Intelligent Scatter Radio, RF Harvesting Analysis, and Resource Allocation for Ultra-Low-Power Internet-of-Things

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Introduction

Nonlinear Far Field RF Energy Harvesting Analysis

Backscatter Radios

- Fundamentals, Detection, and Channel Coding.
- Network Architecture: Extended Scatter Radio Coverage.
- Resource Allocation in Multi-Cell Backscatter Sensor Networks.

Concluding Remarks
What is IoT? – Emerging Applications

- Global network infrastructure composed by a variety of devices interacting with each other through the Internet [1].
  - Fit to customer demands.

IoT applications [1–3]:
- Transportation and smart vehicles.
- Smart buildings.
- Industry.
- Healthcare.
- Environmental sensing.

By 2020: 212 billion IoT devices.
By 2025: 2.7–6.2 trillion $.

80-85% of total water is consumed for agriculture purposes.

Intelligent plant irrigation:
- Save 30% of water $\Rightarrow$ socioeconomic impact.
Dissertation Objectives

- Enhance ultra-low-power IoT technology exploiting novel concepts in wireless communications and networking.

Objectives:

- Accurate RF energy harvesting analysis.
- Ultra-low complexity, increased range, small processing delay, scatter radio receivers.
- New, flexible, scatter radio network architecture with extended coverage.
- Resource allocation for multi-cell backscatter sensor networks (BSNs).
Problem Statement (1/2)

- Diodes in rectifier circuits:
  - Strong nonlinearities on power conversion.
  - Sensitivity and saturation effects.
Prior art in wireless communications uses linear model.

This work offers accurate nonlinear RF harvesting analysis.
Wireless System Model

- Baseband narrowband received signal:

\[ y = \sqrt{P_T} T_s L(d) h_s + w. \]  

(1)

- Block fading model.

- Received power over \( n \)-th coherence block:

\[ P_R^{(n)} = E[|s|^2] P_T L(d) |h^{(n)}|^2 = P(d) \gamma^{(n)}. \]  

(2)

- PDF of \( \gamma^{(n)} \) continuous over \( \mathbb{R}_+ \), e.g., \( \gamma^{(n)} \sim \text{Gamma}(m, \frac{\Omega}{m}) \):

\[ f_{\gamma^{(n)}}(x) = \left( \frac{m}{\Omega} \right)^m \frac{x^{m-1}}{\Gamma(m)} e^{-\frac{m}{\Omega}x}, \quad x \geq 0. \]  

(3)
Harvesting Efficiency Models (1/2)

Harvesting Efficiency Models (2/2)

- Real model harvested power:

\[
P_{\text{har}}^{(n)} \equiv P_{\text{har}}^{(n)}(P_R^{(n)}) = p(P_R^{(n)}) \triangleq \begin{cases} 
0, & P_R^{(n)} \in [0, P_{\text{sen}}], \\
\eta(P_R^{(n)}) \cdot P_R^{(n)}, & P_R^{(n)} \in [P_{\text{sen}}, P_{\text{sat}}], \\
\eta(P_{\text{sat}}^{\text{in}}) \cdot P_{\text{sat}}^{\text{in}}, & P_R^{(n)} \in [P_{\text{sat}}^{\text{in}}, \infty).
\end{cases}
\]

- Prior art:

\[
\tilde{p}_L(P_R^{(n)}) = \eta_L \cdot P_R^{(n)}, \quad \forall P_R^{(n)} \in \mathbb{R}_+, \quad \eta_L \in [0, 1).
\]
Proposed Approximation (1/2)
The PDF of the proposed approximation model is

\[
    f_{\tilde{P}_{\text{har}}}^{(n)}(x) = \begin{cases} 
        \xi_0 \Delta(x), & x = v_0 = 0, \\
        \frac{1}{l_m} f_{P_{\text{R}}}^{(n)}\left(\frac{x - v_{m-1} + l_m b_m - 1}{l_m}\right), & x \in (v_{m-1}, v_m) \setminus \{v_M\}, \ m \in [M], \\
        (1 - \xi_M) \Delta(x - v_M), & x = v_M, \\
        0, & x \in \mathbb{R} \setminus [0, v_M],
    \end{cases}
\]

