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RF Energy Harvesting in Wireless Networks with HARQ

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A promising Solution for Limited Power Wireless Networks

- Ideally, WEH provides an unlimited supply of energy.
  E.g., Sensor Networks.
- Ambient radio frequency (RF) transmissions can be harvested for energy.
  - Motivates studying Simultaneous Wireless Power and Information Transfer (SWIPT).

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Challenges of Wireless Communications Channels

Wireless channel gain fluctuates over time causing outages

- Hybrid Automatic Repeat Request (HARQ).
  - Message is encoded by a mother code of rate R.
  - Divided into N codewords, transmitting each consecutively until receiver can decode the message.
- What is the interplay of HARQ re-transmissions and RF energy harvesting for a receiver without any other power source?

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Contributions

- Analyze trade-off between accumulating mutual information and harvesting RF energy at the receiver of a point-to-point link using HARQ.
- Characterize the optimal time switching (TS) policy to maximize the probability of successful message decoding,
  - where TS policy decides to harvest energy or accumulate information at every slot
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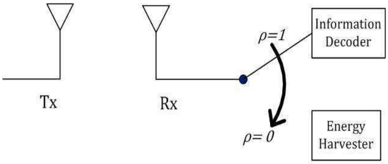
- Transmitter has power supply.
- Receiver harvests energy from the received RF signal.
- Time is slotted.
- Rayleigh flat fading wireless channel.
- Transmitter employs HARQ protocol.



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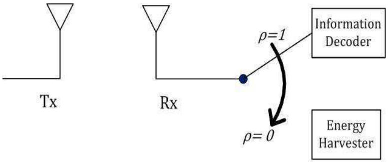

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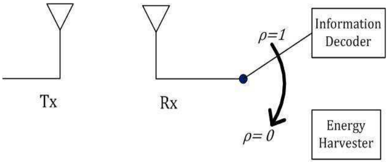

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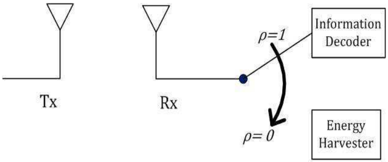

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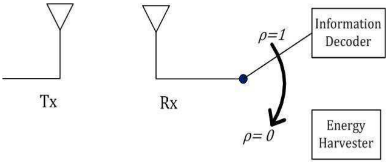

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- Maximum number of message re-transmissions is N.
- Fixed transmission power P per slot.
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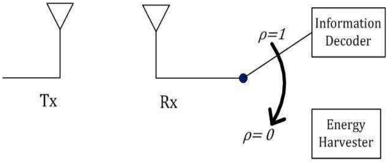
- Receiver has unlimited capacity memory and battery.



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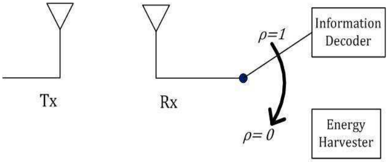

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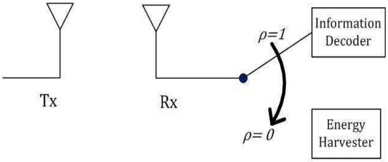

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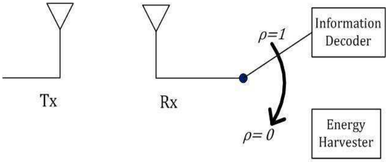

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Dynamic Program (DP) Formulation

- Consider the action at time slot t to be time switching decision ρ_t,

$$a_t = \rho_t = \begin{cases} 0, & \text{for RF energy harvesting} \\ 1, & \text{for information decoding} \end{cases} \quad (1)$$

- System state $s_t = (f_t, g_t)$,

$$f_t = \sum_{k=1}^{t-1} \log\left(1 + \rho_k P h_k\right), \quad (2)$$

$$g_t = \sum_{k=1}^{t-1} \left(1 - \rho_k\right) P h_k, \quad (3)$$

- Reward $x_t(s, a)$ of 1 when message is decoded, i.e.,

$$x_t(s, a) = I\left(f_t + log\left(1 + \rho_t P h_t\right) \geq R\right) \cdot I\left(g_t + \left(1 - \rho_t\right) P h_t \geq \zeta\right), \quad (4)$$

