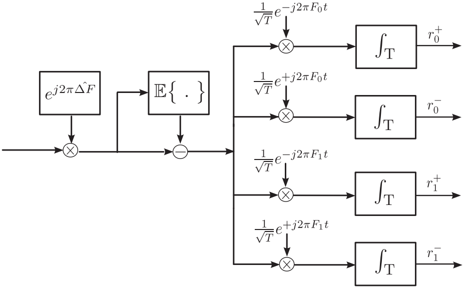
Important Simplification in [11]:

- Baseband signal for scatter radio FSK modulation [Theorem 1, [11]]:

$$\mathbf{r} = [r_0^+ \ r_0^- \ r_1^+ \ r_1^-]^\top = h\sqrt{\frac{\mathrm{E}}{2}}[\mathrm{e}^{+\mathrm{j}\Phi_0} \ \mathrm{e}^{-\mathrm{j}\Phi_0} \ \mathrm{e}^{+\mathrm{j}\Phi_1} \ \mathrm{e}^{-\mathrm{j}\Phi_1}]^\top \odot \mathbf{s}_i + \mathbf{n}. \quad (13)$$

[11] N. Fasarakis-Hilliard, P. N. Alevizos, and A. Bletsas, "Coherent detection and channel coding for bistatic scatter radio sensor networking," *IEEE Trans. Commun.*, vol. 63, pp. 1798–1810, May 2015.

Coherent Symbol-by-Symbol/Sequence Bistatic FSK [11]



$$\mathbf{r} = [r_0^+ \;\; r_0^- \;\; r_1^+ \;\; r_1^-]^\top = h\sqrt{\frac{\mathrm{E}}{2}}[\mathrm{e}^{+\mathrm{j}\Phi_0} \;\; \mathrm{e}^{-\mathrm{j}\Phi_0} \;\; \mathrm{e}^{+\mathrm{j}\Phi_1} \;\; \mathrm{e}^{-\mathrm{j}\Phi_1}]^\top \odot \mathbf{s}_i + \mathbf{n}, \quad (14)$$

$$\mathrm{E} = \kappa^2 P_{\mathrm{C}} \; |\Gamma_0 - \Gamma_1|^2 \mathrm{s}^2 T, \;\; h = a_{\mathrm{CT}} \; a_{\mathrm{TR}} \; e^{(\phi_{\mathrm{CT}}+\phi_{\mathrm{TR}}+\Delta\phi+\angle(\Gamma_0-\Gamma_1))}, \quad (15)$$

$$\mathbf{s}_i = [1-i \;\; 1-i \;\; i \;\; i]^T, \; i \in \{0,1\}, \; \mathbf{n} \sim \mathcal{CN}\left(\mathbf{0}_4, \frac{N_0}{2}\mathbf{I}_4\right). \quad (16)$$

Coherent Symbol-by-Symbol/Sequence Bistatic FSK [11]

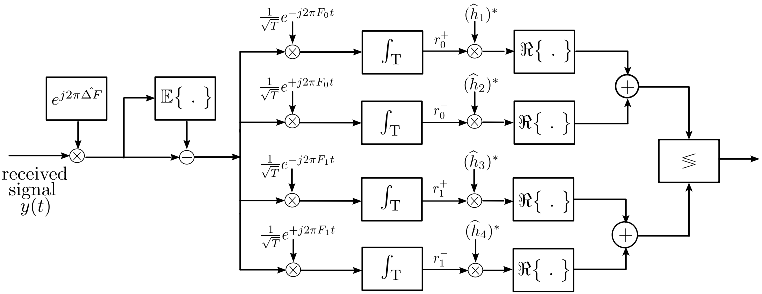
$$\mathbf{r} = [r_0^+ \; r_0^- \; r_1^+ \; r_1^-]^\top = h\sqrt{\frac{\mathrm{E}}{2}}[\mathrm{e}^{+\mathrm{j}\Phi_0} \; \mathrm{e}^{-\mathrm{j}\Phi_0} \; \mathrm{e}^{+\mathrm{j}\Phi_1} \; \mathrm{e}^{-\mathrm{j}\Phi_1}]^\top \odot \mathbf{s}_i + \mathbf{n}, \quad (17)$$

