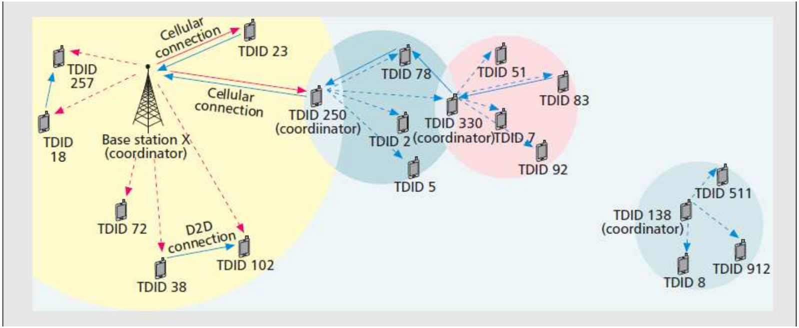
Optimal Transmit Power Control Policies for Device-to-device Networks with Energy Harvesting

July 10, 2016

Outline

- Network assisted device discovery
- Throughput optimal policies for dual EH links

Device Discovery: Motivation[1]



- Achieved utility depends on number of discovered devices
- In EH networks exploration vs exploitation trade-off does not exist

[1] Zou et al., Proximity Discovery for Device-to-Device Communications over a Cellular Network, IEEE Comm. Mag., June 2014

System Model

- The devices are assumed to be distributed according to a homogeneous Poisson point process (PPP) with density λ
- Slotted ALOHA protocol with parameter p
- Discovery phase followed by a communication phase
- Network infrastructure assists in perfect synchronization of the slot boundaries across the nodes
- Also notifies the optimal transmission probability parameter p at the beginning of the discovery phase
- Spatial distribution of the nodes changes in an i.i.d. fashion at the beginning of each discovery phase
- Device choose a resource block uniformly randomly from M FDM RBs

System Model: Contd

- In each slot, a node harvests energy E_s with probability ρ
- A node participates in the discovery process if it has E energy in the battery
- Energy used for transmission and reception are $E = PT_p$ and R, respectively ($R \leq E$)
- Operation of an EHN is constrained by *energy neutrality constraint*
- Battery evolves as

$$B_{n+1} = \max\{(B_n + \mathbb{1}_{\{e_n \neq 0\}} - \mathbb{1}_{\{T \neq 0\}} PT_p + \mathbb{1}_{\{Rx \neq 0\}} R)^+, B_{\max}\}$$

Transition probabilities

$$
B_{n+1} = \begin{cases}
\min\{B_n + 1 - E, B_{\max}\} & \text{w.p.} \quad p\rho \text{ if } B_n \geq E \\
B_n - E & \text{w.p.} \quad p(1-\rho) \text{ if } B_n \geq E \\
\min\{B_n + 1 - R, B_{\max}\} & \text{w.p.} \quad q\rho \text{ if } B_n \geq E \\
B_n - R & \text{w.p.} \quad q(1-\rho) \text{ if } B_n \geq E \\
B_n + 1 & \text{w.p.} \quad (1-p-q)(\rho) \text{ if } B_n \geq E \\
B_n & \text{w.p.} \quad (1-p-q)(1-\rho) \text{ if } B_n \geq E \\
\min\{B_n + 1 - R, B_{\max}\} & \text{w.p.} \quad r\rho \text{ if } E > B_n \geq R \\
B_n - R & \text{w.p.} \quad r(1-\rho) \text{ if } E > B_n \geq R \\
\min\{B_n + 1, B_{\max}\} & \text{w.p.} \quad (1-r)\rho \text{ if } E > B_n \geq R \\
B_n & \text{w.p.} \quad (1-r)(1-\rho) \text{ if } E > B_n \geq R \\
B_n & \text{w.p.} \quad (1-\rho) \text{ if } B_n < R. \\
B_n + 1 & \text{w.p.} \quad \rho \text{ if } B_n < R.
\end{cases}
$$

Goal

- Given: λ, ρ and *R*
- Design *p* and *P* to maximize the number of discovered devices
- Metric: mean number of discovered devices

Mean number of discovered devices, $\mathbb{E}(D)$

Lemma

For an energy harvesting device-to-device network with Rayleigh fading links and path-loss exponent $\alpha = 4$, $\mathbb{E}(D)$, is given as

$$\mathbb{E}(D) = \frac{\lambda_a \pi^{\frac{3}{2}} p(1-p)}{2\sqrt{\gamma_0 \sigma^2}} \exp\left(\left(\frac{\lambda_a \pi^2 p}{4M\sigma}\right)^2\right) \operatorname{erfc}\left(\frac{\lambda_a \pi^2 p}{4M\sigma}\right),$$

where $\operatorname{erfc}(t) = \frac{2}{\sqrt{\pi}} \int_t^\infty \exp(-y^2) dy$, and $\lambda_a = \lambda \pi_a$.
π_a: the stationary probability that the node is active.

