Cross-Layer Protocol Optimization for Green Wireless Network Systems

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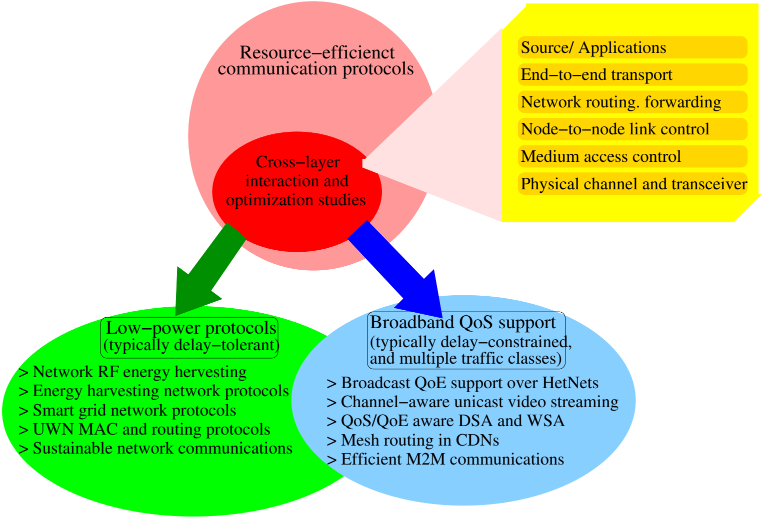
My Current Research Directions



Presentation Outline

1. Motivation
   - Layered versus cross-layer protocol studies
   - Performance measures and evaluation techniques
2. Link-layer Performance
   - Link+PHY cooperation
   - Network cooperation
3. Cross-layer Cooperation
   - Switched MC-DSA versus SC-DSA
   - Efficient DSA strategies: SC-DSA, MC-MAC
4. Network-level Optimizations
   - Multi-hop forwarding optimization and lifetime awareness
   - Distributed power control and lifetime awareness
5. Green Communications
   - Network RF energy harvesting
   - Wireless RF energy transfer
6. Summary

Motivations to Cross-Layer Protocol Optimization Studies

- Basic network layer concepts

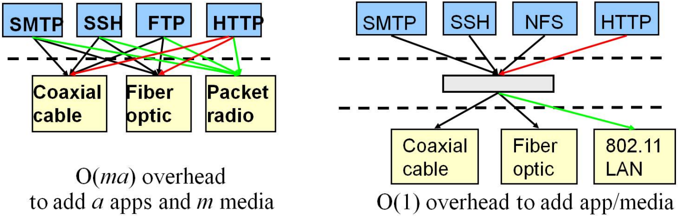


Fig. 1: Network layering motivation

  - Pros and cons of layer-based approach

- **Miniaturization** and **personalization** of mobile wireless devices
- **Green communication systems**
  - Need for **network planning**: e.g., routing, switching, multiplexing
  - Need for **resource management**: e.g., frequency reuse, energy usage
- Cross-layered study objectives and concepts
  - Pros and cons of cross-layered approach
- Need for **system-level performance modeling and analysis**

Cross-Layer Interactions and Examples

Functionalities of a protocol layer are influenced by the other layers. Accounting such dependencies make the protocol design more responsive to the system's needs as a whole.

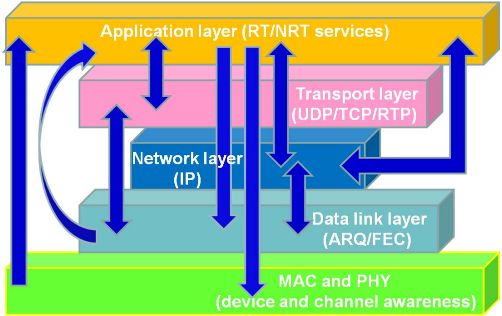


Fig. 2: Cross-layering examples

- Physical layer aware media access control, e.g., in UWSN
- Physical layer aware link layer error control, e.g., stop-and-wait protocol
- Physical channel and device limitations aware source coding adaptation
- Energy efficiency and energy harvesting toward green communications

Performance Measures

- **Capacity**: Measure of the quantity of traffic supported by system (Units: Erlangs, bits/s)
- **Throughput**: Measure of traffic successfully received at intended destination (Units: bits/s)
- **Delay**: Time (service + waiting) required to transmit the traffic
- **Loss probability**: Measure of the chance that traffic being lost
- **Jitter**: Measure of variation in packet delivery timing
- **Utilization**: Fraction of time the resource is busy in servicing requests
- **Bottleneck**: The system resource with a maximum utilization
- **System size**: Average number of customers served in a given time
- **Queue size**: Average number of customers waiting in queue

Performance Evaluation Techniques

Three main evaluation techniques

- **Measurement**
- System **simulation**
- Mathematical or **analytical** modeling

Table 1: Comparison of three techniques

Technique	Requirements	Merits	Demerits
Measurement	Instrumentation and experimental hardware	Most accurate	1. Expensive and time consuming 2. Non-repetitive measurements 3. Not compatible with future designs
Simulation	1. Simulator 2. Programming skills	1. High control over parameters and workload 2. Compatible with future system designs with some extra effort	1. Less accuracy 2. Large effort
Analysis	1. Systems level understanding 2. Mathematical skills	1. Least effort 2. High control over parameters and workload 3. Smooth compatibility to future system designs	1. Least accurate 2. Unrealistic assumptions

Purpose of Mathematical Modeling

- Analytical solution gives insight to more complex problems
- Can provide validation of simulation results
- Helps in algorithm and heuristics designing
- Applications
  - Traffic engineering
  - Call blocking probability
  - Dynamic routing
  - Queuing networks
  - Integrated packet radio networks
- Classification of analytical techniques
  - Markov chains and Markov processes
  - Independent queues
  - Network of queues
  - Stochastic petrinets
  - Markov Decision Process

Link-level Objectives and Current Practices

- Node-level error and flow control
  - Error-prone wireless channel: use error control schemes (AMC, ARQ, FEC)
  - Time-varying channel: ARQ vs. FEC (error bursts, return channel, delay)
  - Limited energy of of portable devices: energy efficiency of interest
- Classical ARQ schemes: SW, GBN, SR
- PHY solutions: MCS (e.g., n-QAM, Hamming codes, RS codes)
- Hybrid ARQ: FEC+limited ARQ
- "Channel-aware" link-layer transmission solutions
  - Probing-based [Zorzi and Rao (IEEE Trans. Comp. '97)]
  - Probabilistic automata [Sampath, et al. (Intl. J. WCMC, 2007)]
- Window flow control (Transport layer)

- Seek and utilize the channel information to adapt *suitably*
  - Need to appropriately filter out the required channel information

Wireless Channel Characterization: Markov Model

- Packet error follow a **first-order Markov model** with transition matrix[1]

$$M(x) = \begin{bmatrix} p(x) & q(x) \\ r(x) & s(x) \end{bmatrix} \quad \text{and} \quad M(1) = \begin{bmatrix} p & q \\ r & s \end{bmatrix}$$

  where $p = 1 - q$ and $r = 1 - s$ are probability of successful and unsuccessful transmissions respectively
- Marginal probability of packet error $\varepsilon = 1 - \frac{r}{1-p+r}$
- Average probability of block error $\varepsilon = P[1] = E[P_w(v)] = \int_0^\infty P_w(a) f_v(a) da$ where fading envelope $f_v(a)$ is pdf of **fading envelope**
- Probability that two successive blocks are in error is:

$$P[1,1] = E[P_w(v_1) P_w(v_2)] = \int_0^\infty \int_0^\infty P_w(a_1) P_w(a_2) f_{v_1 v_2}(a_1, a_2) da_1 da_2$$

$$\text{and} \quad r = 1 - P[1|1] = 1 - \frac{P[1,1]}{P[1]} = 1 - \frac{P[1,1]}{\varepsilon}$$

- For **2nd order SC diversity**, conditional probability of unsuccessful reception:

$$P_w(x) = 1 - P[A(x)] \quad \text{with} \quad x = \max\left\{v^{(1)}, v^{(2)}\right\}$$
$$\text{where} \quad F_v(a) = P\left[v^{(1)} \le a\right]\left[v^{(1)} \le a\right]$$

[1] M. Zorzi and R. Rao, "Error control and energy consumption in communications for nomadic computing," *IEEE Trans. Comput.*, vol. 46, no. 3, pp. 279–289, Mar. 1997.

Wireless Channel Characterization – II

- $F_x(a) = [F_v(a)]^2$ and $\varepsilon = E[P_w(x)] = \int_0^\infty P_w(a) 2F_v(a) f_v(a) da$
- $F_{x_1 x_2}(a_1) = [F_{x_1 x_2}(a_1, a_2)]^2$ and

$$P_d[1,1] = E[P_w(x_1)P_w(x_2)] = \int_0^\infty \int_0^\infty P_w(a_1)P_w(a_2) f_{x_1 x_2}(a_1, a_2)\, da_1 da_2$$

- If $P_w(v) \begin{cases} 0, & v^2 > b \\ 1, & v^2 \le b, \end{cases}$, then

$$\varepsilon = F_v(\sqrt{v}), P[1,1] = F_{v_1 v_2}\left(\sqrt{b}, \sqrt{b}\right) \text{ and } \varepsilon_d = \varepsilon^2$$

$$P_d[1,1] = F_{v_1 v_2}\left(\sqrt{b}, \sqrt{b}\right) \text{ and } \varepsilon_d = \varepsilon^2$$

$$P_d[1,1] = \left[F_{v_1 v_2}\left(\sqrt{b}, \sqrt{b}\right)\right]^2, \varepsilon_d = (P_d[1,1])^2 \text{ and } r_d = 1 - (1-r)^2$$

- For Rayleigh fading, the pdf of envelope is: $f_v(a) = 2ae^{-a^2}$
- Joint pdf is $f_{v_1 v_2}(a_1, a_2) = \frac{a_1 a_2}{1-\rho^2} e^{-\frac{a\left(a_1^2 + a_2^2\right)}{2(1-\rho^2)}} I_0\left(\frac{\rho a_1 a_2}{1-\rho^2}\right)$ with $\rho = J_0(2\pi f_D T)$
- $\varepsilon = 1 - e^{-b}$, $r = \frac{Q(\theta, p\theta), Q(p\theta, \theta)}{e^b - 1}$, where $\theta = \sqrt{\frac{2b}{1-\rho^2}}$.

Stop-and-Wait ARQ Protocols for Short Range Communication[2]

- Performance measures for an ARQ protocol:
  - *Data throughput* $\mathcal{R}$: Average number of successfully delivered frames/sec: $\mathcal{R} \triangleq \lim_{t\to\infty} \frac{E\{\text{number of data frames successful in time } t\}}{t}$
  - *Energy consumption* $\mathcal{E}$ per successful data frame, defined in terms of battery energy consumed (in Joules), including transmit and receive energy per data frame e_d, transmit and receive energy per ACK/NAK frame e_a, per slot idling energy e_w, and per slot total energy consumption e_p per probing frame.
- $p_{11}(m) = \frac{[p_{21}+(1-p_{21}-p_{12})^m p_{12}]}{p_{21}+p_{12}}, \quad p_{21}(m) = \frac{p_{21}[1-(1-p_{21}-p_{12})^m]}{p_{21}+p_{12}}$

SW cycle

The length of a cycle in basic SW protocol is defined as the duration starting from an unsuccessful frame to the end of its successful transmission.

- $E\{\mathbf{K}\} = \sum_{\kappa=1}^{\infty} \kappa \cdot \Pr[\mathbf{K} = \kappa] = \frac{p_{12}(m)+p_{21}(m)}{p_{21}(m)}$
- Since a SW cycle has only one successful data frame, the throughput of basic SW is: $\mathcal{R}_{SW} = \frac{1}{E\{\mathbf{K}\}\cdot m \cdot s}$
- The energy consumed per successful data frame in basic SW approximately given by: $\mathcal{E}_{SW} = E\{\mathbf{K}\}\,[e_d + e_a + (m-1)e_w]$

[2] S. De, et al. (IET Commun., 6(14), 2012)

Channel Oblivious Probing (COP) Scheme based SW

- Once a NAK is received, the transmitter enters into probing mode, with a periodicity independent of the fading margin
- The probing frames are continued until a probing ACK is received
- The average number $E\{\mathbf{P}\}$ in a set of contiguous probing is: $E\{\mathbf{P}\} = \frac{1}{p_{21}(t_p)}$

COP cycle

The length of a cycle in COP based SW is defined as the duration between two probing phases, which gives a single probing ACK.

- $E\{\mathbf{K}\} = \frac{1+p_{12}(m)}{p_{12}(m)}$
- The data throughput in COP based SW is: $\mathcal{R}_{COP} = \frac{E\{\mathbf{K}\}-1}{(E\{\mathbf{K}\}-1)ms+s+T_p+E\{\mathbf{P}\}t_p s+2T_p}$
- Average energy consumed per successful data frame is approximately given by: $\mathcal{E}_{COP} = \frac{E\{\mathbf{K}\}(e_d+e_a)+(E\{\mathbf{K}\}-1)(m-1)e_w+E\{\mathbf{P}\}(e_p+t_p e_w)}{E\{\mathbf{K}\}-1}$

Channel Aware Probing (CAP) and Channel Aware SW (CASW) schemes

- Average waiting time in in CAP2 is:
  $E\{\mathbf{W}^{(x)}\} = \sum_{i=0}^{L-1} W_i^{(x)} \; p_{i|nak}$ where $x = 1, 2$
- $E\{\mathbf{P}\} = \frac{p_{21}(w_2)+p_{22}(w_1)}{p_{21}(w_2)}$
- Expected total waiting time in CAP3 probing mode in a fading cycle $\mathbf{w_p}$ is:

$$E\{\mathbf{w_p}\} = E\{\mathbf{W}^{(1)}\} + E\{\mathbf{W}^{(2)}\}\frac{p_{22}(w_1)}{p_{21}(w_2)}$$

- $\mathcal{R}_{CAP3} = \frac{E\{\mathbf{K}\}-1}{\left[\left(E\{\mathbf{K}\}-1\right)ms+s+T_p\right]+\left\lceil\frac{E\{\mathbf{w_p}\}}{s}\right\rceil s+2T_p}$
- $\mathcal{E}_{CAP3} = \frac{E\{\mathbf{K}\}(e_d+e_a)+\left(E\{\mathbf{K}\}-1\right)(m-1)e_w+E\{\mathbf{P}\}e_p+\left\lceil\frac{E\{\mathbf{w_p}\}}{s}\right\rceil e_w}{E\{\mathbf{K}\}-1}$

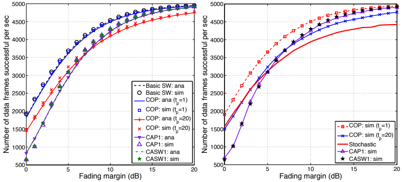
CASW cycle

A *CASW cycle* is the duration between the ends of two consecutive lost data frames.