- Estimate with preamble/LS $\hat{\mathbf{h}} = \begin{bmatrix} \hat{h}_1 & \hat{h}_2 & \hat{h}_3 & \hat{h}_4 \end{bmatrix}^T$ of $\mathbf{h} = h\sqrt{\frac{\mathrm{E}}{2}}[\mathrm{e}^{+\mathrm{j}\Phi_0} \; \mathrm{e}^{-\mathrm{j}\Phi_0} \; \mathrm{e}^{+\mathrm{j}\Phi_1} \; \mathrm{e}^{-\mathrm{j}\Phi_1}]^\top$.
- Perform ML:

$$b_i^{\mathrm{ML}} = \arg \max_{b_i \in \{0,1\}} \exp\left\{-\frac{2}{N_0}||\mathbf{r} - \hat{\mathbf{h}} \odot \mathbf{s}_{b_i}||^2\right\} \quad (18)$$

$$\Leftrightarrow \mathcal{R}\left((\hat{h}_1)^* r_0^+ + (\hat{h}_2)^* r_0^-\right) \overset{\text{bit } 0}{\geq} \mathcal{R}\left((\hat{h}_3)^* r_1^+ + (\hat{h}_4)^* r_1^-\right) \quad (19)$$

Coherent Symbol-by-Symbol/Sequence Bistatic FSK [11]



- ML Symbol-by-Symbol detector (above)...
- ML Sequence detector also tested with Reed-Muller (RM) and BCH channel coded sequences!

Noncoherent Symbol-by-Symbol Bistatic FSK: HCHT

Work in [12], [13]:

- Statistics: $\mathrm{f}(\mathbf{r}|i, h, \mathbf{\Phi}) \equiv \mathcal{CN}\left(h\, \mathbf{x}_i(\mathbf{\Phi}), N_0\, \mathbf{I}_4\right)$, with $\mathbf{x}_i(\mathbf{\Phi}) = \sqrt{\frac{\mathrm{E}}{2}} \left[\mathrm{e}^{+\mathrm{j}\Phi_0}, \mathrm{e}^{-\mathrm{j}\Phi_0}, \mathrm{e}^{+\mathrm{j}\Phi_1}, \mathrm{e}^{-\mathrm{j}\Phi_1}\right]^\top \odot \mathbf{s}_i,\ \ i \in \mathbb{B}$.

Lemma

Noncoherent Hybrid Composite Hypothesis-Testing (HCHT) Symbol-By-Symbol FSK Detection:

$$\arg\max_{i \in \mathbb{B}} \left\{ \mathop{\mathbb{E}}_{\mathbf{\Phi}} \left[\max_{h \in \mathbb{C}} \ln[\mathrm{f}(\mathbf{r}|i, h, \mathbf{\Phi})] \right] \right\} \Longleftrightarrow |r_0^+|^2 + |r_0^-|^2 \underset{i=1}{\overset{i=0}{\gtrless}} |r_1^+|^2 + |r_1^-|^2. \quad (20)$$

[12] P. N. Alevizos and A. Bletsas, "Noncoherent composite hypothesis testing receivers for extended range bistatic scatter radio WSNs," in *Proc. IEEE Int. Conf. on Commun.*, London, U.K., Jun. 2015.
[13] P. N. Alevizos, A. Bletsas, and G. N. Karystinos, "Noncoherent short packet detection and decoding for scatter radio sensor networking," *IEEE Trans. Commun.*, vol. 65, no. 5, pp. 2128-2140, May 2017.

Noncoherent Symbol-by-Symbol Bistatic FSK: GLRT

Work in [12], [13]:

- Statistics: $\mathrm{f}(\mathbf{r}|i, h, \mathbf{\Phi}) \equiv \mathcal{CN}\left(h\,\mathbf{x}_i(\mathbf{\Phi}), N_0\,\mathbf{I}_4\right)$, with $\mathbf{x}_i(\mathbf{\Phi}) = \sqrt{\frac{\mathrm{E}}{2}}\left[\mathrm{e}^{+\mathrm{j}\Phi_0}, \mathrm{e}^{-\mathrm{j}\Phi_0}, \mathrm{e}^{+\mathrm{j}\Phi_1}, \mathrm{e}^{-\mathrm{j}\Phi_1}\right]^\top \odot \mathbf{s}_i,\;\; i \in \mathbb{B}$.

Theorem

Noncoherent Generalized Likelihood-Ratio Test (GLRT) Symbol-By-Symbol FSK Detection:

$$\arg\max_{i\in\mathbb{B}}\left\{\max_{\mathbf{\Phi}\in[0,2\pi)^2}\max_{h\in\mathbb{C}}\ln[\mathrm{f}(\mathbf{r}|i,h,\mathbf{\Phi})]\right\} \Longleftrightarrow |r_0^+| + |r_0^-| \underset{i=1}{\overset{i=0}{\gtrless}} |r_1^+| + |r_1^-|. \tag{21}$$

[12] P. N. Alevizos and A. Bletsas, "Noncoherent composite hypothesis testing receivers for extended range bistatic scatter radio WSNs," in *Proc. IEEE Int. Conf. on Commun.*, London, U.K., Jun. 2015.
[13] P. N. Alevizos, A. Bletsas, and G. N. Karystinos, "Noncoherent short packet detection and decoding for scatter radio sensor networking," *IEEE Trans. Commun.*, vol. 65, no. 5, pp. 2128-2140, May 2017.