(6)

with \( \xi_m = F_{P_{\text{R}}}^{(n)}(b_m), \ m = 0, 1, \ldots, M, \ l_m \triangleq \frac{v_m - v_{m-1}}{b_m - b_{m-1}}, \ m = 1, 2, \ldots, M. \)
Expected harvesting energy: $T_p \mathbb{E} \left[ \sum_{n=1}^{N} P_{\text{har}}^{(n)} \right] = N T_p \mathbb{E} \left[ P_{\text{har}}^{(n)} \right]$. 
Successful reception at interrogator:

\[ \mathbb{P}(S) \triangleq \mathbb{P}(A \cap B). \]
Scatter Radios: Communication via means of reflection [6].
- Ultra-low power
- Low monetary cost.

Inherent problems:
- Large path-loss attenuation $\Rightarrow$ Limited range.
- Passive tags $\Rightarrow$ Powering issues $\Rightarrow$ Limited range.
- High bitrate $\Rightarrow$ Reduced energy per bit $\Rightarrow$ Limited range.

This work:
- Short-packet communication.
- Optimal receiver design for scatter radio signals.
Wireless and Signal Model

- Flat Rician fading: $h_m(t) = h_m \sim CN\left(\sqrt{\frac{\kappa_m}{\kappa_m+1}}\sigma_m, \frac{\sigma_m^2}{\kappa_m+1}\right)$, $m \in \{CR, CT, TR\}$ [7].

- Baseband signal for scatter radio FSK modulation [Theorem 1, 8]:

$$r = \begin{bmatrix} r_0^+ & r_0^- & r_1^+ & r_1^- \end{bmatrix}^\top = h\sqrt{\frac{E}{2}}[e^{+j\Phi_0} e^{-j\Phi_0} e^{+j\Phi_1} e^{-j\Phi_1}]^\top \odot s_i + n. \quad (7)$$

Noncoherent Symbol-by-Symbol Detectors (1/2)

- Statistics: \( f(r|i, h, \Phi) \equiv \mathcal{CN}(hx_i(\Phi), N_0I_4) \), with
  \[
x_i(\Phi) = \sqrt{\frac{E}{2}} \left[ e^{j\Phi_0}, e^{-j\Phi_0}, e^{j\Phi_1}, e^{-j\Phi_1} \right]^\top \otimes s_i, \quad i \in \mathcal{B}.
  \]

Lemma

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

\[
\arg \max_{i \in \mathcal{B}} \left\{ \mathbb{E}_\Phi \left[ \max_{h \in \mathbb{C}} \ln[f(r|i, h, \Phi)] \right] \right\} \iff |r_0^+|^2 + |r_0^-|^2 \overset{i=0}{\gtrless} \sum_{i=1}^{i=0} |r_1^+|^2 + |r_1^-|^2.
\]

(8)
Noncoherent Symbol-by-Symbol Detectors (2/2)

Statistics: \( f(r|i, h, \Phi) \equiv \mathcal{CN}(hx_i(\Phi), N_0 I_4) \), with

\[
x_i(\Phi) = \sqrt{\frac{E}{2}} \left[ e^{j\Phi_0}, e^{-j\Phi_0}, e^{j\Phi_1}, e^{-j\Phi_1} \right]^\top \odot s_i, \quad i \in \mathbb{B}.
\]

Theorem

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

\[
\arg \max_{i \in \mathbb{B}} \left\{ \max_{\Phi \in [0, 2\pi]^2} \max_{h \in \mathbb{C}} \ln[f(r|i, h, \Phi)] \right\} \iff |r_0^+| + |r_0^-| \overset{i=0}{\geq} |r_1^+| + |r_1^-|.
\]
Noncoherent GLRT Sequence Detector

- Static environments: Coherence time $\geq$ Packet duration.
- Transmitted sequence: $i = [i_1 \ i_2 \ \ldots \ i_{Ns}]^\top \in \mathbb{B}^{Ns}$.
- Received sequence: $r_{1:Ns}$ with statistics
  \[ f(r_{1:Ns}|i, h, \Phi) \equiv \mathcal{CN}(h x_i(\Phi), N_0 l_{4Ns}). \] (10)
- GLRT sequence detector:
  \[ i_{GLRT} = \arg \max_{i \in \mathbb{B}^{Ns}} \max_{\Phi \in [0,2\pi)^2} \max_{h \in \mathbb{C}} \ln[f(r_{1:Ns}|i, h, \Phi)]. \] (11)

**Theorem**

There exists algorithm that finds $i_{GLRT}$ with complexity $O(N_s \log N_s)$, based on [9].