Optimization Problem

$$\begin{aligned} \max_{p,P} \quad & \mathbb{E}(D) \\ \text{subject to} \quad & P \leq P_{\max} \end{aligned}$$

and energy neutrality constraint

- For a node operating under average power constraint

$$\pi_a = 1 - \Theta(e^{r*B_{\max}})$$

- Reformulated problem:

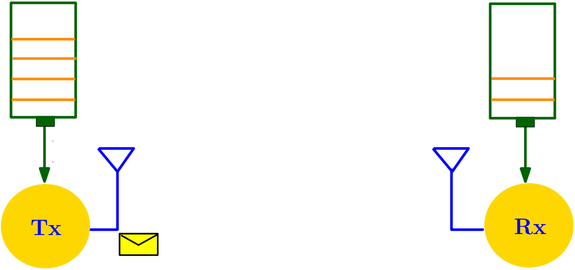
$$\begin{aligned} \max_{p,P} \quad & \mathbb{E}(D) \\ \text{subject to} \quad & P \leq P_{\max}, \\ & pE + (1-p)R \leq \rho E_s. \end{aligned}$$

Proof

We work out

Throughput optimal policies for dual EH links

System Model



- ACK/NACK signal provides the perfect synchronization

Goal

- Goal: Maximize the long-term time averaged utility

$$\max_{e_n^t, e_n^r} \quad \mathcal{U} = \max_{e_n^t, e_n^r} \left(\liminf_{T \to \infty} \sum_{n=1}^{T} \mathbb{1}_{\{e_n^r \neq 0\}} U(e_n^t) \right)$$

  where $U(.)$ is a concave non-decreasing function.

- **Lemma**
  For an uncoordinated dual EH link the time-averaged utility is upper bounded as

$$\mathcal{U} \leq \min \left(\frac{U(\mu_t)}{U(B_{\max}^t)}, \mu_r \right) U(B_{\max}^t).$$

Proof

Using ergodicity, the time-averaged utility is written as

$$
\begin{aligned}
\mathcal{U} &= \liminf_{T\to\infty} \sum_{n=1}^{T} \mathbb{1}_{\{e_n^r \neq 0\}} U(e_n^t), \\
&\stackrel{(a)}{=} \mathbb{E}\left[\mathbb{1}_{\{e_n^r \neq 0\}} U(e_n^t)\right], \\
&\stackrel{(b)}{=} \min\left(\frac{\mathbb{E}\left[U(e_n^t)\right]}{U(B_{\max}^t)}, \mathbb{E}\left[\mathbb{1}_{\{e_n^r \neq 0\}}\right]\right) U(B_{\max}^t), \\
&\stackrel{(c)}{\leq} \min\left(\frac{U\left[\mathbb{E}(e_n^t)\right]}{U(B_{\max}^t)}, \mathbb{E}\left[\mathbb{1}_{\{e_n^r \neq 0\}}\right]\right) U(B_{\max}^t), \\
&\stackrel{(d)}{\leq} \min\left(\frac{U(\mu_t)}{U(B_{\max}^t)}, \mu_r\right) U(B_{\max}^t).
\end{aligned}
$$

Optimal Policy

- CASE I: $\frac{\mu_r}{R} \geq 1$

$$e_n^t = \begin{cases} \mu_t + \delta, & \text{if } B_n^t \geq \frac{B_{\max}^t}{2}, \\ \min\{\mu_t - \delta, B_n^t\}, & \text{if } B_n^t < \frac{B_{\max}^t}{2}. \end{cases} \tag{1}$$

- CASE II($\frac{\mu_r}{R} > 1$): The receiver employs a policy where it turns on after every N_r slot which is given as follows

$$N_r = \begin{cases} \lceil N \rceil, & \text{if } B_n^r \leq \frac{B_{\max}^r}{2}, \\ \lfloor N \rfloor, & \text{if } B_n^r < \frac{B_{\max}^r}{2}. \end{cases}$$

In each slot transmitter allocates the energy according to (1), and transmits the accumulated energy in the next slot when the receiver is on.

Performance: CASE I

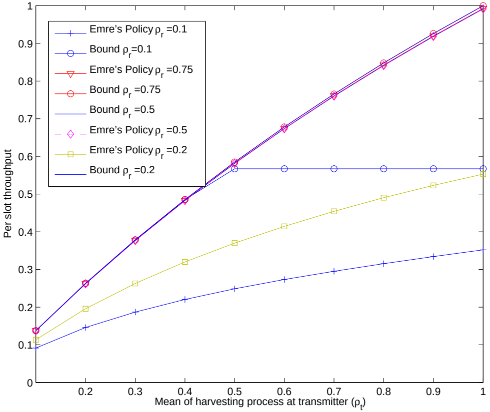


Figure: Comparison of upper bound with policy in (1). The parameters chosen are $B^t_{\max} = B^r_{\max} = 50$

Performance: CASE II

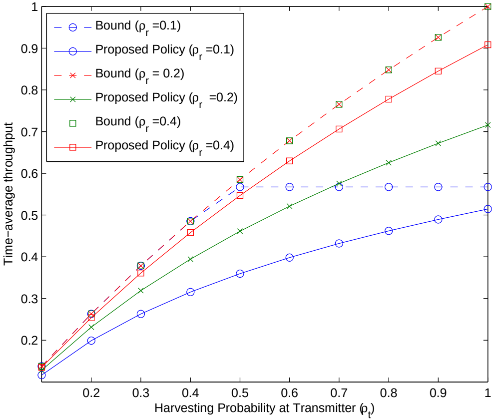


Figure: Case II: Comparison of upper bound and policy in (15) and (15). The parameters chosen are $B^t_{\max} = B^r_{\max} = 50$