Noncoherent Uncoded Sequence Detector: GLRT

- Static environments: Coherence time $\geq$ Packet duration.
- Transmitted sequence: $\mathbf{i} = [i_1 \ i_2 \ \ldots \ i_{N_\mathrm{s}}]^\top \in \mathbb{B}^{N_\mathrm{s}}$.
- Received sequence: $\mathbf{r}_{1:N_\mathrm{s}}$ with statistics

$$\mathrm{f}(\mathbf{r}_{1:N_\mathrm{s}} | \mathbf{i}, h, \mathbf{\Phi}) \equiv \mathcal{CN}\left(h\, \mathbf{x}_{\mathbf{i}}(\mathbf{\Phi}), N_0\, \mathbf{I}_{4N_\mathrm{s}}\right). \quad (22)$$

- GLRT sequence detector:

$$\mathbf{i}_{\mathrm{GLRT}} = \arg \max_{\mathbf{i} \in \mathbb{B}^{N_\mathrm{s}}} \max_{\mathbf{\Phi} \in [0, 2\pi)^2} \max_{h \in \mathbb{C}} \ln[\mathrm{f}(\mathbf{r}_{1:N_\mathrm{s}} | \mathbf{i}, h, \mathbf{\Phi})]. \quad (23)$$

Theorem

There exists algorithm that finds $\mathbf{i}_{\mathrm{GLRT}}$ with complexity $\mathcal{O}(N_\mathrm{s} \log N_\mathrm{s})$, based on [14], [15], instead of $\mathcal{O}(2^{N_\mathrm{s}})$

[15] P. N. Alevizos, Y. Fountzoulas, G. N. Karystinos, and A. Bletsas, "Log-linear-complexity GLRT-optimal noncoherent sequence detection for orthogonal and RFID-oriented modulations," *IEEE Trans. Commun.*, vol. 64, no. 4, pp. 1600–1612, Apr. 2016. Conf. version [14] received ICASSP 2015 Best Paper Award.

Noncoherent Coded Sequence Detector: HCHT

- Diminish long-bursts of fading: *interleaving* of depth D.
- Baseband coded signal using interleaving [16], [12], [13]:

$$\mathbf{r}_{1:N_c} = \begin{bmatrix} \mathbf{r}_1 \\ \mathbf{r}_2 \\ \vdots \\ \mathbf{r}_{N_c} \end{bmatrix} = \begin{bmatrix} h_1 \mathbf{x}_{c_1}(\boldsymbol{\Phi}) \\ h_2 \mathbf{x}_{c_2}(\boldsymbol{\Phi}) \\ \vdots \\ h_{N_c} \mathbf{x}_{c_{N_c}}(\boldsymbol{\Phi}) \end{bmatrix} + \begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \\ \vdots \\ \mathbf{n}_{N_c} \end{bmatrix}. \tag{24}$$

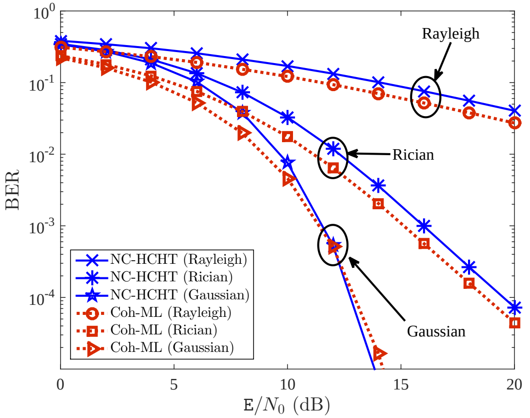
Theorem ([12], [13])

For $DT \geq T_{\mathrm{coh}}$, noncoherent HCHT soft-decision decoding

$$\arg\max_{\mathbf{c}\in\mathcal{C}} \left\{ \mathbb{E}_{\boldsymbol{\Phi}} \left[\max_{\mathbf{h}\in\mathbb{C}^{N_c}} \ln[\mathrm{f}(\mathbf{r}_{1:N_c}|\mathbf{c},\mathbf{h},\boldsymbol{\Phi})] \right] \right\} \Longleftrightarrow \arg\max_{\mathbf{c}\in\mathcal{C}} \sum_{n=1}^{N_c} w_n c_n, \tag{25}$$

