Adaptive Mode Switching Algorithm for Dual Mode SWIPT with Duty Cycle Operation

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Motivation: Unified Design of WIT & WPT

<table>
<thead>
<tr>
<th>WIT</th>
<th>For unified SWIPT...</th>
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<tbody>
<tr>
<td>Wireless Information Transfer</td>
<td>- Low receive sensitivity (-60dBm)</td>
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<td>- Long range (~km)</td>
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<td>- Objective: Data rate</td>
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<td>- Modulation and coding scheme (MCS)</td>
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<td>- Requires wide range of receive sensitivity</td>
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<td>- Duty cycle operation for self-powering</td>
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<td>- Adaptive mode switching (MS) between ID and EH</td>
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<td>- Needs R-E tradeoff optimization</td>
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<td>Power management module (PMM)</td>
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Motivation: RF-to-DC PCE of SWIPT

- To improve R-E tradeoff performance:
  - Cross-over of PCE!

→ Mode Switching btw. single/multi-tone
  - Single tone for high rate, short range
  - Multi-tone for low rate, long range

- Adaptable Mode Switching (MS) threshold ($P_{th}$) for flexible R-E tradeoff optimization

Main Contribution:

- Duty Cycle based Dual Mode SWIPT system
- Mixed time-scale Adaptive Mode Switching algorithm

*PCE: Power Conversion Efficiency
System Model: Dual Mode SWIPT

- **Dual Mode SWIPT Receiver**

  - **Energy Path**
    - Rectifier
    - DC-DC Converter
    - Battery
  
  - **Information Path**
    - Envelope Detector
    - Energy-level Detector
    - Decoder
  
  - **PAPE Path**
    - Envelope Detector
    - PAPR Estimator
    - Decoder

- **Harvested energy at Energy Path**
  \[ E_{EH} = \frac{D_v}{D_v + 1} T_v \times \Phi_{EH}(P_R) \times P_R \]

- **Data rate at Information/PAPR Path**
  \[ R_v = \begin{cases} 
  \frac{1}{D_v + 1} (1 - p_{out}(M)) \log_2 M, & \text{for single tone} \\
  \frac{1}{D_v + 1 BT_m} \left( \frac{1}{1 - p_{out}(Q)} \right) \log_2 Q, & \text{for multi-tone} 
  \end{cases} \]

  \[ \Phi_{EH}: \text{Estimated PCE function} \]
  \[ p_{out}: \text{Outage probability} \]
  \[ M: \text{Modulation index} \]
  \[ Q: \# \text{ of multi-tone} \]

- $P_{th}$ is updated over each long-term window.

- Duty ratio ($D_v$) is calculated in each channel block.
System Model: Multi-tone/PAPR Modulation

- Example of PAPR modulation:

<table>
<thead>
<tr>
<th></th>
<th>2bits</th>
<th>N</th>
<th>$PAPR_{RX}$</th>
<th>$F_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0 0]</td>
<td>1</td>
<td>2</td>
<td>${f_{(1)}}$</td>
<td></td>
</tr>
<tr>
<td>[0 1]</td>
<td>2</td>
<td>4</td>
<td>${f_{(1)}, f_{(2)}}$</td>
<td></td>
</tr>
<tr>
<td>[1 1]</td>
<td>3</td>
<td>6</td>
<td>${f_{(1)}, f_{(2)}, f_{(3)}}$</td>
<td></td>
</tr>
<tr>
<td>[1 0]</td>
<td>4</td>
<td>8</td>
<td>${f_{1}, f_{2}, f_{3}, f_{4}}$</td>
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</table>

- Receiver just estimates the PAPR value, thus low complexity and low energy consuming.

- The received PAPR at the PAPR estimator:

$$PAPR = \frac{\max_{t \in [0,T_m]} |y_{ID}(t)|^2}{\frac{1}{T_m} \int_{t} |y_{ID}(t)|^2 dt} \approx 2N$$
Adaptive Mode Switching Algorithm

- Adaptive MS control module do..
  - Adjust duty ratio ($D_v$) for self-powering (MS between ID/EH)
  - Proper mode selection between single tone and multi-tone
  - Optimize modulation index ($M$) and # of multi-tone ($Q$) for R-E tradeoff
  - Adaptable MS threshold ($P_{th}$) for flexible R-E tradeoff

Feedback MS information:
- Mode, $M$ or $Q$

Outer Loop
- Estimate $P_R$
- Update $P_{th}$

Inner Loop
- Select mode $P_R \geq P_{th}$
- Find feasible index $P_b \leq P_{tag}$
- Compute $D_v$
- $D_v$, $M$ or $Q$

Global Optimization

(P1): $\max_{P_{th}} E_v[R_v]$
\hspace{1cm} s.t. $E_{EH} \geq E_{C,i}$
\hspace{1cm} $P_b \leq P_{tag}$

Long-term Optimization

(P2): $\max_{P_{th}} E_v[R_v^+]$

Short-term Optimization

(P3): $\max_{D_v} R_v$
\hspace{1cm} s.t. $D_v \geq \frac{P_{C,i}}{P_{EH}}$
\hspace{1cm} $P_b \leq P_{tag}$

- Outer loop: Update $P_{th}$ \rightarrow MS between single and multi-tone
- Inner loop: Update $D_v$, $M$ or $Q$ \rightarrow MS between ID and EH
Adaptive Mode Switching Algorithm

- Mode selection example:

<table>
<thead>
<tr>
<th>Case</th>
<th>Operation Description</th>
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<tr>
<td>A</td>
<td>Short range, large M for high data rate</td>
</tr>
<tr>
<td>B</td>
<td>Single tone but <em>outage occurred</em>, switch to multi-tone SWIPT</td>
</tr>
<tr>
<td>C</td>
<td>Multi-tone SWIPT, small Q for R-E tradeoff</td>
</tr>
<tr>
<td>D</td>
<td>Long range, large Q for self-powering</td>
</tr>
<tr>
<td>E</td>
<td>Self-powering <em>infeasible</em>, WPT only with maximum Q</td>
</tr>
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Boundary between single and multi-tone is subject to change as $P_{th}$ is updated via each long-term optimization (P2).
Channel estimation affects power consumption:

- As $\beta$ increases, the rate is penalized since more power is required.
- Large $\beta$ forces $P_{th}$ to be increased → more likely multi-tone mode selection.

### Parameter | Value
--- | ---
Fading channel | Frequency-flat Rayleigh fading, 900MHz center freq.
Path-loss exponent | 2.5
Transmit power | 40dBm
Bandwidth | 1MHz
Noise power | -130dBm/Hz
Smoothing parameter | 0.3472
Circuit power consumption | Single tone 0.2mW, Multi-tone 0.12mW
Target BER | 0.01

$\beta$: the ratio of power consumption for channel estimation to that for information decoding (i.e., $\beta = \frac{P_{ch,est}}{P_{C,s}}$).