Noncoherent HCHT Soft-decision Decoding

- Diminish long-bursts of fading: interleaving of depth $D$.
- Baseband coded signal using interleaving:

$$
\begin{bmatrix}
  r_1 \\
  r_2 \\
  \vdots \\
  r_{N_c}
\end{bmatrix} = 
\begin{bmatrix}
  h_1 x_{c_1}(\Phi) \\
  h_2 x_{c_2}(\Phi) \\
  \vdots \\
  h_{N_c} x_{c_{N_c}}(\Phi)
\end{bmatrix} + 
\begin{bmatrix}
  n_1 \\
  n_2 \\
  \vdots \\
  n_{N_c}
\end{bmatrix}.
\tag{12}
$$

**Theorem**

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

$$
\arg\max_{c \in \mathcal{C}} \left\{ \mathbb{E} \Phi \left[ \max_{h \in \mathbb{C}^{N_c}} \ln[f(r_{1:N_c} | c, h, \Phi)] \right] \right\} \iff \arg\max_{c \in \mathcal{C}} \sum_{n=1}^{N_c} w_n c_n, \tag{13}
$$

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

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Ph.D Defense
**Numerical Results (1/2)**

- Wireless and signal parameters: \( T = 1 \) msec, \( T_{coh} = 100 \) msec, 30 training bits.
Numerical Results (2/2)

Wireless and signal parameters: $T = 1$ msec, $T_{\text{coh}} = 100$ msec, 30 training bits.
Parameters: $d_{CT} = 8$ m, $T = 1$ msec, $F_1 = 2F_0 = 250$ kHz, 16 training + 31 data coded bits.
Experimental Results (2/2)

- Reception algorithms: Energy-based synchronization, Periodogram-based CFO estimation.
Asymmetric scatter radio architecture can reduce path-loss:

- 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 \rightarrow 0 or x \rightarrow 100.
This work proposes multistatic architecture.

Outperforms globally state-of-the-art monostatic architecture.
BER Analysis (1/2)

Theorem

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

\[
\mathbb{P}(e_{l,n}^{[m]}) \leq \frac{1}{2} \left( \frac{M_n + M_n^2}{2 \text{SNR}^{[m]}_n} \right)^{\frac{M_n}{2}} \text{U} \left( \frac{M_n}{2}, \frac{1}{2}, \frac{M_n + M_n^2}{2 \text{SNR}^{[m]}_n} \right),
\]

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

The above BER expression coincides with noncoherent envelope monostatic scatter radio detection.

BER Analysis (2/2)

Theorem

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

$$P(e_{l,n}^{[b]}) \leq \frac{1}{2} \left( \frac{2 M_{ln} M_n}{\text{SNR}_{l,n}^{[b]}} \right)^{M_n} U \left( M_n, 1 + M_n - M_{ln}, \frac{2 M_{ln} M_n}{\text{SNR}_{l,n}^{[b]}} \right), \quad (15)$$

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

- The above BER expression coincides with noncoherent envelope bistatic scatter radio detection.
**Numerical Results (1/2)**

- **Wireless and signal parameters:** Equal average received SNR, $M_n = 5.7619$ and $M_{ln} = 5.2632$. 
Numerical Results (2/2)

Wireless and signal parameters: $M_n = 5.7619$ and $M_{ln} = 1$. 
Problem Statement

- Resource allocation in multi-cell BSNs:
  - Maximize coverage.
  - Reduce installation cost.
System Model

- Cores, tags, and frequency sub-channels: $\mathcal{B}$, $\mathcal{K}$, $\mathcal{C}$.
- Rician MIMO wireless downlink and uplink channels between core $b$ and tag $k$: $h_{bk}^{d}$ and $h_{kb}^{u}$.
- Orthogonal pilot sequences $\{x^{(1)}, x^{(2)}, \ldots, x^{(M_{tr})}\} \subset \{\pm 1\}^{M_{tr}}$.
- $C$ orthogonal frequency sub-channels.
- Sets: $\mathcal{K}_{C}(c)$, $\mathcal{K}_{B}(b)$, $\mathcal{K}_{M_{tr}}(m)$, $\mathcal{K}_{bmc} = \mathcal{K}_{B}(b) \cap \mathcal{K}_{M_{tr}}(m) \cap \mathcal{K}_{C}(c)$.