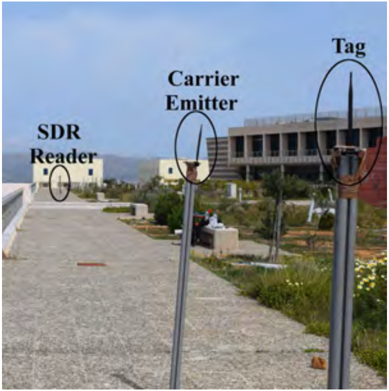
where $w_n \triangleq |r_1^+(n)|^2 + |r_1^-(n)|^2 - \left(|r_0^+(n)|^2 + |r_0^-(n)|^2\right)$, $n = 1, 2, \ldots, N_c$.

Numerical Results (1/2)



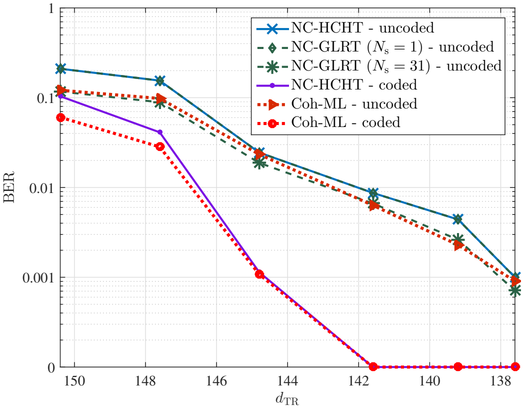
- Bit duration $T = 1$ msec, $T_{\text{coh}} = 100$ msec, 30 preamble (training) bits, 100-bit packet.

Experimental Results (1/2)



- $P_{\mathrm{TX}} = 13$ dBm, receiver NF=$7-12$ dB, $d_{\mathrm{CT}} = 8$ m, $T = 1$ msec, $F_1 = 2F_0 = 250$ kHz, 16 training (preamble) + 31 data coded bits.

Experimental Results (2/2)



- Housekeeping: Energy-based synchronization, Periodogram-based CFO estimation.

A note on RFID/Gen2

RFID industry Gen2 incorporates Miller and FM0 line coding. In FM0:

- level (line) always changes at bit boundaries...
- level (line) changes in the middle of bit, when bit is '0'...
- Gen2 exploits OOK not FSK...

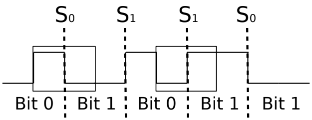


Figure: FM0 line coding.

- FM0 can be seen as orthogonal signaling...
- Technology on orthogonal signaling in the previous sections is readily applicable!

A note on RFID/Gen2

⇒ FM0 can be seen as orthogonal signaling! Observe half-bit before and half-bit after the bit of interest (totally $2T$ interval for bit duration T).

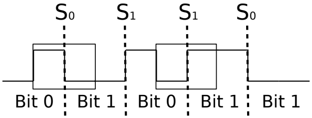
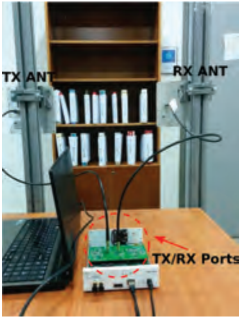


Figure: FM0 line coding.

- 2 possible T-duration orthogonal waveforms: S_0 and S_1 ⇒ 2 filters!
- $\mathbf{r} = [r_1 \;\; r_2]^T = h\sqrt{E}\;\mathbf{e}_i + \mathbf{n}$, $i \in \{0, 1\}$,
  $h \in \mathcal{C}$, $\mathbf{e}_0 = [1 \;\; 0]^T$, $\mathbf{e}_1 = [0 \;\; 1]^T$, $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, N_0\mathbf{I}_2)$

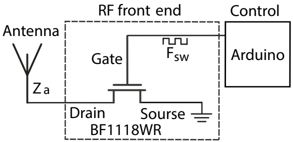
A note on RFID/Gen2

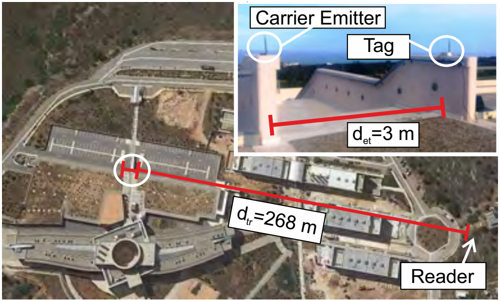


- Exploit Gen2 preambles, estimate channel and perform coherent detection with (differential) orthogonal signaling [17].
- Full SDR chain for Gen2/FM0 RFID, open source code [17]!