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Discrete State DP

- A closed form solution of DP with continuously varying states is intractable.
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Greedy Time Switching Algorithm

- Computationally efficient greedy policy with good performance results.
- The decision policy, ρ_t^*, minimizes the probability of decoding failure at time slot t,

$$\rho_t^* = \begin{cases} 0, & \text{if } 2^{fr_t} - 1 \geq gr_t, \\ 1, & \text{Otherwise.} \end{cases} \quad (5)$$

where fr_t and gr_t are the remaining amount of mutual information and RF energy needed for successful decoding.

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Sub-optimal TS Policy ($STSP - CSI$)

- Observation: Including the instantaneous channel gains significantly increases the computational complexity of the DP.
- A simple heuristic TS policy inspired by the previous DP formulation.
- Remarks:
  - Receiver either collects the required mutual information or energy in a time slot, whichever has the higher probability of successful decoding depending on the channel gain.
  - If both memory and battery thresholds cannot be met in the current slot, storing mutual information always results in a higher probability of successful decoding.

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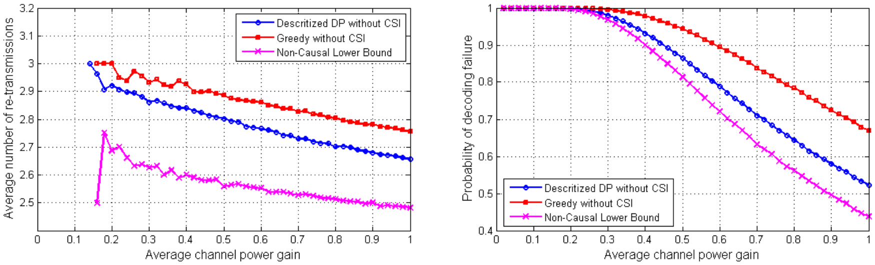
Greedy Time Switching Algorithm

- When the instantaneous CSI is available for TS decision, we design a greedy TS policy that aims to minimize the decoding failure probability in the subsequent slot
  - Remark: Failure is either due to insufficient mutual information accumulation or insufficient battery level.
- The optimal decision taken at every slot is given by,

$$\rho_t = \begin{cases} 1, & \text{if } \frac{2^{f_t}}{1+h_t P} \geq 2^{f_t} - h_t P, \\ 0, & \text{Otherwise.} \end{cases} \tag{6}$$

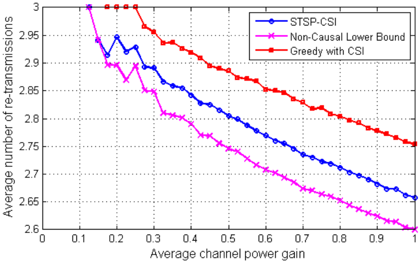
CSI not available for TS decision

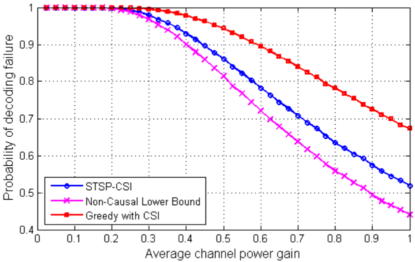
- Max transmissions is 3, R=1, P=1, the required energy to decode is $0.8 \cdot P$. Average over 10^5 runs.



- The non-causal policy has all future channel state information for making TS decisions.
- Channel is discretized into 50 states, resulting in an approximate channel behavior.

CSI available for TS decision





- Unlike the previous case, the channel state is not discretized, giving smoother and more accurate results.

Summary

- Studied a point-to-point link in a wireless RF-energy harvesting network employing HARQ protocol
- When CSI at the receiver is unavailable .
  - Formulated a dynamic programming problem.
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Future Directions

- Future research should address the following:
  - The assumption of infinite capacity for both energy and information is ideal.
  - The receiver power consumption should also be taken into account.
  - The potential extension to the general case with multiple users.