Theorem

The baseband signal at core $b \in \mathcal{B}$ over the $i$-th time instant, at the output of $c$-th frequency filter is

$$ r_{b,i}^{(c)} = \sum_{k \in \mathcal{K}_{C}(c)} \xi_{kb}^{(c)} x_{k,i}^{(c)} + n_{b,i}^{(c)}, \quad i = 1, 2, \ldots, M. $$

(16)
Mult-Cell Training Signal

Training signal for tag $k \in \mathcal{K}_{bmc}$, $|\mathcal{K}_{bmc}| = 1$:

$$\tilde{R}_{b, tr}^{(c)} \frac{\mathbf{x}^{(m)}}{\|\mathbf{x}^{(m)}\|_2^2} \triangleq \mathbf{r}_{b, tr}^{(c)} = \mathbf{\xi}_{kb}^{(c)} + \sum_{b' \neq b} \sum_{k' \in \mathcal{K}_{b'mc}} \mathbf{\xi}_{k'b}^{(c)} + \mathbf{v}_{b, tr}^{(c)}, \quad (17)$$

Proposition

For vectors $\{\mathbf{\xi}_{kb}^{(c)}\}_{k \in \mathcal{K}_c(c), \forall c \in \mathcal{C}, \forall b \in \mathcal{B}}$, mean $\mathbf{E}[\mathbf{\xi}_{kb}^{(c)}] = \mathbf{0}_{N_R}$ and covariance $\mathbf{C}_{\mathbf{\xi}_{kb}^{(c)}}$ can be found in closed-form.
Theorem

For a tag \( k \in \mathcal{K}_{bmc} \) the LMMSE estimate of \( \xi_{kb}^{(c)} \) based on training signal \( r^{(c)}_{b,\text{tr}} \) is given by

\[
\hat{\xi}_{kb}^{(c)} = C_{\xi_{kb}}^{(c)} \left( \sum_{b' \in \mathcal{B}} \sum_{k' \in \mathcal{K}_{b'mc}} C_{\xi_{k'b}^{(c)}} + \frac{N_0}{M^2_{\text{tr}}} I_{N_R} \right)^{-1} r^{(c)}_{b,\text{tr}}. \tag{18}
\]

Vectors \( \hat{\xi}_{kb}^{(c)} \) and error vector \( \epsilon_{kb}^{(c)} = \hat{\xi}_{kb}^{(c)} - \xi_{kb}^{(c)} \) are uncorrelated.

- Linear detection \( \text{sign} \{ \Re \{ z_{k,i} \} \} \) for tag \( k \in \mathcal{K}_{bmc}, z_{k,i} = (a_{kb}^{(c)})^H r^{(c)}_{b,i} \).
- Maximum-ratio combining (MRC).
- Zero-forcing (ZF).
SINR Calculation and Problem Formulation

- Measure long-term SINR for pair \((k, c) \in \mathcal{K} \times \mathcal{C}\): \(\overline{\text{SINR}}_{kb}^{(c)}\).
- Assign frequency sub-channels to tags \(k \in \mathcal{K}_B(b)\) according to:

\[
\begin{align*}
\text{maximize} & \quad \sum_{k \in \mathcal{K}_B(b)} \sum_{c \in \mathcal{C}} g\left(\overline{\text{SINR}}_{kb}^{(c)}\right) \cdot v_{kc} & (19a) \\
\text{subject to} & \quad \sum_{k \in \mathcal{K}_{bm}} v_{kc} \leq 1, \quad \forall (m, c) \in \mathcal{M}_{tr} \times \mathcal{C}, & (19b) \\
& \quad \sum_{c \in \mathcal{C}} v_{kc} = 1, \quad \forall k \in \mathcal{K}_B(b), & (19c) \\
& \quad v_{kc} \in \mathbb{B}, \quad \forall (k, c) \in \mathcal{K}_B(b) \times \mathcal{C}. & (19d)
\end{align*}
\]
Resource Allocation Algorithm (1/2)