[17] N. Kargas, F. Mavromatis, and A. Bletsas, "Fully-coherent reader with commodity SDR for Gen2 FM0 and computational RFID," *IEEE Wireless Commun. Lett.*, vol. 4, no. 6, pp. 617–620, Dec. 2015.

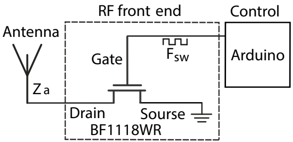
A note on Embedded Receivers [18]

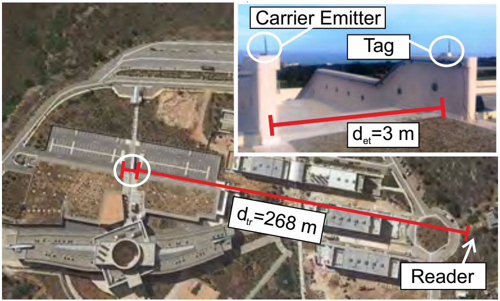




- Marconi Radio Embedded Receivers, Bistatic Architecture...
- Tag also backscatters preamble/protocol bits that embedded receiver expects...
- High sensitivity embedded receivers $\Rightarrow$ extended ranges!

A note on Embedded Receivers [18]

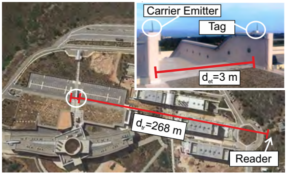




- Bluetooth low energy (BLE) receiver backscatter reception [19].
- FSK, SI1064 or TI CC1101, Tx power +13 dBm [18].

[18] G. Vougioukas, S. N. Daskalakis, and A. Bletsas, "Could battery-less scatter radio tags achieve 270-meter range?", in Proc. IEEE Wireless Power Transfer Conf. (WPTC), Aveiro, Portugal, May 2016.
[19] J. F. Ensworth and M. S. Reynolds, "Every smart phone is a backscatter reader: Modulated backscatter compatibility with bluetooth 4.0 low energy (BLE) devices", in Proc. IEEE RFID, San Diego, CA, Apr. 2015.

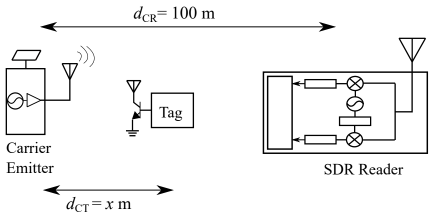
A note on Embedded Receivers [18]

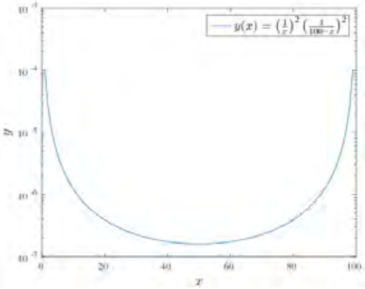


- FSK, SI1064 or TI CC1101, Tx power +13 dBm [18].
- LORA backscatter reception [20]...
- ...with about 20 dB additional illuminator Tx power and about 30 dB higher sensitivity (due to smaller bandwidth), compared to [18].
- REMEMBER: 100 times smaller rate/bandwidth ⇒ 20 dB higher sensitivity...

[20] V. Talla, M. Hessar, B. Kellogg, A. Naja, J. R. Smith and S. Gollakota,"Lora backscatter: Enabling the vision of ubiquitous connectivity", Proc. ACM Interact. Mob. Wearable Ubiquitous Technol., vol. 1, no. 3, Sep. 2017.

Bistatic (vs Monostatic) Helps!

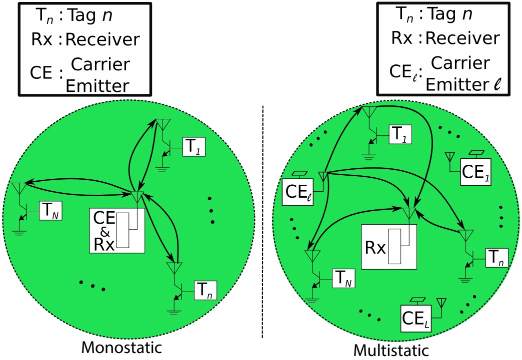




- Asymmetric scatter radio architecture can reduce path-loss:
  - $\mathrm{PL} \propto y(x) = \left(\frac{1}{x}\right)^2 \left(\frac{1}{100-x}\right)^2$.
  - $y(x)$ is minimized at $x = d/2 = 50$ m.
  - $y(x)$ increases as $x \longrightarrow 0$ or $x \longrightarrow 100$.