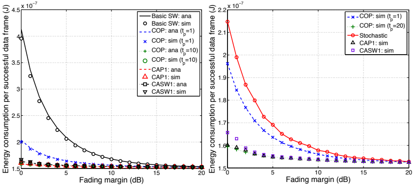
- $E\{\mathbf{J}\} = \frac{p_{21}(\pi)}{p_{12}(m)}$
- Data throughput of the CASW protocol is given by
  $\mathcal{L}_{CASW} = \frac{E\{\mathbf{J}\}}{(E\{\mathbf{J}\}ms+s+T_p)+\pi s}$
- The energy consumption per successful frame is approximately given by:
  $\mathcal{E}_{CASW} = \frac{1}{E\{\mathbf{J}\}}\left[(E\{\mathbf{J}\}+1)(e_d+e_a)+E\{\mathbf{J}\}(m-1)e_w+\pi e_w\right]$

Numerical Results

- Throughput performance with binary feedback
- Energy consumption with binary feedback
- Performance with received signal power feedback



(a) Comparison with basic SW and COP (b) Physical layer aware approaches



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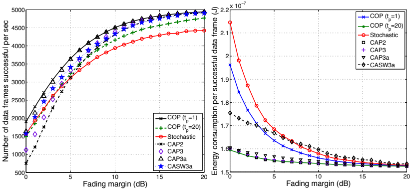
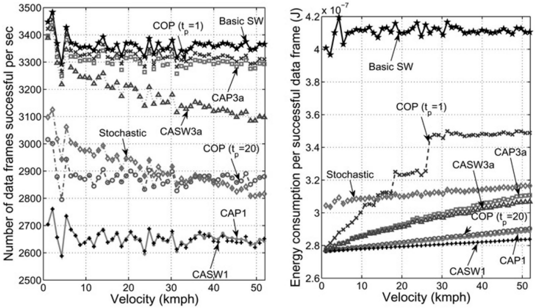


(a) Data throughput (b) Energy consumption

Effect of Mobility and Energy Saving-Throughput Tradeoff Results

- Effect of mobility on Throughput and Energy consumption performance



- Performance improvement provided by proposed schemes over basic SW protocol

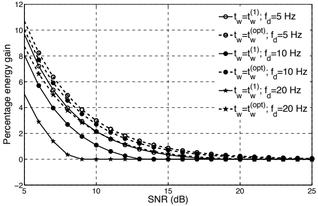
Energy saving (*E*-gain) and throughput trade-off (*R*-loss) in CASW1 and CAP3a protocols over basic SW protocol at different fading margins (FM), $f_D = 50$ Hz

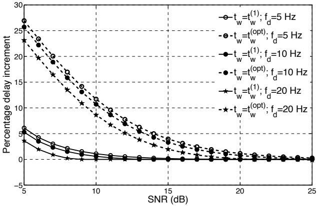
FM, dB	CASW1		CAP3a	
	E-gain, %	*R*-loss, %	*E*-gain, %	*R*-loss, %
4	29.9	21.5	29.4	2.3
6	19.9	13.0	19.4	1.4
8	13.0	8.0	12.3	1.0
10	8.2	5.2	7.7	0.8
12	5.0	3.4	4.7	0.6

Exploiting fading dynamics along with AMC[3]

- $\varepsilon = 1 - e^{-\frac{1}{F}}, p_{11}(1) = 1 - \frac{p_{21}(1)\varepsilon}{1-\varepsilon}, p_{21}(1) = \frac{Q(\theta,\rho\theta)-Q(\rho\theta,\theta)}{e^{\frac{1}{F}}-1}$

  where ε is steady state error probability in a slot, $\theta = \sqrt{\frac{2}{F(1-\mu^2)}}$, and $\mu = J_0(2\pi f_d T_f)$, $F = \frac{\overline{\gamma}}{\gamma_1}$ with γ_1 as the mode 0 switching threshold.
- In FD-AMC, a frame transmission is postponed for s slots, where $s = \left\lceil \frac{t_w}{T_f} \right\rceil$.
- For basic AMC, $s = 1$.
- The s-step transition probabilities are:
  $p_{11}(s) = \frac{[p_{21}(1)+\eta^s p_{12}(1)]}{1-\eta}$, $p_{21}(s) = \frac{p_{21}(1)[1-\eta^s]}{1-\eta}$, where $\eta = 1 - p_{21}(1) - p_{12}(1)$.
- Energy saving versus delay trade-off – Relationship between energy consumption $\mathcal{E}_p$ and waiting time s slots:
  $\mathcal{E}_p(s) = \frac{1}{\omega}\left[(e_t + e_r)T_f + \frac{(2e_w T_f s + H)(1-\eta)p_{12}(1)}{(1-\eta^s)p_{21}(1)}\right]$, where $H = (e_t + e_r - 2e_w)T_h$.





[3] A. Sharma and S. De (IEEE Commun. Lett., 15(11), 2011)

ARQ-based switched antenna diversity in Markov channels[4]

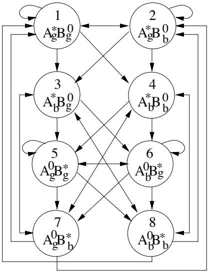
- $T_{R_A} = \begin{pmatrix} p_1 & p_3 \\ p_4 & p_2 \end{pmatrix}$ and $T_{R_B} = \begin{pmatrix} q_1 & q_3 \\ q_4 & q_2 \end{pmatrix}$
- $\mathrm{PER}_A = \frac{1-p_1}{2-p_1-p_2}$ and $\mathrm{PER}_B = \frac{1-q_1}{2-q_1-q_2}$
- $P =$

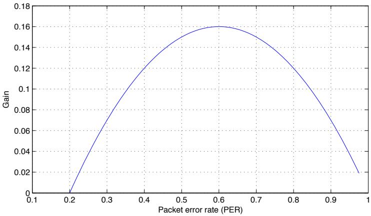
$$\begin{bmatrix} p_1q_1 & p_1q_3 & p_3q_1 & p_3q_3 & 0 & 0 & 0 & 0 \\ p_1q_4 & p_1q_2 & p_3q_4 & p_3q_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & p_4q_1 & p_2q_1 & p_4q_3 & p_2q_3 \\ 0 & 0 & 0 & 0 & p_4q_4 & p_2q_4 & p_4q_2 & p_2q_2 \\ 0 & 0 & 0 & 0 & p_1q_1 & p_3q_1 & p_1q_3 & p_3q_3 \\ 0 & 0 & 0 & 0 & p_4q_1 & p_2q_1 & p_4q_3 & p_2q_3 \\ p_1q_4 & p_1q_2 & p_3q_4 & p_3q_2 & 0 & 0 & 0 & 0 \\ p_4q_4 & p_4q_2 & p_2q_4 & p_2q_2 & 0 & 0 & 0 & 0 \end{bmatrix}$$

- Throughput of the SSC-ARQ combined scheme: $\eta_{SSC-ARQ} = \pi_1 + \pi_2 + \pi_5 + \pi_6$
- If the channels are symmetrical (i.e., $p_1 = q_1$ and $p_2 = q_2$),

$$\eta_{SSC-ARQ-sym} = \frac{(1-p_2)^2+(1-p_1)(1-p_2)(p_1+p_2)}{(2-p_1-p_2)^2}$$

- Throughput of ARQ system with only one receive antenna: $\eta_{ARQ} = (1 - \mathrm{PER}) = \frac{1-p_2}{2-p_1-p_2}$
- Throughput gain achieved with SSC-ARQ: $\mathrm{Gain} = \eta_{SSC-ARQ} - \eta_{ARQ}$





[4] S. S. Chakraborty, et al. (IET Electron. Lett., 44(25), 2008)

Network Cooperation

- Cooperation between different networks or BS of same network can increase the performance of users (current state-of-the-art: **CoMP**)
- **Network-level cooperation for cell-edge and handoff users**[5,6,7]: Content is split intelligently across different BSs to provide higher QoS
- **Heterogeneous networks**[8]: User devices capable of connecting to different networks simultaneously (increased capacity and lower delays)
- **Cognitive Multihoming**[9]: Cellular BSs enabled with cognitive radio functionalities (improves QoS while decreasing cost)

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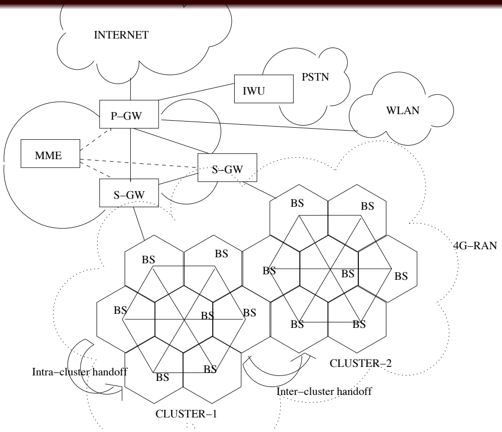
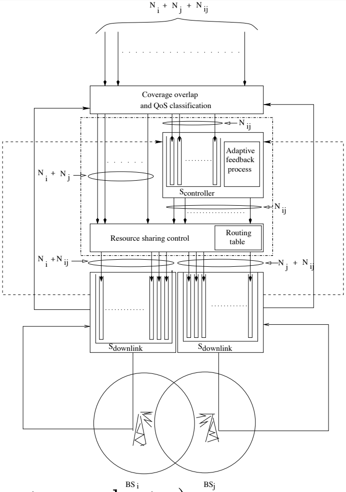
[5] S. Kumar et al. (Proc. IEEE WCNC 2012)
[6] C. Singhal, et al. (IEEE TMC, 13(1), 2014)
[7] S. Agarwal. et al. (IEEE TVT, 64(6), 2015)
[8] C. Singhal and S. De (IGI Pub. book chapter 2013)
[9] S. Agarwal and S. De (*due* in IEEE GLOBECOM Wksp., Dec. 2015)

QoS-aware Split Handoff





Two major problems at the cell-edge

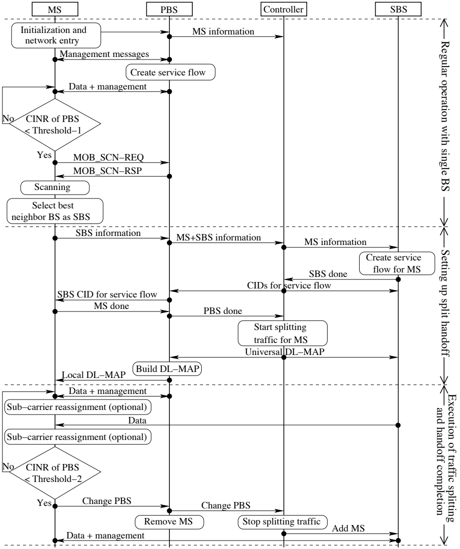
- Handoff (based on SNR, load, interference, cost, speed, etc.)
- Inter-cell Interference (ICI)

Proposed approach: QoS-aware resource splitting across the different BSs

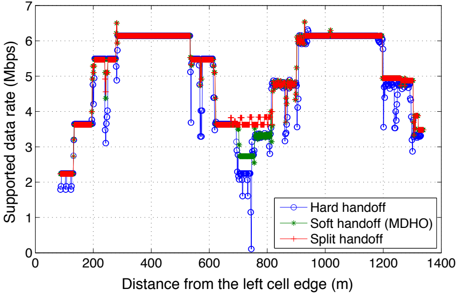
- Inherent SNR awareness, load balancing, interference control

The Algorithm and Differentiated QoS Performance

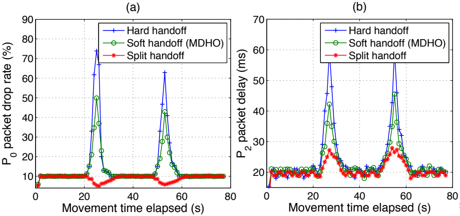
Split handoff algorithm:



Rate supported at the cell-edge:



Differentiated QoS performance:



Analysis

Outage Probability

- SINR $\gamma_{i,x} = \frac{P \cdot L_{i,x}}{I^0_{i,x} + I^s_{i,x} + N_0 B}$ $I^s_{i,x} \approx 0$ and $I^0_{i,x} >> N_0 B$
- Collision probability from j^{th} BS:
  $P_{col,j} = P_{sel}(j|i) = \frac{P_{sel}(j) \cdot P_{sel}(i)}{P_{sel}(i)} = P_{sel}(j)$. $P_{sel}(j) = \rho_j$ (load on BS_j)
- ICI is $I^0_{i,x} = \sum_{j=1}^{N_{oc}} P \cdot L_{j,x} \cdot \rho_j$
- The outage probability in BS_i at position x is

$$P_{out,x}(i) = P[\gamma_{i,x} < \gamma_{th}] = P_i.$$

- P_{out} for hard handoff is

$$P^{hard}_{out,x}(i) = \sum_{i}^{N_c} P_x(i) \cdot P_{out,x}(i),$$

- For the proposed scheme:

$$P^{prop}_{out,x}(i) = \sum_{i}^{N_c} P_x(i) \cdot P_{out,x}(i) \cdot \prod_{j}^{N_{oc}} P_{out,x}(j) \ \ \forall \ \ i \neq j.$$

Analysis (Contd.)

Scheduling of Shared Users

- Effective capacity: $\bar{E}_C^u(\theta^u) = -\frac{1}{\theta^u S} log E\{e^{-\theta^u \mu_i^u}\}$
- If the same user is schedule from two BSs, BS_i and BS_j

$$\overline{E}_{C,joint}^{u,opt}(\theta^u) = \max_{\{S_{i,1}^u, S_{j,2}^u\}} -\frac{1}{\theta^u S}\left[\ln\left[\{e^{-\theta^u \mu_{i,1}^u}(1-P_i)+P_i\} \cdot \{e^{-\theta^u \mu_{j,2}^u}(1-P_j)+P_j\}\right]\right]$$

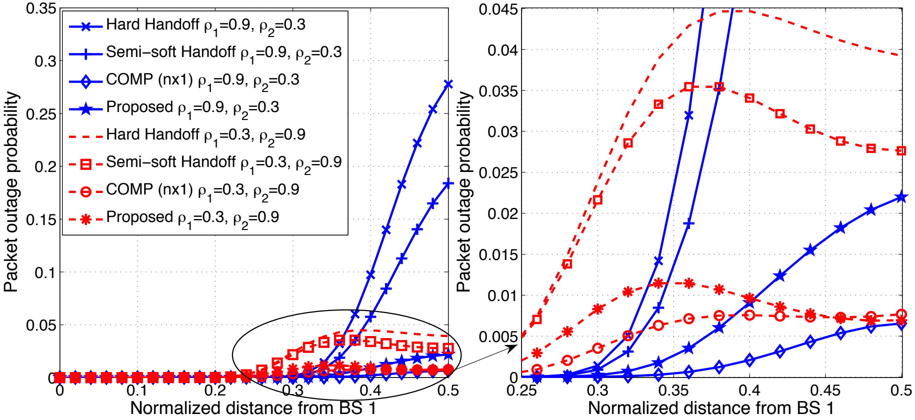
$$\text{s.t.} \quad S_{i,1}^u + S_{j,2}^u = S^u, \quad S_{i,1}^u, S_{j,2}^u > 0, \quad \text{and} \quad \gamma_{i,x} > \gamma_{th}, \quad \gamma_{j,x} > \gamma_{th}$$

- Solution:

$$S_{i,1}^u = \frac{S_i^u}{2} + \frac{S_i^u}{2\theta^u r} log\left[\frac{(1-P_i)/P_i}{(1-P_j)/P_j}\right]$$

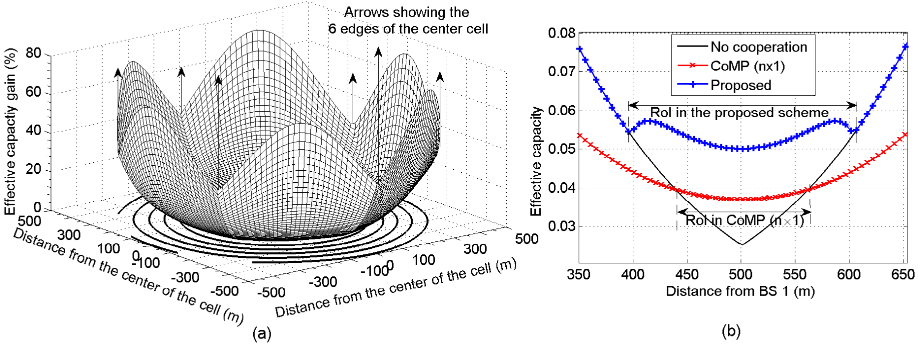
$$S_{j,2}^u = \frac{S_i^u}{2} + \frac{S_i^u}{2\theta^u r} log\left[\frac{(1-P_j)/P_j}{(1-P_i)/P_i}\right]$$

Results I



Comparison of packet outage probability in HHO, SSHO, CoMP $n \times 1$, and the proposed scheme in different traffic loading conditions with $[336, 320, 16]_2$ linear coding and and 4-QAM. $\gamma_{th} = 3$ dB, path loss factor $l = 3$, shadow fading mean 0 and standard deviation 6 dB. 2-cell cooperation $(n = 2)$ is considered with neighboring cell loads same as ρ_2.

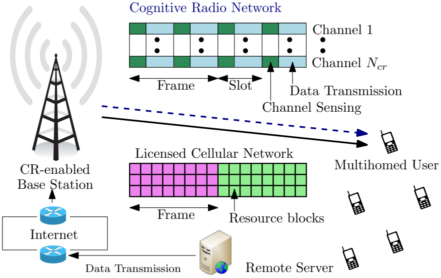
Results II



(a) Effective capacity gain of the proposed scheme with respect to no cooperation, for $\theta = 0.9$, $\gamma_{th} = 3$ dB, and $\rho = 0.9$. (b) Capacity comparison with $\rho = 0.7$ and all other parameters same as in (a).