Theorem

The FG message-passing update rules to solve optimally resource allocation problem (19)

\[
\phi_{kc}^{(n)} = \max_{c' \in C \setminus c} \left\{ -\rho_{kc'}^{(n-1)} + g\left(\frac{\text{SINR}_{k'c}^{(c')}}{\text{SINR}_{k'c}}\right) \right\},
\]

\[
\rho_{kc}^{(n)} = \left[ \max_{k' \in K_{bm} \setminus k} \left\{ -\phi_{k'c}^{(n)} + g\left(\frac{\text{SINR}_{k'c}^{(c')}}{\text{SINR}_{k'c}}\right) \right\} \right]^+, \quad k \in K_{bm},
\]

where \([x]^+ \triangleq \max\{x, 0\}\). Moreover, to infer the value for variable \(v_{kc} \in B\) at the \(n\)-th iteration,

\[
\hat{v}_{kc}^{(n)} = 1\left\{ \phi_{kc}^{(n)} + \rho_{kc}^{(n)} \leq g\left(\frac{\text{SINR}_{kb}^{(c)}}{\text{SINR}_{kb}}\right) \right\}.
\]
Resource Allocation Algorithm

- Amenable to distributed implementation.
- If LP has integral and unique solution then message passing converges to the exact solution after $\mathcal{O}(C |\mathcal{K}_B(b)|)$ iterations [11].
- Per iteration computation cost: $\mathcal{O}(C |\mathcal{K}_B(b)|^2 + C^2 |\mathcal{K}_B(b)|)$.
- 5 to 15 iterations suffice for the algorithm to converge.

Numerical Results (1/3)

Wireless and signal parameters: $B = 21$, $K = 500$, $C = 15$, $M_{tr} = 8$, $\kappa_{kb}^{u} = \kappa_{bk}^{d} = 10$ dB, $\sigma_{bk}^{2} = \sigma_{kb}^{2} = \left(\frac{d_{0}}{d_{bk}}\right)^{\nu_{bk}} \left(\frac{\lambda}{4\pi d_{0}}\right)^{2}$, with $\nu_{bk} = 2.1$, $\Gamma_{k,0} = 0.92$ and $\Gamma_{k,1} = -0.91$, $\eta_{k} = 0.2$, $f^{(c)} = \frac{2c}{T}$, with $T = 0.1$ msec, $\sigma_{b}^{2} = -170$ dBm/Hz.
Numerical Results (2/3)

![Numerical Results Graph]

- **MRC (Orthogonal)**
- **MRC (LP)**
- **MRC (Max-Sum)**
- **ZF (Orthogonal)**
- **ZF (LP)**
- **ZF (Max-Sum)**

The graph shows the sum of average SINRs as a function of $P_{tx}$ (dBm). The SINRs are measured in various settings: MRC (Max-Sum) and ZF (Max-Sum) are represented by a star and a square, respectively. The orthogonal and linear properties are denoted by circles and diamonds, respectively.
Numerical Results (3/3)

![Graphs showing numerical results](image_url)
Contributions

- Enhance ultra-low-power IoT technology exploiting novel concepts in wireless communications and networking.

Objectives:

- Accurate RF energy harvesting analysis.
- Ultra-low complexity, increased range, small processing delay, scatter radio receivers.
- New, flexible, scatter radio network architecture with extended coverage.
- Resource allocation for multi-cell backscatter sensor networks (BSNs).
Future Work

- Accurate resource allocation with nonlinear RF energy harvesting.
- Multistatic scatter radio cooperative localization.
- Linear detection performance analysis in multi-cell BSNs and comparison with existing WSN technology.
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Questions?

- Thank You!!
Conference Publications

10 P. N. Alevizos and A. Bletsas, “Scatter Radio Receivers for Extended Range Environmental Sensing WSNs,” in Proc. IEEE Communication Theory Workshop (CTW), May 2016, Nafplio, Greece. Student and Early Researcher Travel Grant Award.


6 P. N. Alevizos, Y. Foutzoulas, G. N. Karystinos, and A. Bletsas, “Noncoherent Sequence Detection of Orthogonally Modulated Signals in Flat Fading with Log-Linear Complexity,” in Proc. IEEE ICASSP, Brisbane, Australia, Apr. 2015, Conference-wide Student Paper Award and Best Student Paper Award in Communications and Networks track.


Journal Publications