[1] P. Alevizos, "Intelligent scatter radio, RF harvesting analysis, and resource allocation for ultra-low-power Internet-of-things", Ph.D. dissertation, School of ECE, Technical University of Crete, Chania, Greece, 2017.

Why don't we exploit several emitters?



- Several emitters/illuminators: multistatic architecture.
- Does multistatic outperform state-of-the-art monostatic architecture?

BER & Diversity Order Analysis (1/2) [1] [21]

Theorem

Under dyadic Nakagami fading, the BER of monostatic architecture with ML coherent detection can be bounded as

$$\mathbb{P}\left(e_{l,n}^{[\mathrm{m}]}\right) \leq \frac{1}{2}\left(\frac{\mathtt{M}_n + \mathtt{M}_n^2}{2\,\mathtt{SNR}_n^{[\mathrm{m}]}}\right)^{\frac{\mathtt{M}_n}{2}} \mathsf{U}\left(\frac{\mathtt{M}_n}{2}, \frac{1}{2}, \frac{\mathtt{M}_n + \mathtt{M}_n^2}{2\,\mathtt{SNR}_n^{[\mathrm{m}]}}\right), \qquad (26)$$

where $\mathtt{M}_n$ is the Nakagami parameter for link TR, and $\mathsf{U}(\cdot,\cdot,\cdot)$ is given in [Eq. (13.4.4), 10], and $\mathtt{SNR}_n^{[\mathrm{m}]}$ is the average received SNR for monostatic system.
For dyadic Rayleigh fading ($\mathtt{M}_n = 1$), the diversity order is $\frac{1}{2}$.

- The above BER bound coincides with noncoherent envelope monostatic scatter radio detection!

[10] F. W. J. Olver *et. al*, *NIST handbook of mathematical functions*, 2010.

BER Analysis & Diversity Order (2/2)[1] [21]

Theorem

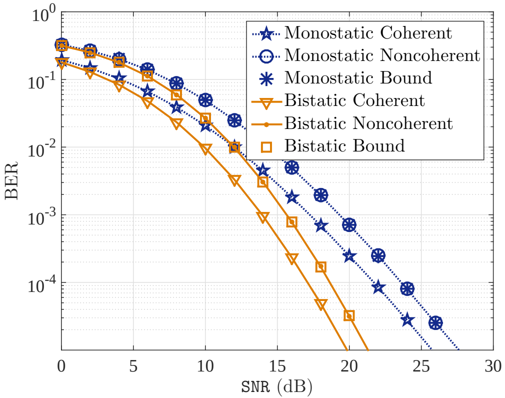
Under dyadic Nakagami fading, the BER of bistatic architecture with ML coherent detection can be bounded as

$$\mathbb{P}\left(e_{l,n}^{[\mathrm{b}]}\right) \leq \frac{1}{2}\left(\frac{2\,\mathtt{M}_{ln}\mathtt{M}_{n}}{\mathtt{SNR}_{l,n}^{[\mathrm{b}]}}\right)^{\mathtt{M}_n} \mathsf{U}\left(\mathtt{M}_n, 1+\mathtt{M}_n-\mathtt{M}_{ln}, \frac{2\,\mathtt{M}_{ln}\mathtt{M}_{n}}{\mathtt{SNR}_{l,n}^{[\mathrm{b}]}}\right), \qquad (27)$$

where $\mathtt{M}_n$ and $\mathtt{M}_{ln}$ are the Nakagami parameters for links TR and CT, respectively, while $\mathtt{SNR}_{l,n}^{[\mathrm{b}]}$ is the average received SNR for bistatic system. Under dyadic Rayleigh fading ($\mathtt{M}_n = \mathtt{M}_{ln} = 1$), the diversity order is 1.

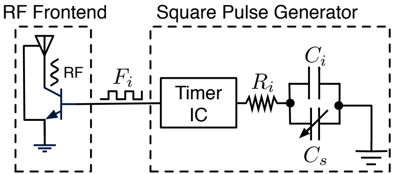
- The above BER bound coincides with noncoherent envelope bistatic scatter radio detection!

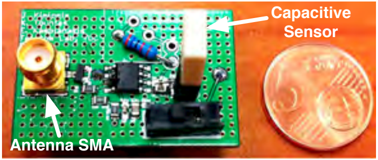
Some Numerical Results



- Wireless and signal parameters: Equal average received SNR, $\mathtt{M}_n = 5.7619$ and $\mathtt{M}_{ln} = 5.2632$.