Cognitive Multihoming

- QoS guarantee over CRNs difficult: intermittent PU activity
- Licensed cellular networks can ensure high QoS to users
- However, cellular networks suffer from spectrum scarcity issue and users are served at a higher cost
- CM: CR-enabled cellular BSs simultaneously transmit content to the multihomed users over the licensed cellular bands (LCN) and opportunistically over the PU bands
- User's cost is reduced by simultaneous transmission over LCN and CRN



Analysis

- User provides data rate requested d_{req} and cost preference α (maximum fraction of cost as compared to LCN user is willing to pay)
- Denote a_{ce}: number of RBs allocated to the user from LCN and $a_{cr,k}$: number of slots allocated over the kth channel of CRN per frame
- Probability of transmission success over LCN is s_{ce} and over CRN is s_{cr}
- The total number of successful slots for a user is given as:

$$d_{suc} = a_{ce} d_{ce} s_{ce} + \sum_{k=1}^{N_{cr}} a_{cr,k} d_{cr,k} s_{cr,k}$$

- Cost $\mathcal{C}$ to a user is:

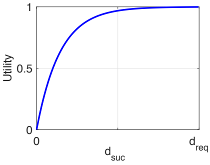
$$\mathcal{C} = b_{ce} d_{ce} \Phi_{ce} + \sum_{k=1}^{N_{cr}} b_{cr,k} d_{cr,k} \Phi_{cr}$$

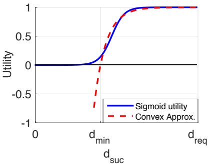
- User's cost is bounded by $\mathcal{C} \leq c_{max} = \alpha d_{req} \Phi_{ce}$

Optimization Problem

User's utility $\mathcal{U}$ depends on the traffic type requested:

$$\mathcal{U} = \begin{cases} 1 - e^{(-c_1 d_{suc}/d_{req})}, & \text{NRT app.} \\ \frac{1}{1+c_2 e^{(-c_3 d_{suc}/d_{req})}}, & \text{RT app.} \end{cases}.$$



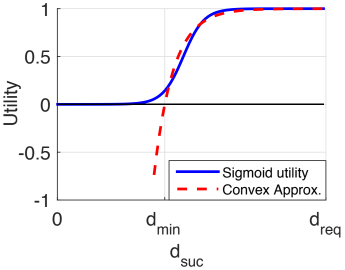


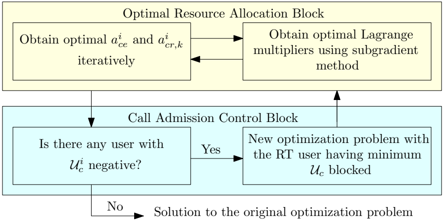
$$\begin{aligned} \underset{a^i_{ce}, a^i_{cr,k}}{\text{maximize}} \quad & \sum_{i=1}^{N} \mathcal{U}^i \\ \text{subject to} \quad & \mathcal{C}^i \leq c^i_{max}, \ \forall i = 1, 2, \cdots, N, \\ & \frac{(\sum_{i=1}^{N} \sum_{k=1}^{N_{cr}} a^i_{cr,k} d_{cr,k})^2}{N \sum_{i=1}^{N} (\sum_{k=1}^{N_{cr}} a^i_{cr,k} d_{cr,k})^2} \geq \gamma, \\ & \sum_{i=1}^{N} a^i_{ce} \leq N_{ce}, \\ & \sum_{i=1}^{N} a^i_{cr,k} \leq \frac{\tau}{\tau_{cr}}, \ k = 1, \ldots, N_{cr}. \end{aligned}$$

Solution to the Optimization Problem

- Approximation to RT user's utility function:

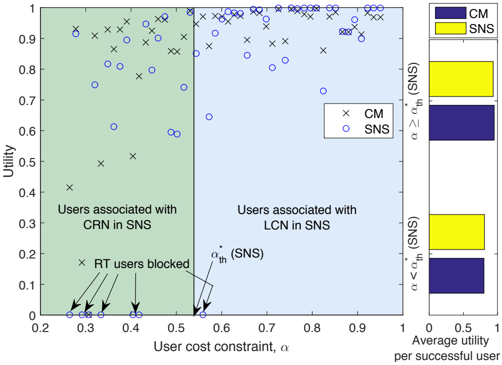
$$\mathcal{U}_c = 1 - e^{-c_4(d_{suc}-d_{min})/d_{req}}$$





Algorithm for optimal resource allocation

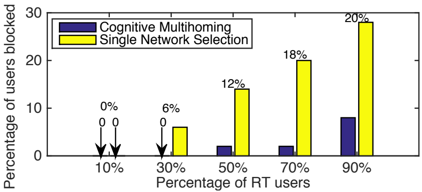
Results I

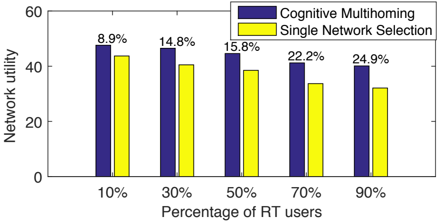


Users' utility along with their cost constraint (α) and average utility observed by successful users in different α regimes for the network with 50% RT users. $\gamma = 0.7$.

CM offers a high QoS to the users at low cost (low to moderate α users) along with high-paying users, while SNS can provide high QoS only to high-paying LCN users.

Results II



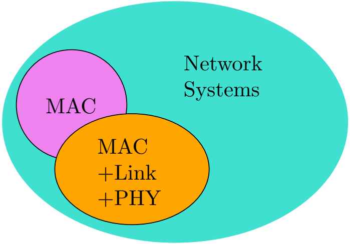


Number of users blocked and network utility obtained. $\gamma = 0.7$. Values above the bar shows the percentage gain in CM.

CM ensures lesser service outage to the RT users even with low α, thus serving a higher number of users at lower costs. CM attains high network utility, which indicates high QoS to the users in the system than in the SNS.

MAC, Link Layer, and PHY Cooperation

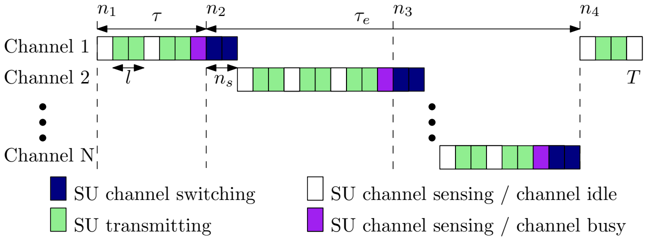
- MAC layer affects many aspects like user throughput, delay, energy consumption
- **Switched MC-DSA and SC-DSA**[10]: study single channel and multichannel operation over device's performance
- **Single channel access protocol**[11]: PHY and link layer optimization in cognitive radio networks
- **Multi-channel access protocol**[12]: PHY and MAC optimization while ensuring QoS to users in CRN



[10] S. Agarwal and S. De (IEEE Commun. Lett., 19(6), 2015)
[11] S. Agarwal and S. De (Proc. Nat. Conf. Commun. 2015)
[12] S. Debroy, et al. (IEEE TMC, 13(12), 2014)

Impact of Channel Switching in Energy Constrained Cognitive Radio Networks

- Consider two channel access schemes:
- SUs are assigned multiple channels and the channels are switched whenever a primary user (PU) returns (MC-DSA)
- SU operates on a single channel without switching to other channels (SC-DSA)
- Trade-off between SU channel utilization and energy efficiency is analyzed
- Switching time n_s slots, Φ_{sw} switching energy consumption per channel switch



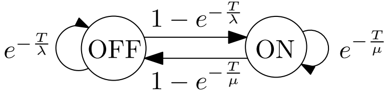
Markov Chain Representing Channel State

- Markov chain with states 'idle' (OFF) and 'busy' (ON) is employed to represent the states of the channel
- The transition probability from state 'idle' to 'busy' by:

$$P_{idle \rightarrow busy} = \int_0^T \frac{1}{\lambda} exp(-x/\lambda)\, dx = 1 - exp(-T/\lambda)$$

- Markov transition probability matrix

$$\mathbf{P} = \begin{bmatrix} e^{-T/\lambda} & 1 - e^{-T/\lambda} \\ 1 - e^{-T/\mu} & e^{-T/\mu} \end{bmatrix}$$



Computation of Optimal SU Packet Length

- Given PU collision ratio threshold η, PU can tolerate $\eta\mu$ in a single ON duration
- SU transmission length l ($l \ll \mu/T$) is

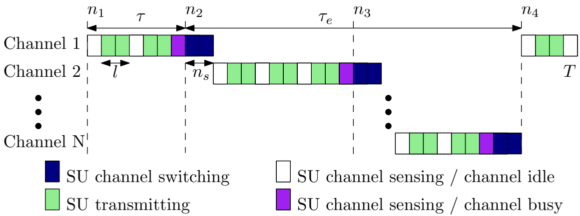
$$\mathbb{E}[\text{SU transmission collision}|\text{transmission collided}] \leq \frac{\eta\mu}{T}$$

$$\text{i.e.,} \quad \sum_{k=1}^{l} \frac{(l-k+1)e^{-\frac{T(k-1)}{\lambda}}(1-e^{-\frac{T}{\lambda}})}{1-e^{-\frac{T(l+1)}{\lambda}}} \leq \frac{\eta\mu}{T}, \quad \text{or,}$$

$$l \leq \frac{r+e^{-\frac{T}{\lambda}}}{1-e^{-\frac{T}{\lambda}}} + \frac{\lambda}{T}\mathbf{W}\left(\frac{e^{-\frac{T}{\lambda}}T(1+r)}{\lambda(e^{-\frac{T}{\lambda}}-1)}e^{-\frac{T\left(e^{-T/\lambda}+r\right)}{\lambda\left(1-e^{-T/\lambda}\right)}}\right)$$

- $\mathbf{W}(\cdot)$ is the Lambert-W function and $r = \eta\mu(1-e^{-T/\lambda})/T$

Analysis of Switched MC-DSA – I



- PMF of τ, G_τ is given as:

$$G_\tau = \begin{cases} 1 - p_0(n_1) & \tau = 1 \\ p_0(n_1)(\mathbf{P}_{(\mathbf{l+1})}(1,1))^{k-1}\mathbf{P}_{(\mathbf{l+1})}(1,2) & \tau = (l+1)k + 1 \\ 0 & \text{otherwise} \end{cases}$$

- PMF of τ_e, H_{τ_e} is given as $H_{\tau_e} = G^{\star(N-1)}(\tau_e - Nn_s)$

Analysis of Switched MC-DSA – II

- Probability of channel 1 being in OFF state at time n_4 is

$$p_0(n_4) = \sum_{i=Nn_s+1}^{\infty} H_{\tau_e=i} \left(\mathbf{P_c}\right)^i(2,1)$$

- From an initial value of p_0, iteration gives p_0 in steady state

$$\mathcal{U}_{\mathrm{MC}} = \frac{lv - p_0\eta\mu/T}{1+(l+1)v+n_s}$$

$$\mathcal{E}_{\mathrm{MC}} = \frac{lvT - p_0\eta\mu}{(1+v)\Phi_{se} + lv\Phi_t + \Phi_{sw} + n_s\Phi_i}$$

$v = p_0/\mathbf{P_{(l+1)}}(1,2)$ is the expected number of transmission instances by the SU between two channel switchings

Analysis of SC-DSA – I

- Number of transmission instances (k_l) is distributed as

$$Pr(k_l = k) = (\mathbf{P}_{(\mathbf{l+1})}(1,1))^{(k-1)}\mathbf{P}_{(\mathbf{l+1})}(1,2)$$

  with mean $\mathbb{E}[k_l] = 1/\mathbf{P}_{(\mathbf{l+1})}(1,2)$
- Number of times (k_s) SU senses the channel busy is distributed as

$$Pr(k_s = k) = (\mathbf{P}(2,2))^{(k-1)}\mathbf{P}(2,1)$$

  with mean $\mathbb{E}[k_s] = 1/\mathbf{P}(2,1)$

$$\mathcal{U}_{\text{SC}} = \frac{l\ \mathbb{E}[k_l] - \eta\mu/T}{(l+1)\mathbb{E}[k_l] + \mathbb{E}[k_s]}$$

$$\mathcal{E}_{\text{SC}} = \frac{lT\mathbb{E}[k_l] - \eta\mu}{\mathbb{E}[k_l](l\Phi_t + \Phi_{se}) + \mathbb{E}[k_s]\Phi_{se}}$$

Analysis of SC-DSA – II

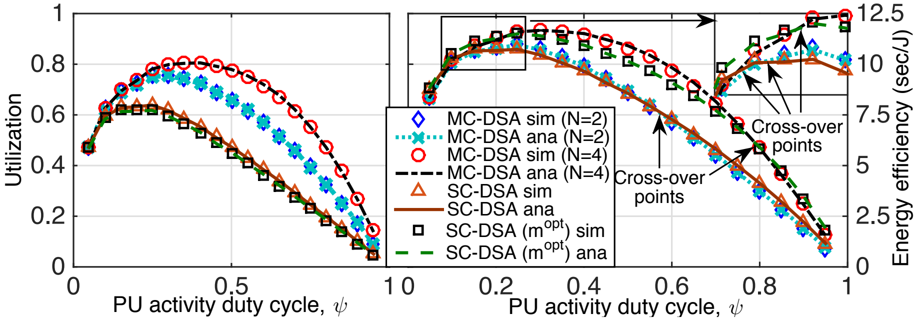
For m slot inter-sensing interval

- Number of times SU senses the busy channel to find it available is modified to
$$Pr(k_s = k) = (\mathbf{P_m}(2,2))^{(k-1)}\mathbf{P_m}(2,1)$$
with mean $\mathbb{E}[k_s] = 1/\mathbf{P_m}(2,1)$
-
$$\mathcal{U}_{\text{SC}}^{(m)} = \frac{l\ \mathbb{E}[k_l] - \eta\mu/T}{(l+1)\mathbb{E}[k_l] + m\mathbb{E}[k_s]}$$
$$\mathcal{E}_{\text{SC}}^{(m)} = \frac{lT\mathbb{E}[k_l] - \eta\mu}{\mathbb{E}[k_l](l\Phi_t + \Phi_{se}) + \mathbb{E}[k_s](\Phi_{se} + (m-1)\Phi_i)}$$
- Optimal m is given by setting $d\mathcal{E}_{\text{SC}}^{(m)}/dm = 0$

$$m^{opt} = \left\lfloor \frac{1}{\ln(\kappa)}\mathbf{W}\left(-e^{\frac{(\Phi_{se}-\Phi_i)\ln(\kappa)-\Phi_i}{\Phi_i}}\right) - \frac{(\Phi_{se}-\Phi_i)\ln(\kappa)-\Phi_i}{\Phi_i\ln(\kappa)}\right\rfloor$$

$\kappa \triangleq 1 - e^{-T/\lambda} - e^{-T/\mu}$

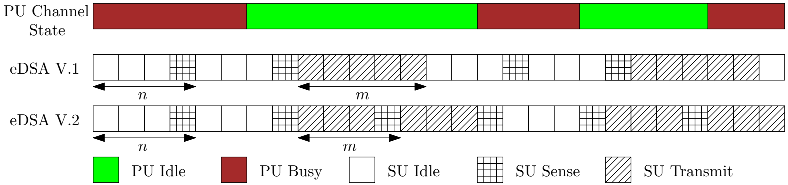
Results



$\mathcal{U}$ and $\mathcal{E}$ at different PU channel activity for exponentially distributed PU idle and busy periods with slot duration $= 50\mu s$, $\lambda = 5$ms, $n_s = 4$, $\Phi_{se} = 40mW$, $\Phi_i = 16.9mW$, $\Phi_{tx} = 69.5mW$, $\Phi_{sw} = 20\mu J$

Persistent Link Layer Transmission Strategy for Efficient DSA

- Optimal spectrum access policy in an agile PU channel ensuring high channel utilization and energy efficiency
- Joint optimization of SU packet lengths and SU inter-sensing intervals
- Single PU channel with a pair of SUs operating
- PU activity ON (busy), OFF (idle) periods exponentially distributed (average periods μ and λ respectively)
- Two phases: spectrum sensing phase and data transmission phase
- Spectrum sensing phase duration n slots. SU remains idle for $n-1$ slots and senses the channel in the last slot
- Data transmission phase duration m slots. SU enters this phase when channel is sensed idle. Transmits data in this phase



Performance Metrics

- **SU Goodput:** Amount of data payload transmitted per unit time

$$\mathcal{G} = \lim_{t \to \infty} \frac{(d \cdot k_c - H) \cdot Pr\{\text{Rx Success}\} \cdot \#\text{ Packets sent in time } t}{\text{Total time } t}$$

  Total message size d bits; k_c fraction of bits representing payload in the encoded message bits; H header length

- **SU energy efficiency:** goodput achievable by investing a unit amount of energy

$$\mathcal{G}_E = \frac{\text{SU Goodput}}{\text{Energy consumption by SU}}$$

- **PU collision ratio:** proportion of time SU's transmission interferes with PU's

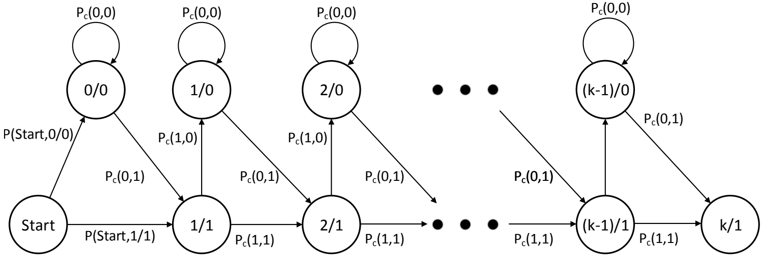
$$\mathcal{R}_c = \frac{\text{Number of slots in which PU experienced collision}}{\text{Number of slots in which PU transmitted}}$$

