Wireless Power Transfer and Communication for Sensors: Dynamic Frame-Switching (DFS) Policy

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Outline

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  – EH-ID Receiver Structures
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• Proposed Dynamic Frame-Switching (DFS)
  – EH Maximization problem of DFS
  – Frame switching policies
  – Analytical results and rate-energy tradeoff results

• Conclusion
Why Energy Harvest (EH)?

• Massive wireless sensors: key enabler for IoT
• Sensor needs frequent change of batteries
  – high maintenance cost
• **Ambient energy harvesting**
  – [1]: energy causality constraints
  – [2]: beamforming for EH and ID

EH-ID Methods

• **Concurrent** EH-ID: impractical as any electrical ID signal must have some of its current diverted from being used for EH

• **Multiplexed** EH-ID
  – Time sharing (TS): in time domain
  – Frequency division (FD): in freq. domain
  – Power splitting (PS): in power domain
Multiplexed EH-ID Receiver Structure: Integrated receiver structure

Multiplexed EH-ID Receiver Structure: *Separated* receiver structure

- More conventional structure
Implementation Challenges

- **DTS**
  - Rx switching between ID and EH over different symbols based on CSI
  - Requiring accurate symbol-level synchronization
  - Switching time overhead

- **DPS**
  - Rx splitting the received signals for ID or EH based on CSI
  - Tx power control can be considered with full CSI at Tx
  - Requiring precise power ratio
  - Conversion losses in power splitting

- Simple EH-ID receiver is desired!

Proposed Dynamic Frame-Switching (DFS)

- **Threshold** $\gamma$ based decision for switching
- Only **partial CSI** needed at the Rx:
  - received signal power, $g_n$, for $n$th frame decision
• Much lower complexity in DFS
  – Frame-level synchronization
  – Received signal power captured by an energy detector
  – No power control at Tx
  – No power splitting at Rx
DFS System Model

- Data and energy Tx: single-antenna access point
- ID and EH Rx: single-antenna sensors
- Tx broadcasts common data to all sensors over $N$ frames
  - $L$ symbols per frame
- Baseband received signal of symbol $l$ in frame $n$

$$y[n, l] = h[n] \sqrt{P} x[n, l] + v[n, l]$$

- Invariant channel in frame
- $P$: transmit power
- $x[n, l]$: Tx symbol
- $v[n, l]$: AWGN
  - $\sim \mathcal{CN}(0, 1)$
  - $\sim \mathcal{CN}(0, \sigma_v^2)$
ID and EH of DFS

• ID: information rate (mutual information)

\[ r(g_n) = \log(1 + \frac{g_n}{\sigma^2_v}) \text{ bits/sec/Hz} \]

- \( g_n = |h[n]|^2 P \) : Rx sig. pow. at energy detector
- All data bits can be decoded reliably when

\[ \frac{1}{N} \sum_{n=1}^{N} r(g_n) \geq \bar{R} \]

minimum average achievable rate

• EH: with energy conversion efficiency \( 0 < \eta \leq 1 \)

\[ e(g_n) = \eta g_n \]
Optimization Problem of DFS

• To find the optimal policy

\[
\begin{align*}
\max_{u(g_n) \in \Pi} E & \triangleq \frac{1}{N} \sum_{n=1}^{N} e(g_n)u(g_n) \\
\text{s.t. } R & \triangleq \frac{1}{N} \sum_{n=1}^{N} r(g_n(1 - u(g_n))) \geq \bar{R}
\end{align*}
\]  

– Maximize EH, subject to a minimum average achievable rate, i.e., an ID constraint

– \(\Pi\) : functions that take a positive input and binary output
Problem Relaxation

\[
\max_{\{0 \leq s_n \leq 1\}} \frac{1}{N} \sum_{n=1}^{N} \eta g_n s_n \quad \text{s.t.} \quad \frac{1}{N} \sum_{n=1}^{N} r(g_n (1 - s_n)) \geq \overline{R}
\]

- Binary decision \( u(g_n) \) to real-valued decision \( s_n \)
- Effectively the decision \( s_n \) a time-sharing variable
- Convex optimization in DPS problem in [6]
- Optimal solution from KKT conditions

\[
s_n^* = \begin{cases} 
1 - \frac{\tau}{g_n} & \text{(EH\&ID), if } g_n \geq \tau \\
0 & \text{(ID), if } g_n < \tau
\end{cases}
\]

\[
\tau \triangleq \frac{\lambda}{\eta \ln 2} - \sigma_v^2 > 0, \quad \lambda > \sigma_v^2 \eta \ln 2
\]