Greenhouse Environmental Humidity [22, 23]

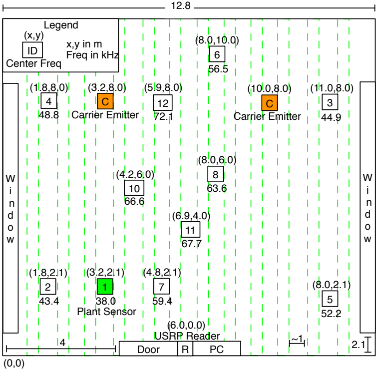


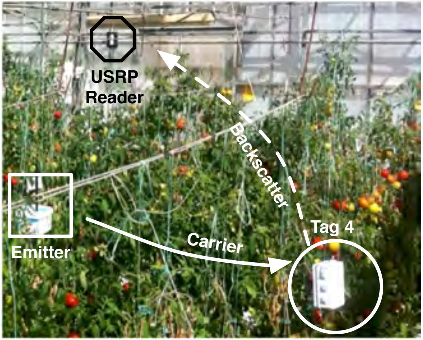


- Principle: capacitor changes ⇒ freq. of backscattered signal.
- Cost:∼ 3Euro (quantity of 1), Power: 220μWatt, RMS: $1 - 2\%$ RH.
- Networking: simple, multiple-access (FDMA).

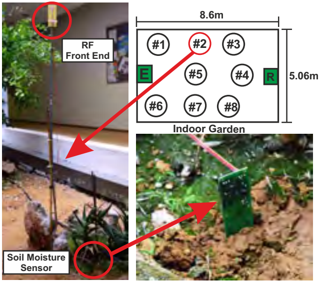
[22] E. Kampianakis, J. Kimionis, K. Tountas, C. Konstantopoulos, E. Koutroulis, and A. Bletsas, "Wireless environmental sensor networking with analog scatter radio & timer principles", IEEE Sensors J., vol. 14, no. 10, pp. 3365-3376, Oct. 2014. Conf. version [23] received IEEE Sensors Conf. 2013 distinction.

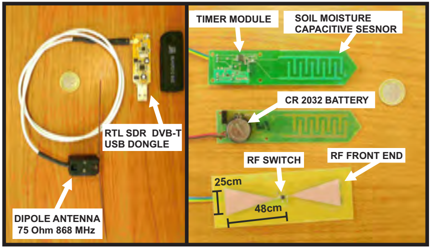
Greenhouse Environmental Humidity [22, 23]





Soil Moisture Humidity Across a Field [24, 25]

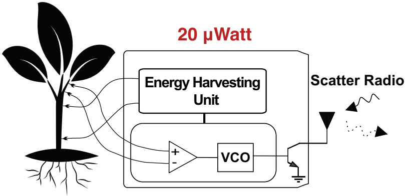


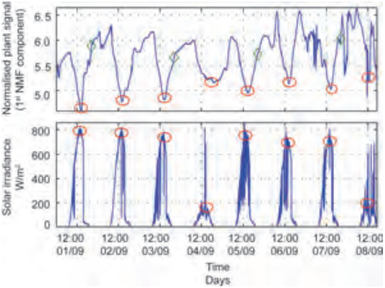


- Principle: capacitor changes ⇒ freq. of backscattered signal.
- Cost:$\sim$ 5Euro (quantity of 1), Power: $\sim$ 100μWatt, RMS: 1.9% RH.
- Networking: simple, multiple-access (FDMA).

[24] S. N. Daskalakis, S. D. Assimonis, E. Kampianakis, and A. Bletsas, "Soil moisture scatter radio networking with low power", IEEE Trans. Microw. Theory Techn., vol. 64, no. 7, pp. 2338-2346, Jul. 2016.

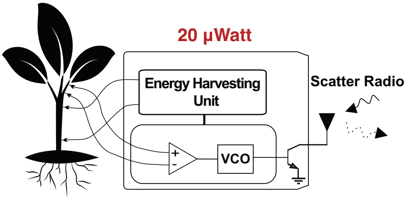
Plants as Backscatter Sensors & Batteries [26],[27]

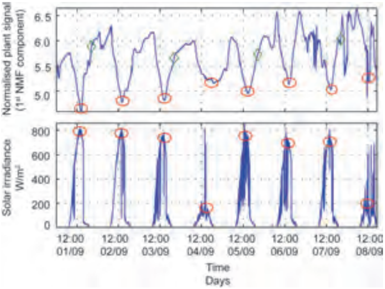




- Principle: measure Electric Potential (EP) accross two electrodes in the plant stem.
- Transmit EP with backscatter FM. Use Plant as Battery.
- EP signal is correlated with solar irradiance and plant watering!