Analysis I

- C_k denotes channel state at slot k:

$$C_k = \begin{cases} 1 & \text{if channel is busy (ON) at slot } k \\ 0 & \text{if channel is idle (OFF) at slot } k. \end{cases}$$

- Characterize PU activity in the two phases of operation
- State = (# of PU occupied slots upto slot k, state of channel at slot k)



Analysis II

- Expected number of PU slots occupied in m slot SU data transmission phase
- 'Start' is 0/0

$$E_c(m) = \mathbf{E}[\text{PU occupied slots}] = \sum_{i=1}^{m-1} i \cdot \underline{P}_{tm}^{m}(start, i/0) + \sum_{i=1}^{m} i \cdot \underline{P}_{tm}^{m}(start, i/1)$$

- Expected number of PU slots occupied in n slot SU channel sensing phase
- 'Start' is 0/1

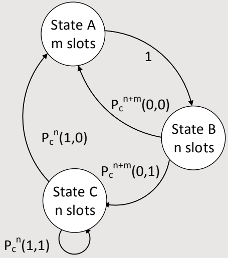
$$E_t(n) = \mathbf{E}[\text{PU occupied Slots}] = \sum_{i=1}^{(n-1)} i \cdot \underline{P}_{in}^{n}(start, i/0) + \sum_{i=1}^{n} i \cdot \underline{P}_{in}^{n}(start, i/1)$$

- Probability of packet success with k_e as allowable error ratio

$$P_s(m) = \Pr\{\text{Packet success}\} = \sum_{i=0}^{\lfloor k_e \cdot m \rfloor} \{\underline{P}_{tm}^{m}(start, i/0) + \underline{P}_{tm}^{m}(start, i/1)\}$$

Analysis III

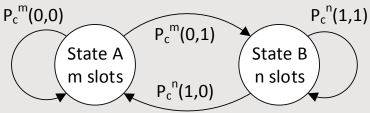
FSM representation eDSA V.1



$\underline{P^{V_1}} =$

	A	B	C
A	0	1	0
B	$\mathbf{P}_c^{m+n}(0,0)$	0	$\mathbf{P}_c^{m+n}(0,1)$
C	$\mathbf{P}_c^{n}(1,0)$	0	$\mathbf{P}_c^{n}(1,1)$

FSM representation eDSA V.2



$\underline{P^{V_2}} =$

	A	B
A	$\mathbf{P}_c^{m}(0,0)$	$\mathbf{P}_c^{m}(0,1)$
B	$\mathbf{P}_c^{n}(1,0)$	$\mathbf{P}_c^{n}(1,1)$

Analysis IV

eDSA V.1:

- Goodput:

$$\mathcal{G}^{V_1}(\mathbf{m}, n) = \frac{\pi^{V_1}(A) \cdot (d_m \cdot k_c - H) \cdot P_s(m)}{T \cdot (\pi^{V_1}(A) \cdot m + \pi^{V_1}(B) \cdot n + \pi^{V_1}(C) \cdot n)}$$

- PU collision ratio:

$$R_c^{V_1}(\mathbf{m}, n) = \frac{\pi^{V_1}(A) \cdot E_c(m)}{\pi^{V_1}(A) \cdot E_c(m+n) + \pi^{V_1}(C) \cdot E_t(n)}$$

- Energy consumption:

$$\Phi^{V_1}(\mathbf{m}, n) = \frac{\pi^{V_1}(A) \cdot \Phi_t \cdot m + \pi^{V_1}(B) \cdot (\Phi_s + \Phi_i \cdot (n-1)) + \pi^{V_1}(C) \cdot (\Phi_s + \Phi_i \cdot (n-1))}{T \cdot (\pi^{V_1}(A) \cdot m + \pi^{V_1}(B) \cdot n + \pi^{V_1}(C) \cdot n)}$$

- Energy efficiency:

$$\mathcal{G}_E^{V_i} = \frac{\mathcal{G}^{V_i}}{\Phi^{V_i}}$$

$d_m = m \cdot b$, b per slot bits transmission, $\mathbf{m} = (m)$ or (m_1, m_2, m_3). Energy consumed per slot: Φ_s for channel sensing, Φ_t for packet transmission, and Φ_i in SU idling state

Analysis V

eDSA V.2:

- Goodput:

$$\mathcal{G}^{V_2}(\mathbf{m},n) = \frac{\pi^{V_2}(A)\cdot(d_{m-1}\cdot k_c - H)\cdot P_s(m-1)}{T\cdot(\pi^{V_2}(A)\cdot m + \pi^{V_2}(B)\cdot n)}$$

- PU collision ratio:

$$R_c^{V_2}(\mathbf{m},n) = \frac{\pi^{V_2}(A)\cdot E_c(m-1)}{\pi^{V_2}(A)\cdot E_c(m) + \pi^{V_2}(B)\cdot E_t(n)}$$

- Energy consumption:

$$\Phi^{V_2}(\mathbf{m},n) = \frac{\pi^{V_2}(A)\cdot(\Phi_t\cdot(m-1)+\Phi_s) + \pi^{V_2}(B)\cdot(\Phi_s+\Phi_i\cdot(n-1))}{T\cdot(\pi^{V_2}(A)\cdot m + \pi^{V_2}(B)\cdot n)}$$

- Optimizing SU goodput and energy efficiency

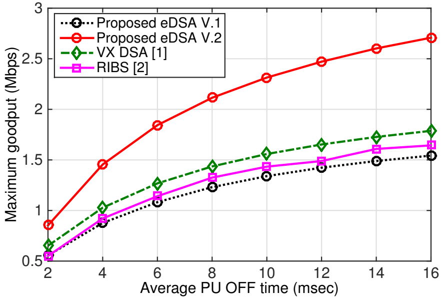
$$(P1)\quad \mathcal{G}_{opt}^{V_i} = \max_{\mathbf{m},n} \mathcal{G}^{V_i}(\mathbf{m},n) \qquad\qquad (P2)\quad \mathcal{G}_{\mathcal{E}}{}_{opt}^{V_i} = \max_{\mathbf{m},n} \mathcal{G}_{\mathcal{E}}{}^{V_i}(\mathbf{m},n)$$

$$\text{s.t.}\quad R_c^{V_i}(\mathbf{m},n) < \eta \qquad\qquad \text{s.t.}\quad R_c^{V_i}(\mathbf{m},n) < \eta$$

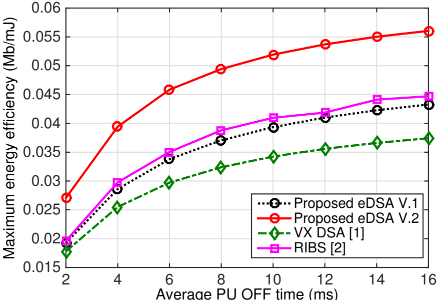
Above problems are integer programming problems and solved using branch-and-bound

Results

Relative goodput performance[13,14]



Relative energy efficienct



λ = 20 - 160 ms, μ = 50 ms, η = 0.05

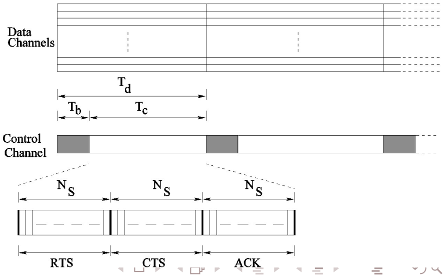
[13] [1] S. Huang, X. Liu, and Z. Ding, "Opportunistic spectrum access in cognitive radio networks," in *Proc. IEEE INFOCOM*, Phoenix, AZ, USA, Apr. 2008, pp. 2101 – 2109.

[14] [2] M. Sharma and A. Sahoo, "Stochastic model based opportunistic channel access in dynamic spectrum access networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 7, pp. 1625 – 1639, Jul. 2014.

Multi-Channel MAC for CRNs

- Designing efficient MAC protocols for distributed CRNs require a tight coupling between the spectrum access and spectrum sensing modules
- A distributed secondary network with multiple sensors is considered
- Sensor nodes broadcast periodic beacon advertising channel availability
- SUs under the purview of a sensor undergo a contention process for idle channel access advertised in the beacon
- Each SU is allowed to contend for only one mini-slot to avoid bandwidth/resource hogging and ensures long term fairness

- Contention process comprise of
  - RTS from potential transmitters
  - CTS from intended receiver
  - ACK with NAV
- Successful contention guarantees channel reservation
- SUs use the channel in the immediate next slot



Analysis I

Blocking probability at jth mini-slot: probability that a request for free channels at the jth mini-slot by any secondary transmitter-receiver pair will be blocked

$$BP = \begin{cases} 0 & \forall N_A \geq N_{SW} \\ \frac{N_{SW} - N_A}{\lambda_s N_S} & \text{otherwise} \end{cases}$$

N_A, N_{SW}, and λ_S is number of available channels, number of mini-slots won in RTS window, and secondary rate of contention, respectively.

Idle channel grabbing: Measure of how many channels the secondary nodes have grabbed among the idle channels after successfully winning the contention

$$N_{CG} = \begin{cases} N_{SW} & \forall N_A \leq N_S \\ N_A & \text{otherwise} \end{cases}$$

Analysis II

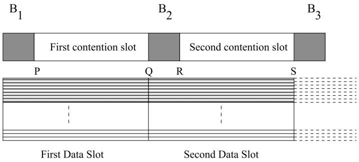
Idle channel utilization: Number of channels that are successfully utilized by SUs without any interruption from PU during the data transmission slot

$$\mathbb{E}[\text{Idle channel utilization}] = \frac{N_{CG} \cdot N_{DS}}{N_A}$$

PU QoS degradation: amount of time PU experiences interference from any SU

$$P_{PU}^{P \to Q} = 1 - \frac{\lambda_p e^{-\mu_p T_c} - \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)}$$

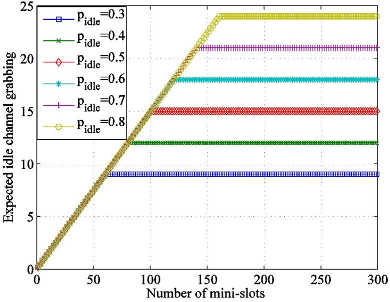
$$P_{PU}^{Q \to S} = 1 - \frac{\lambda_p e^{-\mu_p T_d} - \mu_p e^{-\lambda_p T_d}}{(\lambda_p - \mu_p)}$$



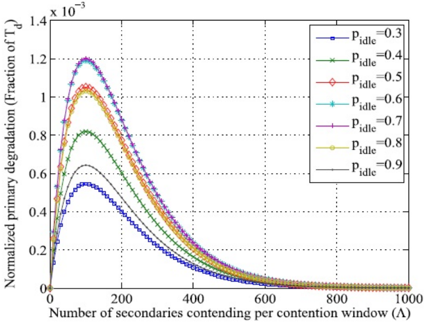
$$P_{SU} = \begin{cases} p_s & \forall N_A > N_S \\ \sum_{k=1}^{N_A} \frac{p_s}{N_S^k} \begin{pmatrix} N_A \\ k \end{pmatrix} (1 - \frac{1}{N_S})^{N_A - k} & \text{otherwise} \end{cases}$$

$$D_{PU} = P_{SU} \left[\left(\frac{T_C}{2} + T_D \right) P_{PU}^{P \to Q} + \frac{T_D}{2} P_{PU}^{Q \to S} \right]$$

Results I

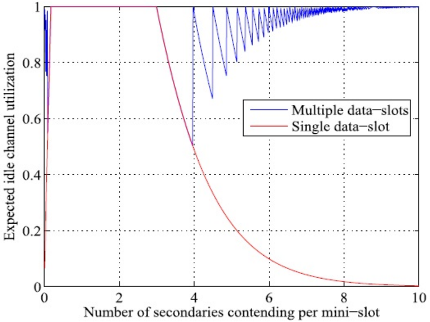


Idle channel grabbing characteristics, with $N_T = 30$ and $\lambda_s = 3$.

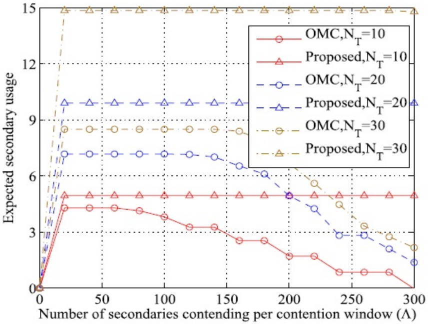


Expected PU degradation with $N_T = 30$ and $N_s = 100$.

Results II



Average idle channel utilization for single and multiple data-slots with N_T = 30 and N_S = 100.



Expected secondary usage comparison with OMC-MAC [15] [3] with p_{idle} = 0.5 and N_S = 100.

[15] [3] S. Jha, U. Phuyal, M. Rashid, and V. Bhargava, "Design of OMC-MAC: An opportunistic multi-channel MAC with QoS provisioning for distributed cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3414 – 3425, Oct. 2011.

Multi-hop Forwarding Optimizations

- Relaying decision[16]
- Greedy forwarding[17]
- Multi-criteria optimality[18,19,20]
- Lifetime-aware forwarding[21,22,23]

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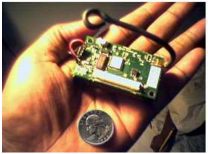
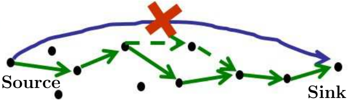
[16] K. Egoh and S. De (Proc. IEEE IWCMC 2006)
[17] S. De (IEEE Commun. Lett., 9(11), 2005)
[18] K. Egoh and S. De (Proc. IEEE MILCOM 2006)
[19] S. De and K. Egoh (US Pat. no. 7,872,977 B2, 2011; European Pat. no. EP2151100, 2010; Intl. Pat. no. WO/2008/151242, Nov. 2008)
[20] K. Egoh, et al. (Book Chapter, CRC Press, 2012)
[21] B. Panigrahi, et al. (Proc. IEEE Wksp. IAMCOM, 2009)
[22] B. Panigrahi, et al. (Proc. IEEE VTC-Spring, 2010)
[23] B. Panigrahi, et al. (IET Commun. 2012)

Multi-hop Forwarding Optimization

Multiple contrasting constraints:

- End-to-end delay
- Link error performance
- Energy consumption
- Nodal remaining energy





- Problem with centralized (ad hoc) routing algorithms:
  - larger storage (proactive routing)
  - larger bandwidth (reactive routing)
- Possible approach :- bluecolorDistributed Greedy forwarding : Packet forwarding decision is hop-by-hop, depending on some cost factors, till destination is reached
- Factors that influence the most :
  - Distance advancement toward destination
  - Average retransmissions due to packet drops (link layer)
  - Remaining energy at the receiver node
  - Interference at the receiver

Cross-Layer Issues in Multihop Relaying

The forwarding task of sending source information to the intended destination via intermediate relays

- **What to achieve**
  "Optimal" forwarding decision, e.g., minimize delay, error, energy consumption, . . .
- **How to achieve**
  The rule of relay selection, e.g., closest neighbor, least remaining distance, most remaining energy, . . .
- **Where to make the decision**
  Transmitter-side relay selection (TSRS)
  Receiver-side relay election (RSRE)
- **Constraints**
  Distributed decision making
  Asynchronous nodal behavior
  Limited resources, primarily battery power

Where to make Relaying Decision?