\text{constant}
Class of DFS Policies

- Single-threshold DFS policies ($M=1$)
  
  **Policy I (P-I)** when $\{\alpha_1, \beta_1\} = \{\gamma_1, \infty\}$
  
  $$u_1(g_n) = \begin{cases} 
  1 \text{ (EH)}, & \text{if } g_n \geq \gamma_1 \\
  0 \text{ (ID)}, & \text{if } g_n < \gamma_1 
  \end{cases}$$

  **Policy II (P-II)** when $\{\alpha_1, \beta_1\} = \{0, \gamma_2\}$
  
  $$u_2(g_n) = \begin{cases} 
  0 \text{ (ID)}, & \text{if } g_n > \gamma_2 \\
  1 \text{ (EH)}, & \text{if } g_n \leq \gamma_2 
  \end{cases}$$

  similar structure to the optimal DPS policy
  
  another single-threshold policy

- General DFS policy
  
  $$u(g_n) = \begin{cases} 
  1 \text{ (EH)}, & \text{if } g_n \in \mathcal{S}, \\
  0 \text{ (ID)}, & \text{if } g_n \in \mathcal{T} 
  \end{cases}$$

  - The sets $\mathcal{S}$ and $\mathcal{T}$ are non-contiguous.
  - Policy with $M$-pair thresholds

  $\beta_0 = 0 \quad \alpha_1 \quad \beta_1 \quad \alpha_2 \quad \beta_2 \quad \alpha_M \quad \beta_M \quad \alpha_{M+1} = \infty$
Key Results 1/2

• $E_1$ and $E_2$ are max-EH from P-I ($\pi_1$) and P-II ($\pi_2$)

Lemma 1: Suppose that $E_1 \geq E_2$ holds for any problem instance of problem (1), i.e., for any $\{g_n\}$ of any length $N$. Then the optimal DFS policy (over the entire policy space $\Pi$) is P-I, i.e., $\pi^* = \pi_1$.

Theorem 1: $E_1 \geq E_2 - \epsilon(N)$ for any distribution of channel gains, where $\epsilon(N) \geq 0$ is an energy gap with the asymptotic property that $\epsilon(N) = \mathcal{O}(1/N) \to 0$ as the number of frames $N \to \infty$. 
Key Result 2/2

Lemma 2: For any channel gains \( \{g_n\} \), \( E_1 \geq E^* - \epsilon'(N) \), with the asymptotic property that for large \( N \), \( \epsilon'(N) = O(M/N) \) where \( M \) is the number of thresholds of the optimal policy.

Theorem 2: If \( M < O(N) \), then P-I asymptotically solves the DFS problem, i.e., \( E_1 \geq E^* - \epsilon \) where the energy gap \( \epsilon \to 0 \) for large \( N \).

• From the Theorems and Lemmas, we see that “Policy I is asymptotically optimal for DFS”
Numerical Results

• For comparison, we consider P-III that performs ID first with all received frames, then switches to EH once achieves the target rate

– Policy III (P-III): \( u_3(g_1, \ldots, g_n) = \begin{cases} 0 \text{ (ID),} & \text{if } R^t(n) \leq \overline{R}, \\ 1 \text{ (EH),} & \text{otherwise,} \end{cases} \)

– \( R^t(n) = \frac{1}{n} \sum_{m=1}^{n} \log_2(1 + g_m / \sigma_v^2) \) : achievable rate using the first \( n \) frames
Rate-Energy Tradeoff

\[ \eta = 0.6 \]
\[ \sigma_v^2 = 1 \]
\[ h[n] \sim \mathcal{CN}(0, 1) \]
\[ N = 10^6 \]
Conclusion

• **Low-complexity Dynamic Frame-Switching (DFS) policy** is proposed
  – to implement ID and EH for sensor network applications

• **Asymptotically-optimal DFS policy** is analytically and numerically shown
  – ID in weak channels
  – EH in good channels

• **Future extension**
  – online single-threshold FS policy based on battery level and number of frames transmitted