Plants as Backscatter Sensors & Batteries [26],[27]

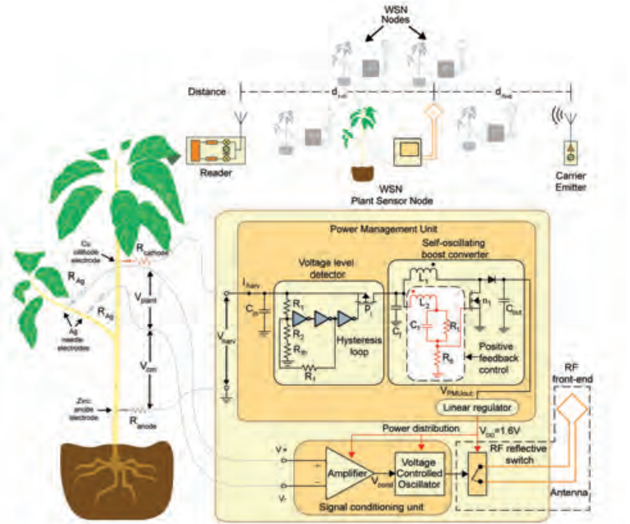




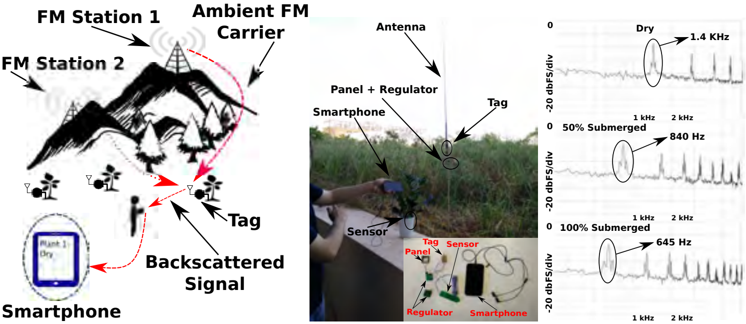
- Transmit EP with backscatter FM. Use Plant as Battery.
- EP signal is correlated with solar irradiance and plant watering!

[27] C. Konstantopoulos, E. Koutroulis, N. Mitianoudis, and A. Bletsas, "Converting a plant to a battery and wireless sensor with scatter radio and ultra-low cost", IEEE Trans. Instrum. Meas., vol. 65, no. 2, pp. 388-398, Feb. 2016. Conf. version at IEEE Sensors 2013 [26].

Plants as Backscatter Sensors & Batteries [26],[27]

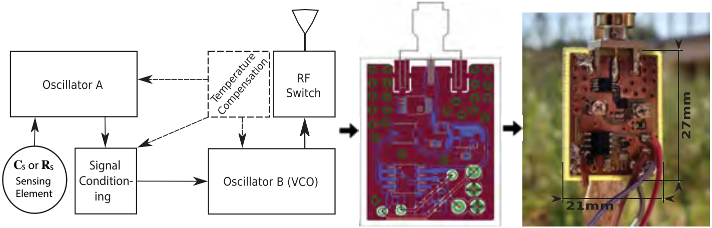


Ambient FM with μWatt Sensors & Smarphone Transmit Diversity Reception [28]



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

Ambient FM with μWatt Sensors & Smarphone Transmit Diversity Reception [28]



- Sensor Power: $12 - 24\mu$W *(even in continuous, non-duty-cycled operation)!*
- Tag-smartphone range: 26m, FM emitter-tag range: 6.5km!

[28] G. Vougioukas and A. Bletsas, "24μW 26m range batteryless backscatter sensors with FM remodulation and selection diversity", in Proc. IEEE RFID Techn. and Applications (RFID-TA), Warsaw, Polland, Sep. 2017. Best Student Paper Award.

Questions Answered?

Questions for today:

- Maximum range/coverage?
  ...extended from tens-of-meters to kilometers under conditions...
- Connection to satellite/underwater communications?
  ...all require power-limited regime orthogonal signaling and symbol/sequence detection advances...
- "Can you measure the water soil moisture of your favorite flower using your cellphone"?
  ...yes, at μWatt consumption (per tag sensor) cost...

Contributions

Ultra-low-power IoT technology:

- Ultra-low complexity, increased range, small processing delay, backscatter radio receivers.
- New, flexible, scatter radio network architectures with extended coverage.
- Noncoherent symbol-by-symbol and sequence detectors can be applied in specific ambient setups as well...

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THANK YOU! Questions?

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