Transmitter Side

- Requires neighborhood info
- Good at low density and stable environment
- Needs wakeup signal or synchronized sleep pattern
- Decision making process "central" (at the transmitter)

Receiver Side

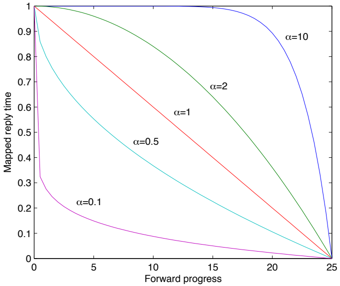
- Neighborhood info not required
- Good at high density and dynamic environment
- Can be opportunistic
- Decision process distributed

Better approach: RSRE

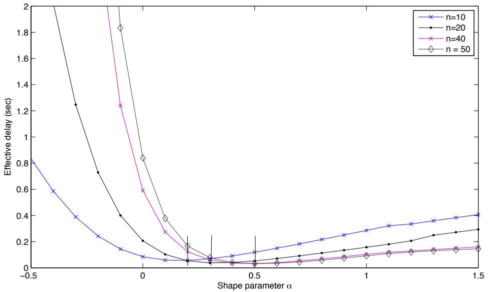
Receiver-side relay election approach offers more flexibility in communication

Mapping Priority-Backoff time

- Mapping function and effect of distribution of X_i's
  - For candidate i, $X_i = g(d_i) = a(\alpha)d_i^{\alpha} + b(\alpha)$,
  - Generalization of the linear mapping



- Existence of optimum α
  - For a given given density, there exists an optimum value α for which the effective delay is minimal



Election failure probability and election delay

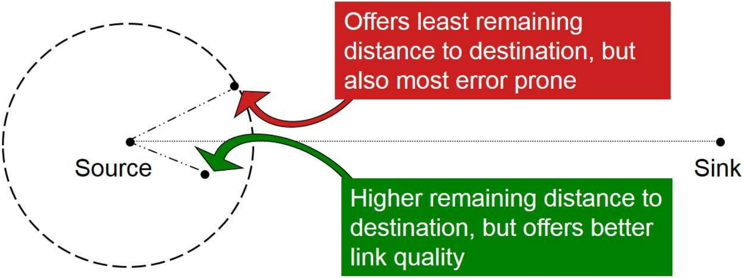
- **Election Failure Probability**
  - $Y = \min\{X_i\}$, $Y^* = \min\{X_i - Y\}$,
  - Failure probability $P_{fail} = \Pr\{Y^* \leq Y + \beta | Y = y\}$
  - $P_{fail} = 1 - \int_{t_1}^{t_2} h(y) S_Y(y + \beta) dy$
  - h: failure rate and S survival rate
  - β: collision vulnerability window

- **Election Delay**
  - Successful election round
  - Time $D = E(Y)$
  - Failure (P_{fail})
  - Timeout at t_1
  - With unlimited retry
  - $D_{\text{eff}} = \frac{P_{fail}}{1 - P_{fail}} t_1 + D$

Problem with Greedy Forwarding

Purely Greedy Forwarding

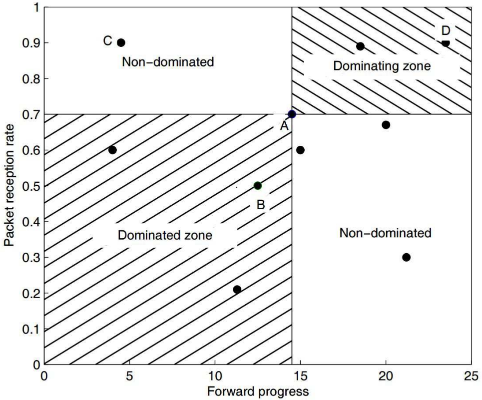
- Unit disk assumption
- Chose neighbor with least remaining distance to the destination



Multi-Criteria Optimality

Basic notion

- Dominated zone
- Dominating zone
- Non-dominated zones

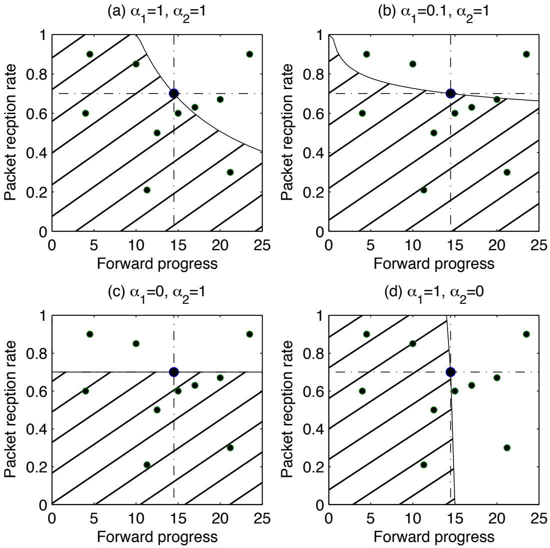


Multi-Criteria Mapping Function

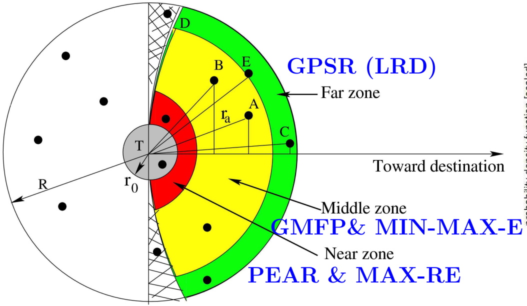
- For a set of k criteria $\Omega_1, \Omega_2, \cdots, \Omega_k$:
  $g_{\overline{\alpha}}\left(\Omega_{i1}, \Omega_{i2}, \cdots, \Omega_{ik}\right) = a\left(\overline{\alpha}\right) \Omega_{i1}^{\alpha_1} \Omega_{i2}^{\alpha_2} \cdots \Omega_{ik}^{\alpha_k} + b\left(\overline{\alpha}\right)$
- Equivalent to cost metric $C_{\overline{\alpha}}\left(\overline{\Omega_i}\right) = \Omega_{i1}^{\alpha_1} \Omega_{i2}^{\alpha_2} \cdots \Omega_{ik}^{\alpha_k}$
  mapped onto time $g_{\overline{\alpha}}\left(\overline{\Omega_i}\right) = a\left(\overline{\alpha}\right) \left[C_{\frac{1}{\alpha_1}\overline{\alpha}}\left(\overline{\Omega}\right)\right]^{\alpha_1} + b\left(\overline{\alpha}\right)$

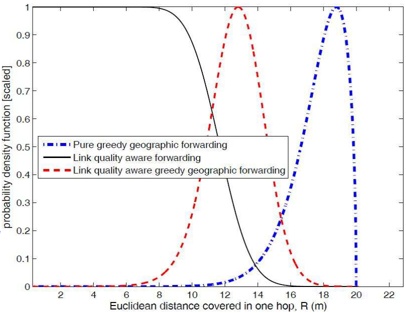
A Two Criteria Example

Forward progress d and link quality p: $C(\alpha_1, \alpha_2)(\mathrm{d,p}) = d^{\alpha_1} p^{\alpha_1}$



Lifetime Aware Forwarding





- GMFP = Greedy geographic forwarding
  + Transceiver energy consumption
  + Link layer quality
- **Min-Max-E** = GMPF + Max. remaining energy
- Local (distributed) data forwarding decision
- Delay tradeoff

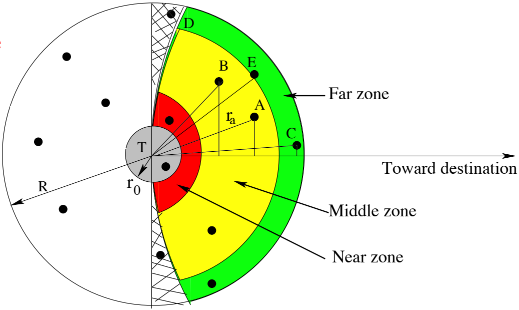
Virtual forwarding zones in lifetime maximization protocols

Maximize network lifetime:

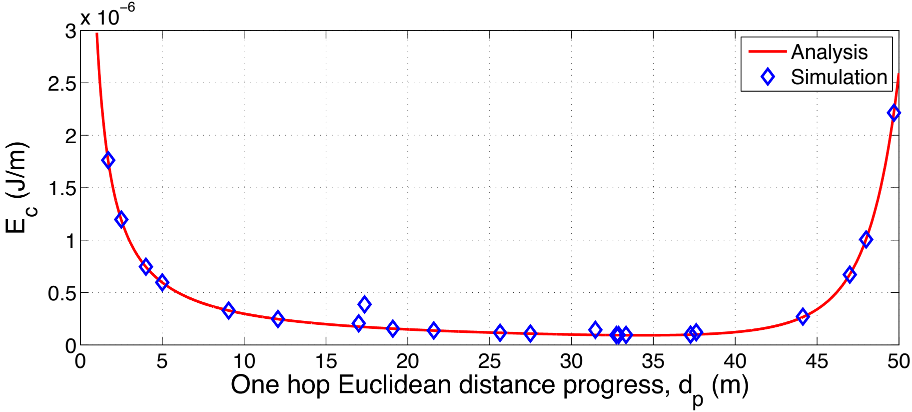
- Network with homogeneous nodal coverage
- Optimum forwarding node selection
- Greedy minimum energy forwarding (GMFP)
- Lifetime maximizing GMFP
- Energy variance minimizing GMFP

Next hop node selection:

- **Far zone** : lesser hops, but more retransmissions : more energy consumption
- **Near zone** : lesser retransmissions, but more hops : more energy consumption
- **Middle zone** : in between : comparatively less energy consumption



Energy/success/unit distance progress, E_c



- Very near and/or very far forwarding node has higher E_c
- LRD chooses very far node whereas PEAR and MAX-RE choose nodes that are very near
- GMFP and LM-GMFP choose node from the intermediate distance

Forwarding Optimization Analysis I

- A static WSN modeled as a weighted graph $\mathcal{G}(\mathcal{V}, \mathcal{A}, \mathcal{W})$ with $|\mathcal{V}|$ number of sensor nodes, vertex weights $w(x) \in \mathcal{W}, \forall\ x \in \mathcal{V}$, and $|\mathcal{A}|$ undirected links
- $(l, m) \in \mathcal{A}$ iff l, $m \in \mathcal{V}$ and both l and m are in transmission range
- *Session* $S^{(i)}\left(s^{(i)}, t^{(i)}, k^{(i)}\right)$ is initiated between a source $s^{(i)}$ and a target $t^{(i)}$, with $k^{(i)}$ number of packets to be transmitted in that session.
- Packets are transmitted only in *slots*, with slot duration of ξ.
- *Active transmission* $a_j^{(i)}(l, m)$: states whether there is an ongoing transmission between two neighbour nodes l and m for the jth packet in session $S^{(i)}$, i.e.,

$$a_j^{(i)}(l, m) = \begin{cases} 1, & \text{if } j\text{th packet transmission in session } i \text{ involves the nodes} \\ 0, & \text{otherwise.} \end{cases}$$

- A neighbour m is said to be a *potential forwarding neighbour* of l iff $d_{mt^{(i)}} \leq d_{lt^{(i)}}$ and $d_{lm} \leq d_{lt^{(i)}}$
- We denote F_l as the set of all such potential forwarding neighbours of l.

Forwarding Optimization Analysis II

- Packet error rate:
  $\rho_j^{(i)}(l,m) = 1 - \sum_{e=0}^{b} \binom{L}{e} \left(\beta_j^{(i)}(l,m)\right)^e \left(1 - \beta_j^{(i)}(l,m)\right)^{L-e}$
- Average number of retransmissions per packet per hop:
  $R_j^{(i)}(l,m) = \frac{1}{1-\rho_j^{(i)}(l,m)}$
- Energy consumption per successful forwarding:
  $Es_j^{(i)}(l,m) = (\mathrm{e}_t + \mathrm{e}_r) \cdot R_j^{(i)}(l,m)$
- Energy consumption per successful packet per unit Euclidean distance progress: $Ec_j^{(i)}(l,m) = \frac{Es_j^{(i)}(l,m)}{d_{p_j}^{(i)}(l,m)}$
- Remaining energy of node i : $\tilde{E}^{(r)}(m)$
- Forward path $\Phi_j^{(i)}$: Path followed by the packet from source to destination variable and time-dependent

Utility Functions

- LRD forwarding: $C_j^{(i)}(l,m,LRD) = \frac{1}{d_{p_j^{(i)}}(l,m)}$
- GEAR: $C_j^{(i)}(l,m,GEAR) = \frac{1}{\tilde{E}^{(r)}(m) d_{p_j^{(i)}}(l,m)}$
- PEAR: $C_j^{(i)}(l,m,PEAR) = \frac{Es_j^{(i)}(l,m)}{\tilde{E}^{(r)}(m)}$
- GMPF: $C_j^{(i)}(l,m,1) = Ec_j^{(i)}(l,m)$
- LM-GMFP: $C_j^{(i)}(l,m,2) = \frac{Ec_j^{(i)}(l,m)}{\tilde{E}^{(r)}(m)}$
- VAR-GMFP: $C_j^{(i)}(l,m,3) = \left(\frac{e_t+e_r}{1+\eta_j^{(i)}(l,m)\ d_{p_j^{(i)}}(l,m)}\right)^2 + \frac{1}{(1+\Gamma_m)^2}$ where $\Gamma_m = \frac{\zeta\ \mu_m}{1+\nu_m}$
- And the next-forwarding-node, m at the transmitter node l $m^* = \underset{m}{\operatorname{argmin}}\ C_j^{(i)}(l,m,1)$

Optimization Problem Formulation

- The average energy consumption by the node l in session $S^{(i)}$ is:

$$\bar{e}_j^{(i)}(l) = \begin{cases} \sum_{m \in F_l} e_t \cdot R_j^{(i)}(l,m) \cdot a_j^{(i)}(l,m), & \text{if } l \text{ is a source node,} \\ \sum_{n: l \in F_m} e_r \cdot R_j^{(i)}(n,l) \cdot a_j^{(i)}(n,l), & \text{if } l \text{ is a destination node,} \\ \sum_{n: l \in F_n} e_r \cdot R_j^{(i)}(n,l) \cdot a_j^{(i)}(n,l) & \\ \quad + \sum_{m \in F_l} e_t \cdot R_j^{(i)}(l,m) \cdot a_j^{(i)}(l,m), & \text{if } l \text{ is an intermideate node,} \end{cases}$$

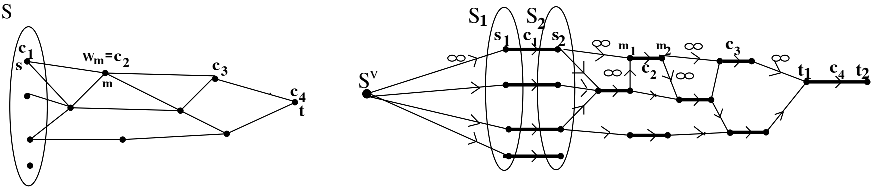
- If node l actively participates in Π number of sessions in its lifetime, then the total energy consumption by node l is given by

$$e(l) = \sum_{i=1}^{\Pi} \sum_{j=1}^{k^{(i)}} \bar{e}_j^{(i)}(l).$$

- With $k^{(i)}$ packets transmitted in session i, the total number transmitted is $n(\Psi) = \sum_{i=1}^{|\Psi|} k^{(i)}$

Maxflow-mincut theorem on theoretical lifetime models

- To calculate number of single packet flows possible from source to destination
- Capacity is on nodes instead edges – convert nodes into edges
- For multiple source/destination – add dummy source/destination (∞ link capacity)
- Apply Maxflow-mincut from source to destination



a. Initial graph b. After final transformation

For Practical lifetime model:

- Implementing theoretical Maxflow algorithms is computationally infeasible
- Practical model with greedy forwarding protocols.
- hop-wise select the route for each packet independently.
- Random source-destination pair with multiple packet transmission sessions.
- This process will continue till the network is dead.

Maximum Lifetime: Max-flow

- The flow maximization problem in the transformed max-flow graph $\mathcal{G}'(\mathcal{V}',\mathcal{A}',\mathcal{W}')$ can be stated as:

$$\text{Maximise } |f| = \sum_{\{x:(S^v,x)\ \in\ \mathcal{A}'\}} f(S^v, x)$$

subject to

$$f(l,m) \geq 0 \quad : \quad (l,m) \in \mathcal{A}',$$
$$f(l,m) \leq C(l,m) \quad : \quad (l,m) \in \mathcal{A}',$$
$$\sum_{\{m:(l,m)\ \in\ \mathcal{A}'\}} f(l,m) - \sum_{\{m:(m,l)\ \in\ \mathcal{A}'\}} f(m,l) = 0 \quad : \quad l \in \mathcal{V}' - \{S^v\}, l \neq t_2.$$

- First set of constraints is to account for the nonzero flows only
- Second set of constraints states that, the flow value is less than or equal to the edge capacity
- Third set of constraints are flow conservation constraints, one for each node

Practical Network Lifetime

Considering $k^{(i)}$ packets transmitted in the i th session,

a packet to be transmitted successfully

subject to

$$k^{(i)} > 0: \ 1 \leq i \leq |\Psi|,$$

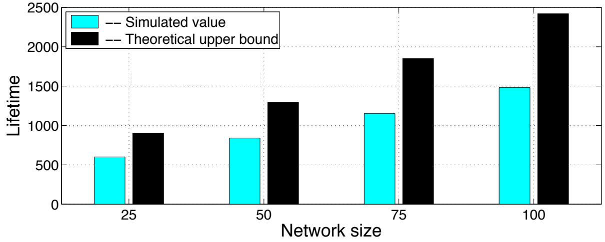
$$\bar{\mathrm{e}}_j^{(i)}(l) \leq \mathcal{E} - \left(\sum_{i'=1}^{i-1} \sum_{j'=1}^{k^{(i')}} e_{j'}^{(i')} - \sum_{j'=1}^{j-1} e_{j'}^{(i')} \right), \qquad \forall\, j, \forall\, l \in \Phi_j^{(i)},$$

$$\mathcal{E} - \left(\sum_{i'=1}^{i-1} \sum_{j'=1}^{k^{(i')}} e_{j'}^{(i')} - \sum_{j'=1}^{j-1} e_{j'}^{(i')} \right) \geq 0, \qquad \forall\, l \in \Phi_j^{(i)}.$$

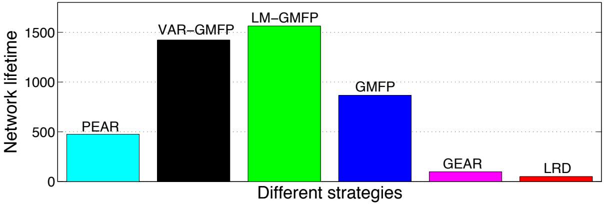
The network lifetime is the sum of all packets successfully transmitted for the maximum value of number of valid sessions i up to which the above optimization is feasible.

Network Lifetime Results

- Theoretical upper bound, as compared to the actual network lifetime in LM-GMFP. R = 20 m.



- GMFP, LM-GMFP, and VAR-GMFP give better lifetime compared to other protocols



Motivations

- Energy constrained sensor network
- Major energy requirement due to communication activities
  - not due to sensing activities
- Recharging nodes is not feasible
- Maximize nodal lifetime
  - Multiple protocol level solutions possible
- Transmit power control objectives
  - Interference minimization and hence increase in spatial reuse
  - Nodal energy saving
  - Judicious feedback for transmit power for energy saving benefit
- Link layer frame size control

Distributed Power Control

- Interference analysis[24,25]
- Effective communication range with distributed power control
- Forwarding protocols with power control[26,27]
- Implementation of automatic transmit power control[28,29]

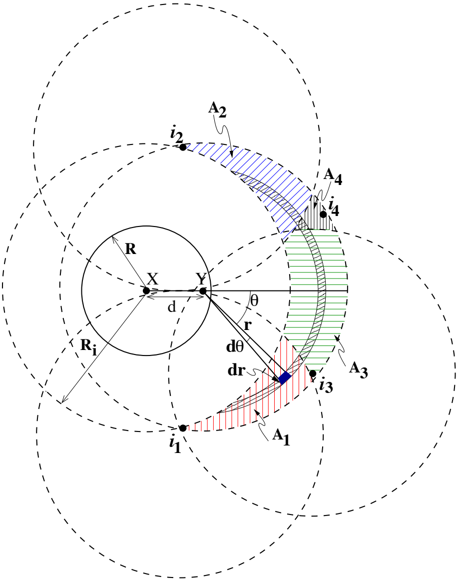
[24] A. Sharma, et al. (Proc. Nat. Conf. Commun., 2011)
[25] B. Panigrahi, et al. (IET Wireless Sensor Systems, 2(1), 2012)
[26] S. De, et al. (Proc. IEEE Sarnoff Symp. 2007)
[27] B. Panigrahi, et al. (Proc. IEEE CSNT 2014)
[28] R. K. Reddy, et al. (Proc. IEEE WMPC 2009)
[29] R. K. Reddy, et al. (IEICE Trans. Commun. 2010)

Number of Simultaneous Interferers

- Area of interference zone of Y: $A(d)$
- d dependent number of hidden nodes
- Due to CSMA, simultaneously transmitting nodes are at least R_c apart
- Total interference area $A(d) = A_1 \cup A_2 \cup A_3 \cup A_4$
- Upper bound on the number of simultaneous interferers
- Maximum when nodes lie on outer rim

$$n_i = \left\lfloor \frac{2\left(\pi - \arccos \frac{d}{2R_i}\right)}{\pi/3} \right\rfloor + 1.$$

- Maximum number of hidden transmitters: 4



Interference Analysis I

- Chop A(d) in small microstrips
- Node existence probability p_e
- Transmission probability p_t
- Interference power $P_i(r)$
- A = Total interfering zone area
- A_1 = first interferer covers
- $A_1^C = A - A_1$ area complementary to A0 (potential interferer zone for the other possible interferers)
- A_1 = the effective interference zone covered by the second interferer
- $A_{12}^C = A - (A_1 + A_2)$
- $F(A)$=probability that node in chosen microchip transmits in area A

$$F(A) = \sum_{J=1}^{\infty} P(A,J) p_t \sum_{j=1}^{J} \frac{1}{j} \binom{J-1}{j-1} p_t^{j-1} (1-p_t)^{J-j}, \quad (1)$$

where J is the total number of nodes in the area A.

- $F^C(A)$= probability no node transmits in area A

$$F^C(A) = \sum_{J=0}^{\infty} P(A,J)(1-p_t)^J. \quad (2)$$

Interference Analysis II

- Interference due to different number of interferes

$$I_1(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) P_i(r) F^C(A_1^C). \quad (3)$$

$$I_2(d) = \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \cdot \sum_{(r_2,\theta_2)} \sum_{\in A_1^C} p_e F(A_1^C) \left[P_i(r_1) + P_i(r_2)\right] F^C(A_{12}^C). \quad (4)$$

$$\begin{aligned} I_3(d) = & \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \cdot \sum_{(r_2,\theta_2)} \sum_{\in A_1^C} p_e F(A_1^C) \sum_{(r_3,\theta_3)} \sum_{\in A_{12}^C} p_e F(A_{12}^C) \\ & \cdot \left[P_i(r_1) + P_i(r_2) + P_i(r_3)\right] F^C(A_{123}^C), \end{aligned} \quad (5)$$

and

$$\begin{aligned} I_4(d) = & \sum_{r=R_i-d}^{R_i} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \sum_{(r_2,\theta_2)} \sum_{\in A_1^C} p_e F(A_1^C) \cdot \sum_{(r_3,\theta_3)} \sum_{\in A_{12}^C} p_e F(A_{12}^C) \\ & \cdot \sum_{(r_4,\theta_4)} \sum_{\in A_{123}^C} p_e F(A_{123}^C) \left[P_i(r_1) + P_i(r_2) + P_i(r_3) + P_i(r_4)\right]. \end{aligned} \quad (6)$$

- The total interference power at Y is: $I(d) = \sum_{k=1}^{4} I_k(d)$

Forwarding Protocols with Power Control

- $f_{\underline{d}}(d|\text{PCN}) = \frac{\rho\pi d\, e^{-\rho\pi d^2/2}}{1-e^{-\rho\pi(R^2-r_0^2)/2}}$
- $f_{\underline{d}}(d|\text{PCG}) = \frac{2\rho\sqrt{R^2-r_0^2-d^2}}{1-e^{-\rho\pi(R^2-r_0^2)/2}}\ e^{-\rho Q(d)}$
  where $Q(d) = R^2\left[cos^{-1}\left(\frac{d}{(R-r_0)}\right) - \frac{d}{(R-r_0)}\sqrt{1-(d/R)^2}\right]$.
- For mutually exclusive $A_1, A_2, \cdots, A_k$ with $A_1 \cup A_2 \cup \cdots \cup A_k = A(d)$,

$$I_k(d) = \sum_{r=R_i^x(d)-d}^{R_i^y} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \sum_{(r_2,\theta_2)} \sum_{\in A_1^C} p_e F(A_1^C) \cdot \sum_{(r3,\theta_3)} \sum_{\in A_{12}^C} p_e F(A_{12}^C) \cdots$$
$$\cdots \sum_{(r_k,\theta_k)} \sum_{\in A_{12\cdots(k-1)}^C} p_e F(A_{12\cdots(k-1)}^C) \cdots \left[P_i(r_1) + P_i(r_2) + \cdots + P_i(r_k)\right] F^C(A_{12\cdots k}^C), \quad (7)$$

where $P_i(r_k)$ is the interference power at Y from the k-th interferer located at a distance r_k from Y, and is given by:

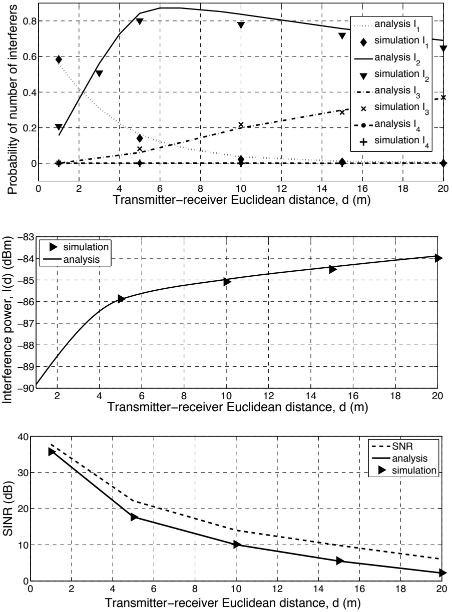
$$\overline{P_i}(r_k) = \frac{\overline{\kappa}}{r_k^{\gamma}} \int_{r_0}^{R} P_t(x) f_{\underline{d}}(x) dx.$$

- Hence, the total interference power at Y in controlled power transmissions is

$$I(d) = \sum_{k=1}^{\infty} I_k(d), \quad (8)$$

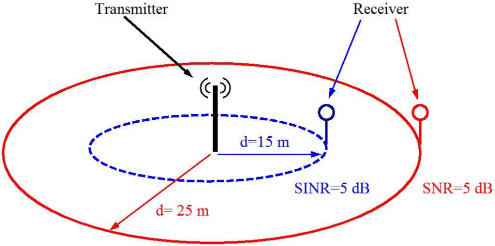
Results

- Probability of interference
  - Probability of two interferers is more than the other cases
  - Probability of very low or very high number of interferers are negligible
- Effect of interference power
  - The effect of increased interference area is apparent
- Role of SINR
  - Receivers located farther affected more by the interference

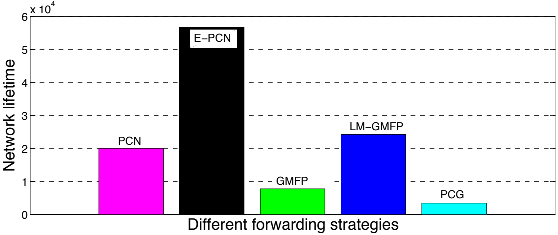


Effective communication range and network lifetime results

- Reduced communication range
  - Effective Communication range for 5 dB threshold level is reduced from 25m to 15m



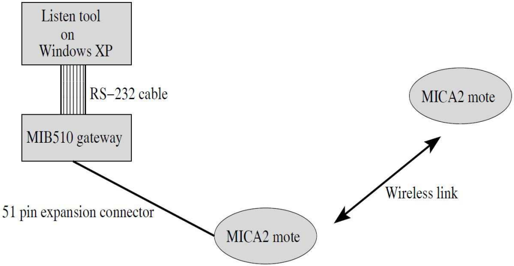
- Network lifetime with power control
  - E-PCN offers 2.8 times increased lifetime w.r.t. PCN



Problem Definition and Solution Methodology

- Problem
  - System dynamics aware automatic power control
  - Power control strategy to effect overall energy saving
  - Effect of frame size on nodal energy saving
- Approach
  - Open loop power control
    - Establish simplex communication between motes
    - Trace the correct packets at the receiver
    - Independent of transmitters external environment
    - Test the automatic power control capability Introduce the concept of (channel dependent) variable link layer frame size
  - Closed loop power control
    - Establish a half-duplex communication
    - Choice of feedback signal
    - Optimum number/level of feedbacks before altering transmit power
    - Joint effect of frame size and power control

Experimental Implementation of Automatic Transmit Power Control

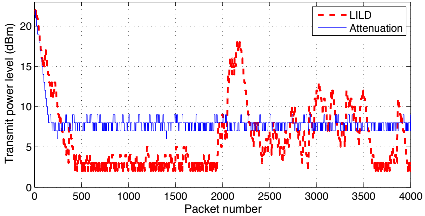


Block diagram

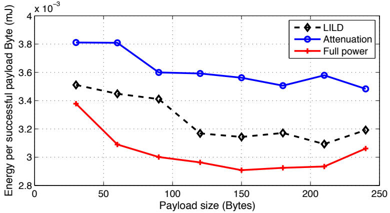
Experimantal setup

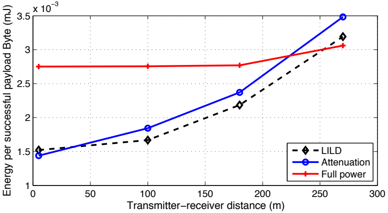
Indoor Experimental Results

- LILD has in it an in-built fluctuating power level, whereas attenuation method is more stable



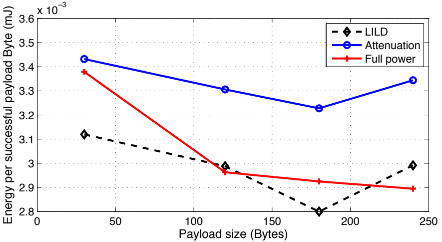
- At a very large distance, beyond a certain frame length (here 210 Bytes) the energy performance degrades
- For a given large frame length, beyond a certain distance no power control starts performing better

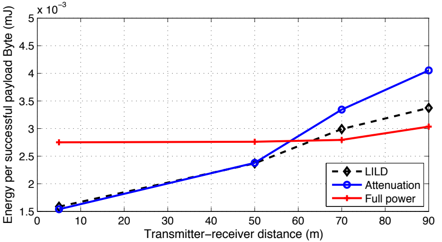




Outdoor Experimental Results

- A similar observation as in the indoor experiments is made The coverage range has drastically reduced from 270m to 90m
- No power control performance starts surpassing that of power control approaches at a short distance
- Maximum acceptable frame size (210 Byte/ 180 Byte at the poorest link conditions) is significantly larger than the default maximum frame size 128 Bytes





Toward green communication networks

- Network energy harvesting analysis[30,31]
- Integrated data and energy mule[32]
- Multi-hop and multi-path RF energy transfer[33,34,35,36]
- Optimum relay placement[37]
- Charging time characterization[38]

[30] S. De, et al. (Proc. IEEE ICC 2010)
[31] S. De and S. Chatterjee (IGI book chapter 2011)
[32] S. De and R. Singhal (IEEE Computer Mag., 45(9), 2012)
[33] P. Gupta, et al. (Proc. NCC 2013)
[34] K. Kaushik, et al. (Proc. IEEE PIMRC 2013)
[35] D. Mishra, et al. (Proc. IEEE PIMRC 2014)
[36] D. Mishra, et al. (IEEE Commun. Mag., 53(4), 2015)
[37] D. Mishra and S. De (IEEE TCOM, 63(5), 2015)
[38] D. Mishra, et al. (IEEE TCAS-II, 62(4), 2015)

Architecture for Network RF Energy Scavenging

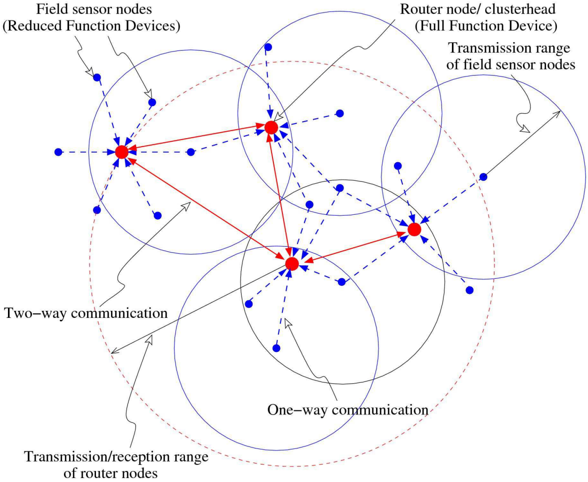
Motivation

In a homogeneous network a node cannot sustain solely from network RF energy

Two tier network architecture

Tier-1: **Energy constrained field nodes** with rudimentary communication

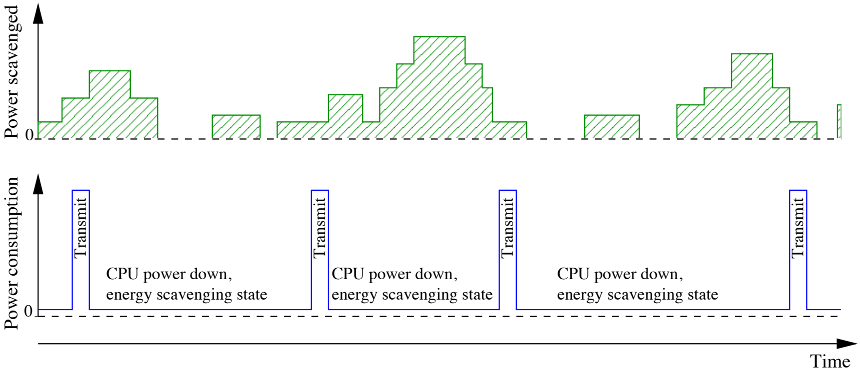
Tier-2: Relatively **powerful router/cluster-head** nodes



[31] S. De and S. Chatterjee, "Network energy driven wireless sensor networks," in *Bio Inspired Communications*, Eds. D. Verma and P. Lio, IGI Publishers, Aug. 2011.

Energy Availability versus Activity Cycle

- For tier-1 nodes, to preserve energy long sleep duration is required and to replenish lost energy it requires sufficient ambient network RF energy



- A stable condition can be achieved by operating tier-2 nodes with uninterrupted power supply (nodal mobility or external energy source)

Available Network RF Energy (I)

Depends on the simultaneous transmitters as well as their positions relative to the scavenger node

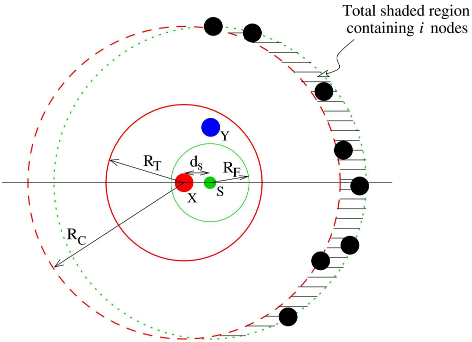
Lemma (1)

In a CSMA/CA wireless network with homogeneous communication coverage, with finite node density the maximum number of simultaneously transmitting neighboring nodes is limited to 5.

$$n_t = \left\lfloor \frac{2\left(\pi - \arccos \frac{d_s}{2R_C}\right)}{\frac{\pi}{3}} \right\rfloor + 2$$

Corollary (1)

n_t is maximum $(= 5)$ when $d_S = R_F \approx \frac{R_C}{4}$



Available Network RF Energy (II)

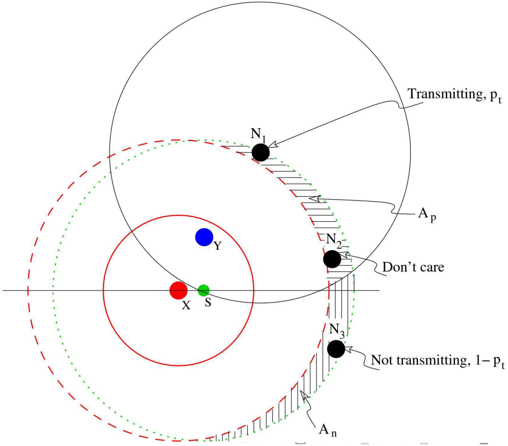
Lemma (2)

More number of simultaneous transmissions around a scavenger node does not imply more energy available for scavenging.

Corollary (2)

The maximum power for scavenging is available when the scavenger is located closest to a transmitter. Total conditional average power available at S is given by:

$$P_{s|X}(d_s) = k\frac{P_t}{d_s^{\gamma}} + \sum_{i=1}^{\infty}\sum_{j=1}^{\min\{i,4\}} p(i)P_{ij}(A)$$



Effective Scavenging Energy Gain: Proof of concept

RF energy scavenging gain

- Tier-1 nodes: data of low power CPU and transceiver
- Tier-2 nodes (CC2520) transmit with probability 0.3, at 5 dBm output power
- Data frame length 40 Byte; transmission speed 250 kbps; frequency = 915 MHz
- $T_{sleep} = \frac{E_{\text{on}}}{P_s^{(\text{scv})} - P_{\text{leak}}}$ where

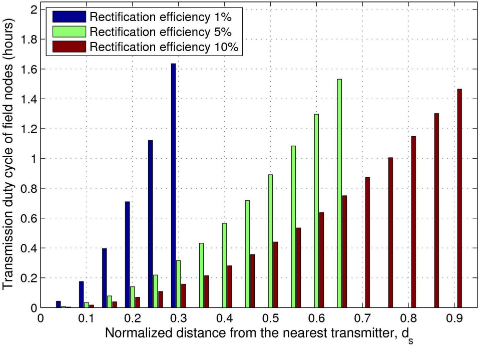
$$P_s^{(\text{scv})} = \eta p_{\text{tr}} \sum_{d_s^{(l)}}^{d_s^{(u)}} \Pr(d_s) P_{s|X}(d_s)$$

Condition on duty cycle

- Limit on sustainable transmission duty cycle for a given transmitter-to-scavenger distance at various rectification efficiency for $ptr = 0.3$ and $P_{leak} = 30$ pW.

Table 2: Energy scavenging gain at $\eta = 0.06\%$

Rectification effy. at 30pW leakage (%)	Avg. sleep duration (min)	Leakage power at rect. effy. of 1% (pW)	Avg. sleep duration (min)
1	142	0	13.36
2	69	30	13.44
5	27	1	16.55
10	13.44	10,000	infeasible



Need for dedicated RF energy transfer

Motivation

- **Energy capacity** of a miniature node's battery **is very limited** item Sheer number and remote deployments: **battery replacement difficult**
- **Network lifetime limited** because of battery constraint

Current practices

- Recharging from ambient resources is of great interest
- Solar energy; vibration; wind; water current; thermal gradient; wirelessly recharging by blasting RF power

RF energy harvesting/ wireless energy transfer

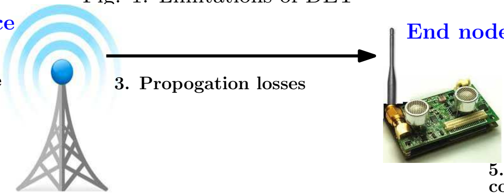
- **RELIABLE**: Available on demand
- One to many charging possible
- Operates anywhere in range of a suitable RF power source
- Commercial units for RF energy harvesting available

Efficient usage of RF energy is required for effective recharging

Limitations of conventional RF energy transfer

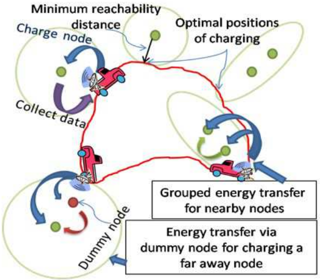
- Recharging by RF energy
  - in-network or ambient
  - dedicated (e.g., RF energy transfer from a remote station)
- RF energy source could be:
  - cluster-head, or
  - energy-surplus peer node, or
  - mobile/stationary RF source
- Each field node has RF-to-DC conversion circuitry
- Wireless energy transfer via dedicated RF source→**better reliability**

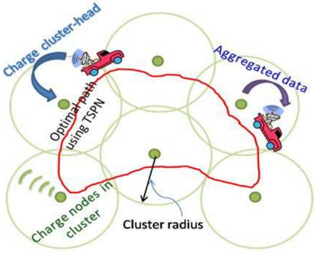
Fig. 1: Limitations of DET

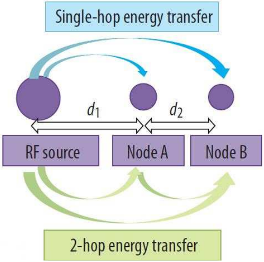


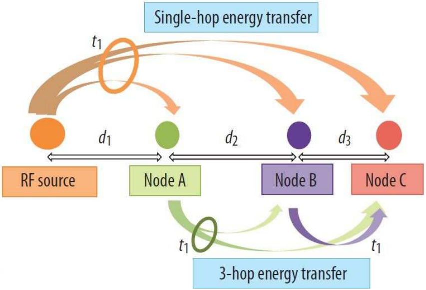
Goal: Novel node level and network level strategies to **boost RFET efficiency** and support **uninterrupted network operation**

Proposed strategies: IDEM and MHET





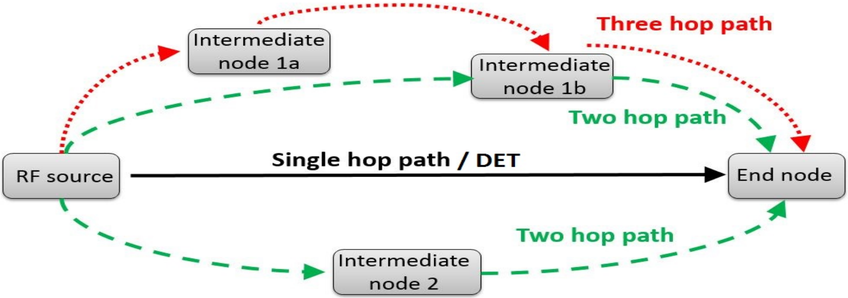




[32] S. De and R. Singhal, "Toward uninterrupted operation of wireless sensor networks," IEEE Computer Mag., vol. 45, no. 9, pp. 24-30, Sep. 2012.

Multi-Path Energy Routing (MPER)

Fig. 2: Illustration of MPER



In MPER, energy routers:

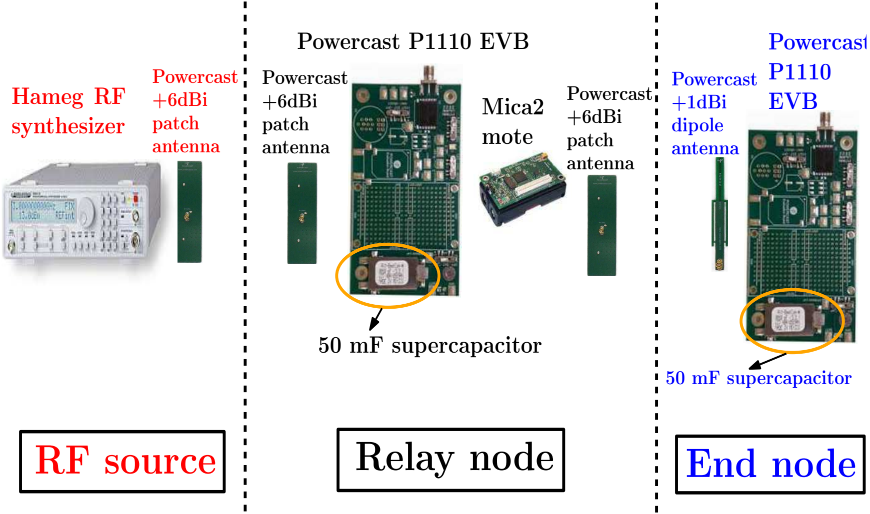
- collect the dispersed RF energy transmitted by RF source
- transfer it to nearby sensor node via alternate multi-hop paths, other than the direct single-hop path

Energy routers or relays : part of network or deployed as dummy nodes
Relay energy transfer: store and forward fashion

[34] K. Kaushik, D. Mishra, S. De, S. Basagni, W. Heinzelman, K. Chowdhury, and S. Jana, "Experimental demonstration of multi-hop RF energy transfer," in *Proc. IEEE Int. Symp. Personal Indoor and Mobile Radio Commun. (PIMRC)*, London, UK, Sep. 2013, pp. 538-542.
[35] D. Mishra, K. Kaushik, S. De, S. Basagni, K. Chowdhury, S. Jana, and W. Heinzelman, "Implementation of multi-path energy routing," in *Proc. IEEE Int. Symp. Personal Indoor and Mobile Radio Commun. (PIMRC)*, Washington D.C., USA, Sep. 2014, pp. 1834-1839.

Three-tier architecture

Fig. 3: Three-tier architecture in MPER



Hardware Specifications

Table 3: Hardware specifications

S. No.	Hardware used	Relevant specifications
1	Powercast P1110 RF energy harvesting kit	Operation down to **-5 dBm** receive power 915 MHz operating band Capacitor of 50 mF, can be charged to 3.3 V
2	Powercast antennas @915 MHz band	+6 dBi PCB patch antennas +1 dBi PCB dipole antenna
3	HAMEG RF synthesizer HM8135	Operating frequency range: 1Hz to 3 GHz Output Power: -135 dBm to **+13 dBm**
4	Crossbow Mica2 sensor motes	RF power range: -20 dBm to **+5 dBm** Receive Sensitivity: -98 dBm Transmit data rate 38.4 kbaud Sleep state current consumption: 8μA

Implementation of MPER in sparse network deployment

Fig. 4(a): 3-path, 2-hop RFET

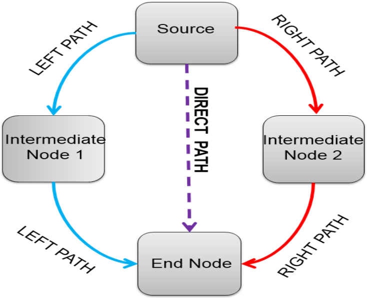


Fig. 4(b): Experimental set-up

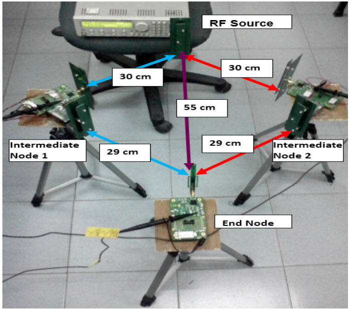


Table 1: Experimental set up and results

(a) System specifications

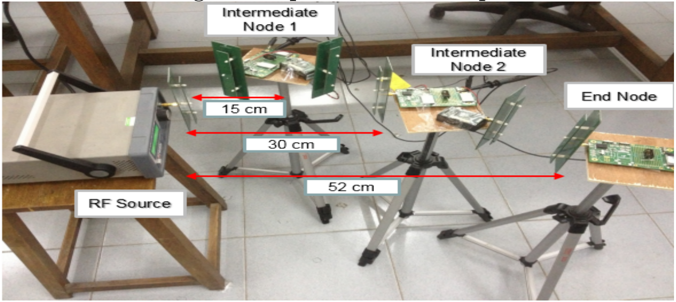
S. No.	Node Type	Components
1	RF Source	HAMEG RF Synthesizer transmitting +13 dBm at 915 MHz Powercast +6 dBi PCB patch antenna
2	Intermediate nodes (1, 2)	Powercast P1110 EVB, modified Mica2 mote Two Powercast +6 dBi PCB patch antennas
3	End node	Powercast P1110 EVB Powercast +1 dBi PCB dipole antenna

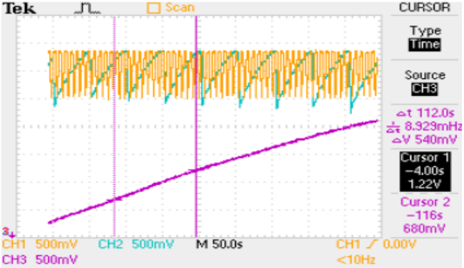
(b) Time Gains

Voltage Level (V)	Average left-direct gain (%)	Average right-direct gain (%)	Average 3-path gain(%)
1	5.17	4.32	10.95
2	8.29	7.96	14.83
3	19.72	18.13	28.84

Implementation of MPER in Dense network deployment

Fig. 5: Experimental set-up





← Fig.6: Feasibility of 3-hop

Table II: Time gains

Voltage Level (V)	Average 2-path gain(%)	Average 3-path gain(%)
1	6.4	12.2
2	6.9	13.5
3	12.1	17.4

Effect of relay position on MHET

Case 1: Left position
1) Close to source
2) More harvested power
3) More path loss

Case 2: Center position
1) Center
2) Low harvested power
3) Low path loss

Case 3: Right position
1) Close to target
2) Very less harvested power
3) Very less path loss

Fig. 7: Number of on-off cycles comparison

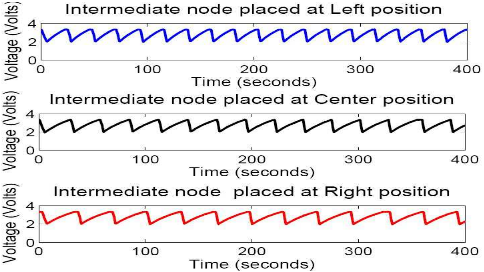


Fig. 8: Contribution of relay ($V_{ON} - V_{OFF}$)

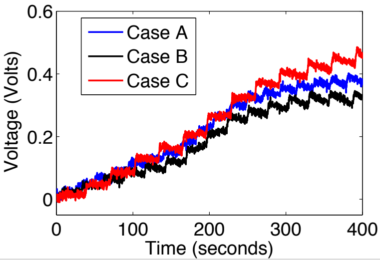
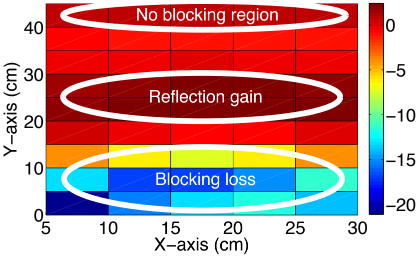


Fig. 9: Blocking characterization (P_r in dBm)



Optimal relay placement in 2-hop RFET

- The efficiency of MHET is strongly influenced by relay node's placement
- Analytical modelling of the store-and-forward energy transfer operation of relay
- ORP on 2-D Euclidean space (P1)
- Modified α-BB algorithm to find ϵ-global optimum solution
- Novel 1-D optimization model using distributed beamforming (P2)
- Fast convergence of P1 and pseudo-concavity of P2 for Powercast P1110 harvester and antennas
- Time to charge from V_i to V_f:

$$T(x_r, y_r, R, V_i, V_f) = \frac{1}{2} RC \log\left(\frac{PRC^2 - (CV_i)^2}{PRC^2 - (CV_f)^2}\right)$$

Fig. 7: Network topology

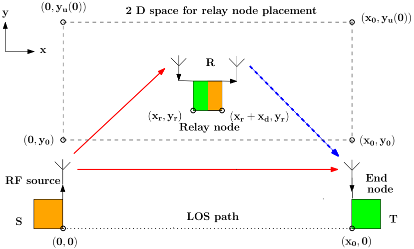


Fig. 8: On-off model

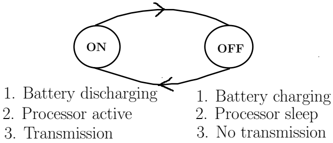
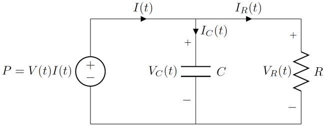


Fig. 9: Circuit model



[21] D. Mishra and S. De, "Optimal relay placement in two-hop RF energy transfer," *IEEE Trans. Commun.*, vol. 63, no. 5, pp. 1635–1647, May 2015.

Problem Formulation I

- ORP on 2-D Euclidean plane

$$(P0): \quad \max_{x_r, y_r} \quad \langle P_T \rangle = P_{2HET}(x_r, y_r) \qquad \text{s.t.} \quad C1: 0 \leq x_r \leq x_0 - x_d, \quad C2: y_0 \leq y_r \leq y_u(x_r) \tag{9}$$

$$\text{where } y_u(x_r) = \left[\sqrt{\left(\frac{\lambda}{2}\right)^2 + y_0^2 + \lambda \sqrt{x_0 - (x_r - x_d)^2 + y_0^2}} \right] \leq y_u(0)$$

$$P_{2HET}(x_r, y_r) = P_{r_1} + P_{r_2}(x_r, y_r) + \sqrt{P_{r_1} P_{r_2}(x_r, y_r)} \times 2e^{-\overline{\psi^2}} cos \left\{ k \left[r_1 - r_2(x_r, y_r) \right] \right\} \tag{10}$$

$$P_{r_2}(x_r, y_r) = \frac{D_c(x_r, y_r) P_{t_2} G_{t_2}(0^\circ) G_{r_T}(\phi_2) \lambda^2}{(4\pi r_2(x_r, y_r))^2}, \; r_2(x_r, y_r) = \sqrt{[x_0 - (x_r + x_d)]^2 + y_r^2}, \; k = \frac{2\pi}{\lambda}$$

$$D_c(x_r, y_r) = \frac{T_{\text{ON}}(x_r, y_r)}{T_{\text{ON}}(x_r, y_r) + T_{\text{OFF}}(x_r, y_r)} = \frac{T(x_r, y_r, R_{ch}, V_i, V_f)}{T(x_r, y_r, R_{ch}, V_i, V_f) + T(x_r, y_r, R_{dch}, V_f, V_i)} \tag{11}$$

- Convex relaxation

$$\mathcal{L}(x_r, y_r) = -P_{2HET}(x_r, y_r) + \alpha \left\{ [0 - x_r] [x_0 - x_d - x_r] [y_0 - y_r] [y_u(x_r) - x_r] \right\} \tag{12}$$

$$\text{where} \quad \alpha \geq \max \left\{ 0, \max_{\substack{i \\ x_i^L \leq x_i \leq x_i^U}} \left(-\frac{1}{2} \lambda_i^{P_{2HET}} \right) \right\} \tag{13}$$

Problem Formulation II

- ORP with distributed beamforming

$$(P2): \quad \max_{x_r} P^{DB}_{2HET} = P_{r_1} + P_{r_2}(x_r, y_0) + 2\sqrt{P_{r_1} P_{r_2}(x_r, y_0)}$$
$$\text{s.t.} \quad C1: 0 \le x_r \le x_0 - x_d \qquad (14)$$

- Constructive and destructive interference regions

$$\mathcal{D}_{\mathcal{I}} = \{(x_r, y_r) \mid P_{2HET}(x_r, y_r) < P_{DET}\} = \{(x_r, y_r) \mid P_{r_2}(x_r, y_r) + P_{r_{12}}(x_r, y_r) < 0\} \qquad (15)$$

where

$$P_{r_{12}}(x_r, y_r) = 2\sqrt{P_{r_1} P_{r_2}(x_r, y_r)}\, e^{-\overline{\psi^2}} cos\{k[r_1 - r_2(x_r, y_r)]\}.$$

- Tradeoff at the relay: Energy scavenged versus energy delivered

$$P^{\text{eff}}_{t_2}(x_r, y_r) = D_c(x_r, y_r) P_{t_2}. \qquad (16)$$

$$P^{\text{cont}}_{r_2}(x_r, y_r) = \frac{P_{t_2} G_{t_2}(\phi_2) G_{r_T}(\phi_2) \lambda^2}{(4\pi r_2(x_r, y_r))^2} \qquad (17)$$

- Modified α-BB based global optimization algorithm

Fig. 10: $\mathcal{C}_{\mathcal{I}}$ and $\mathcal{D}_{\mathcal{I}}$ regions

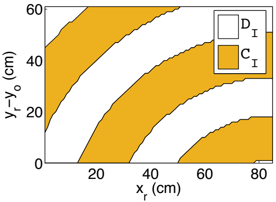
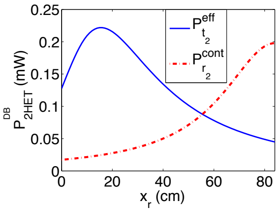


Fig. 11: Tradeoff



Numerical Results I

Fig. 12: Norm. radiation pattern

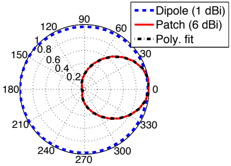


Fig. 13: RF-DC efficiency

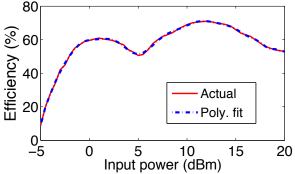


Fig. 14: On-off cycle

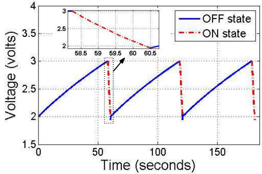


Fig. 15: Mean rx, power (2D case)

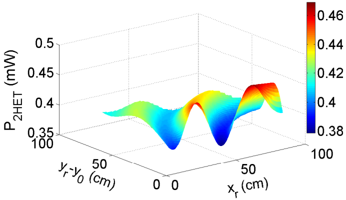


Fig. 16: Convergence results

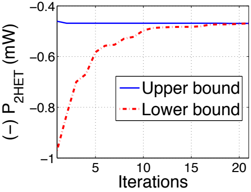
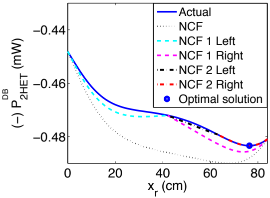


Fig. 17: Mean rx, power (1D case)



Numerical Results II

Fig. 18: Pseudo-concavity

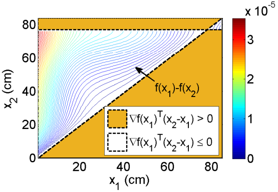


Fig. 19: Gradient for P2

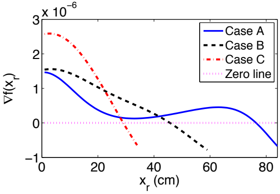


Fig. 20: Energy saved

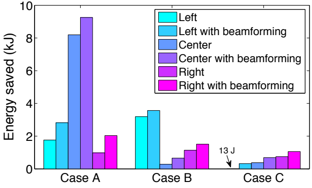
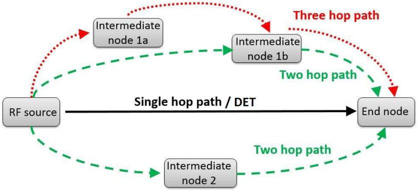


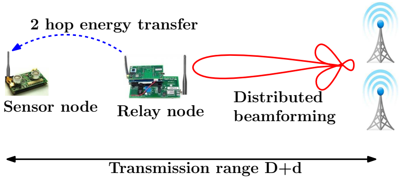
Fig. 19: Optimal relay placement results

Case		Optimal Position (x_r, y_r) (cm)	P_{DET} (mW)	Maximum P_{2HET} (mW)	Efficiency η_E (%)	Energy saved (J)
A	$P1$	$(61.08,\ 4.7\times10^{-10})$	0.4190	0.4690	11.94	4252.10
	$P2$	(76.41, 0)		0.4834	15.38	5309.40
B	$P1$	$(34.49,\ 8.9\times10^{-11})$	0.7342	0.7977	8.65	1808.70
	$P2$	(45.70, 0)		0.8123	10.63	2184.60
C	$P1$	$(3.86,\ 4.9\times10^{-12})$	1.6188	1.6799	3.77	374.62
	$P2$	(29.05, 0)		1.7340	7.12	684.78

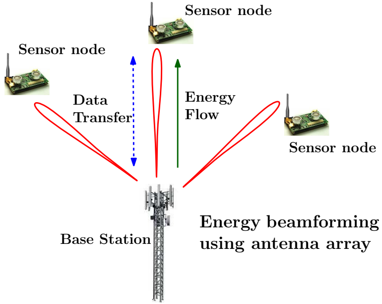
Node level strategies for improving RFET: summary of current work



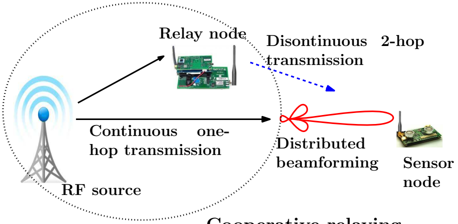
Multipath energy routing



RF energy transfer range extension using two hop energy transfer with distributed beamforming



Energy beamforming using antenna array



Cooperative relaying

RF Charging Time Characterization

- Incident RF waves provide constant power (instead of constant voltage or current) to the storage element
- Analytical model of RF charging process and RF charging equations

The voltage across the capacitor at time t is:

$$V_C(t) = \frac{2\sqrt{RP}\left(1-\frac{1}{Z}\right)}{\sqrt{1-\left(1-\frac{1}{Z}\right)^2}}. \quad (18)$$

$$\text{where, } Z = \frac{1}{2}\left[1+W_0\left(e^{1+\frac{2t}{RC}}\right)\right].$$

The current across the capacitor at time t is:

$$I(t) = \frac{dQ}{dt} = \frac{-\frac{Q(t)}{C} + \sqrt{\left[\left(\frac{Q(t)}{C}\right)^2 + 4RP\right]}}{2R}. \quad (19)$$

Fig. 14: Equiv. RC series ckt.

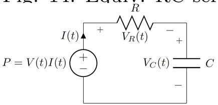


Fig. 15: V_C variation

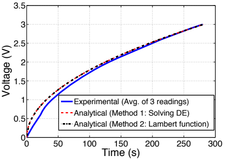


Fig. 16: I_C variation

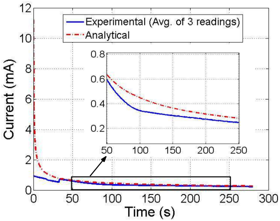


Fig. 17: Source Power variation

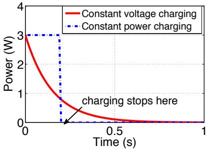
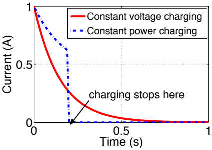


Fig. 18: Current variation



RF charging time distribution

RF charging time → function of residual voltage V' across capacitor: a random variable

$$\begin{aligned} \text{CDF of } T_C, F_{T_C}(t) &= P(T_C \leq t) = P\left[T(V_H) - T(V') \leq t\right] \\ &= P\left[T(V') > T(V_H) - t\right] \\ &= 1 - F_{V'}(v) \qquad (3) \end{aligned}$$

where v is the initial residual voltage,

$$v = \frac{2\sqrt{RP}\left(1 - \frac{1}{Z'}\right)}{\sqrt{1 - \left(1 - \frac{1}{Z'}\right)^2}} \text{ with } Z' = \frac{1 + W_0\left(e^{1 + \frac{2(T(V_H) - t)}{RC}}\right)}{2}.$$

$$\begin{aligned} \text{PDF of } T_C, f_{T_C}(t) &= \frac{dF_{T_C}}{dt} = -f_{V'}(v)\frac{dv}{dt} \\ &= f_{V'}(v)\left\{\frac{1}{C}\sqrt{\frac{P}{RZ''}}\right\} \qquad (4) \end{aligned}$$

where $f_{V'}(v)$ is the PDF of the residual voltage and $Z'' = W_0\left(e^{1 + \frac{2(T(V_H) - t)}{RC}}\right)$.

Fig. 19: CDF of T_C

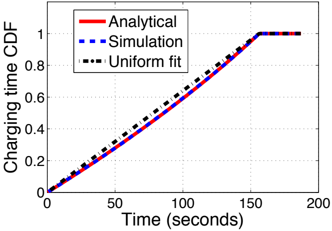
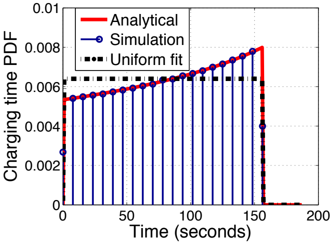
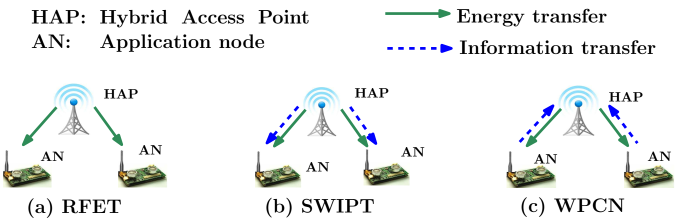


Fig. 20: PDF of T_C



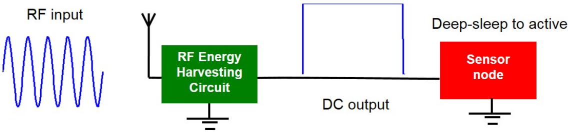
Wireless Information and Energy Transfer



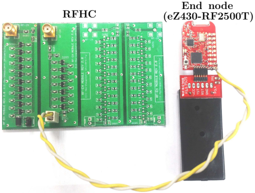
Wireless RF energy transfer scenarios

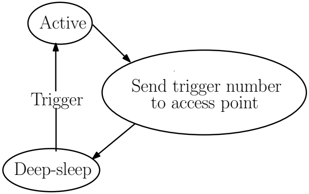
- Only RF energy transfer from AP to the field nodes
- Simultaneous RF energy and information transfer
- Wireless RF powered communication nodes
- Constraints on joint energy and data transfer:
  - Huge discrepancy in receiver's data and energy sensitivities (−60 dBm v/s −10 dBm)
  - Balance time resources for channel estimation and SWIPT in multi-user MIMO systems
  - Synchronization bottleneck in implementation of distributed beamforming to realize increased directivity, spectral efficiency, and enhanced spatial diversity

RF Energy Harvester-based Wake-up Receiver



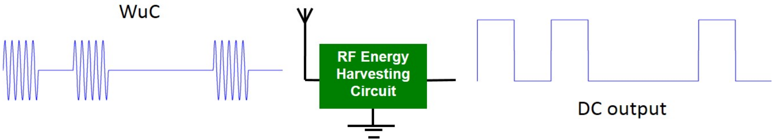
- **Goal:** low-cost, long-range passive wake-up radio capable of both range-based and directed wake-up
- **Advantages:** Lesser hardware and possibility of ID wake-up
- **Range-based Wake up:**
  - Input RF power ($> P_{th}$) to RFHC – triggers μC from deep-sleep to active.
  - High range sensitivity: 4cm/mW in low transmit power regime (< 13 dBm).

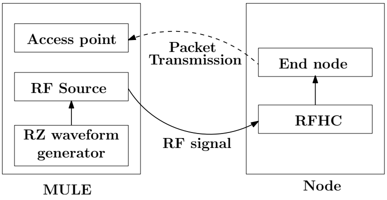




[22] K. Kaushik, D. Mishra, S. De, J.B. Seo, S. Jana, K. Chowdhury, S. Basagni, and W. Heinzelman, “RF Energy Harvester-based Wake-up Receiver,” *IEEE Sensors*, Busan, Nov. 2015.

Directed RFHC-based Wake-up





- Arrival of RF signal: LOW to HIGH
- Removal of RF signal: HIGH to LOW
- ID decoding:
  - interrupt arrival with-in fixed duration **'1'**
  - no interrupt with-in fixed duration **'0'**
- RZ encoding and OOK modulation
- '1' bit preamble added to ID
- For bit-rate < 33.33 kbps, 100% accuracy

S.No.	Device	Specifications
1	Access point	eZ430-RF2500T + eZ430-RF USB connected to laptop
2	End node	eZ430-RF2500T supported by 2 AAA batteries
3	RF source	Agilent N9310A RF Signal Generator transmitting at 915 MHz
4	RZ waveform generator	Agilent 33220A Arbitrary waveform generator
5	RFHC	7-Stage voltage multiplier matched to 915 MHz [?]

Summary

- Discussed the basic needs and tools for network performance modeling
- Presented the research case studies on cross-layer interactions based optimization
- Outlined analyses to some of the networking problems starting with the "first principles"
- Looked into the cases of green solutions to network communications

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  - Satyam Agarwal, Pradipta De, Satish Kumar, Priyatosh Mandal, Nitin Panwar, Ravindra Tonde, Mayur Vegad
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  - Deepak Mishra
  - Satyam Agarwal

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Questions/Comments ?

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