Cross-Layer Protocol Optimization for Green Wireless Network Systems

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My Current Research Directions

- Low-power protocols (typically delay-tolerant)
  - Network RF energy harvesting
  - Energy harvesting network protocols
  - Smart grid network protocols
  - UWN MAC and routing protocols
  - Sustainable network communications

- Cross-layer interaction and optimization studies

- Cross-layer communication protocols

- Broadband QoS support (typically delay-constrained, and multiple traffic classes)
  - Broadcast QoE support over HetNets
  - Channel-aware unicast video streaming
  - QoS/QoE aware DSA and WSA
  - Mesh routing in CDNs
  - Efficient M2M communications

- Source/ Applications
  - End-to-end transport
  - Network routing, forwarding
  - Node-to-node link control
  - Medium access control
  - Physical channel and transceiver
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

![Network Layering Diagram](image)

- 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.

- 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**

<table>
<thead>
<tr>
<th>Technique</th>
<th>Requirements</th>
<th>Merits</th>
<th>Demerits</th>
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</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>Instrumentation and experimental hardware</td>
<td>Most accurate</td>
<td>1. Expensive and time consuming&lt;br&gt;2. Non-repetitive measurements&lt;br&gt;3. Not compatible with future designs</td>
</tr>
<tr>
<td>Simulation</td>
<td>1. Simulator&lt;br&gt;2. Programming skills</td>
<td>1. High control over parameters and workload&lt;br&gt;2. Compatible with future system designs with some extra effort</td>
<td>1. Less accuracy&lt;br&gt;2. Large effort</td>
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Motivation

Link-layer Performance

Cross-layer Cooperation

Network-level Optimizations

Green Communications

Summary

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 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:
  \[
  P[1,1] = E[P_w(v_1)P_w(v_2)] = \int_0^{\infty} \int_0^{\infty} P_w(a_1)P_w(a_2)f_v(a_1)f_v(a_2)da_1da_2
  \]
  and \( r = 1 - P[1|1] = 1 - \frac{P[1,1]}{P[1]} = 1 - \frac{P[1,1]}{\varepsilon} \)

- For **2nd order SC diversity**, conditional probability of unsuccessful reception:
  \[
  P_w(x) = 1 - P[A(x)] \quad \text{with} \quad x = \max \left\{ v^{(1)}, v^{(2)} \right\}
  \]
  where \( F_v(a) = P[v^{(1)} \leq a \mid v^{(1)} \leq a] \)

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Wireless Channel Characterization – II

- $F_x(a) = [F_v(a)]^2$ and $\varepsilon = E[P_w(x)] = \int_0^\infty P_w(a)2F_v(a)f_v(a)da$

- $F_{x_1x_2}(a_1) = [F_{x_1x_2}(a_1,a_2)]^2$ and

$$P_d[1,1] = E[P_w(x_1)P_w(x_2)] = \int_0^\infty \int_0^\infty P_w(a_1)P_w(a_2)f_{x_1x_2}(a_1,a_2)da_1da_2$$

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

$$\varepsilon = F_v(\sqrt{v}), P[1,1] = F_{v_1v_2}\left(\sqrt{b}, \sqrt{b}\right) \text{ and } \varepsilon_d = \varepsilon^2$$

$$P_d[1,1] = F_{v_1v_2}\left(\sqrt{b}, \sqrt{b}\right) \text{ and } \varepsilon_d = \varepsilon^2$$

$$P_d[1,1] = \left[F_{v_1v_2}\left(\sqrt{b}, \sqrt{b}\right)\right]^2, \varepsilon_d = (P_d[1,1])^2 \text{ and } r_d = 1 - (1 - r)^2$$

- For Rayleigh fading, the pdf of envelope is: $f_v(a) = 2ae^{-a^2}$

- Joint pdf is $f_{v_1v_2}(a_1,a_2) = \frac{a_1a_2}{1-\rho^2}e^{-\frac{a(a_1^2+a_2^2)}{2(1-\rho^2)}}I_0\left(\frac{\rho a_1a_2}{1-\rho^2}\right)$ with $\rho = J_0(2\pi f_D T)$

- $\varepsilon = 1 - e^{-b}, \quad r = \frac{Q(\theta,p\theta)Q(p\theta,\theta)}{e^{b-1}},$ where $\theta = \sqrt{\frac{2b}{1-\rho^2}}$. 

Cross-Layer Protocol Optimization for Green Wireless Network Systems

Swades De (IIT Delhi)
Stop-and-Wait ARQ Protocols for Short Range Communication

- 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.
  - $p_{11}(m) = \frac{[p_{21} + (1-p_{21}-p_{12})^m p_{12}]}{p_{21} + p_{12}}$, $p_{21}(m) = \frac{p_{21}[1-(1-p_{21}-p_{12})^m]}{p_{21} + p_{12}}$

**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.

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

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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 $E\{P\}$ in a set of contiguous probing is:
  $$E\{P\} = \frac{1}{p_{21}(t_p)}$$

**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.

- $E\{K\} = \frac{1+p_{12}(m)}{p_{12}(m)}$
- The data throughput in COP based SW is:
  $$R_{COP} = \frac{E\{K\}-1}{(E\{K\}-1)ms+s+T_p+E\{P\}t_ps+2T_p}$$
- Average energy consumed per successful data frame is approximately given by:
  $$E_{COP} = \frac{E\{K\}(e_d+e_a)+(E\{K\}-1)(m-1)e_w+E\{P\}(e_p+t_pe_w)}{E\{K\}-1}$$
Motivation
Link-layer Performance
Cross-layer Cooperation
Network-level Optimizations
Green Computing

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

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

- \( R_{CAP3} = \frac{E\{K\}-1}{\left(\frac{E\{K\}-1}{ms+s+T_p}\right) + \left[\frac{E\{w_p\}}{s}\right] s+2T_p} \]
- \( E_{CAP3} = \frac{E\{K\}(e_d+e_a) + (E\{K\}-1)(m-1)e_w + E\{P\}e_p + \left[\frac{E\{w_p\}}{s}\right] e_w}{E\{K\}-1} \)

**CASW cycle**

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

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

- **Throughput**
  performance with binary feedback

- **Energy**
  consumption with binary feedback

- **Performance with**
  received signal power feedback
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
Exploiting fading dynamics along with AMC\(^3\)

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

where \(\varepsilon\) is steady state error probability in a slot, \(\theta = \sqrt{\frac{2}{F(1-\mu^2)}}\), and \(\mu = J_0(2\pi f_d T_f)\), \(F = \frac{\gamma}{\gamma_1}\) with \(\gamma_1\) as the mode 0 switching threshold.

- In FD-AMC, a frame transmission is postponed for \(s\) slots, where \(s = \left\lfloor \frac{t_w}{T_f} \right\rfloor\).
- 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 \(E_p\) and waiting time \(s\) slots:
  \(E_p(s) = \frac{1}{\omega} \left[(e_t + e_r)T_f + \frac{(2e_w T_f s + H)(1-\eta)p_{12}(1)}{(1-\eta^s)p_{21}(1)}\right]\), where \(H = (e_t + e_r - 2e_w) T_h\).

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ARQ-based switched antenna diversity in Markov channels

\[ T_{RA} = \begin{pmatrix} p_1 & p_3 \\ p_4 & p_2 \end{pmatrix} \quad \text{and} \quad T_{RB} = \begin{pmatrix} q_1 & q_3 \\ q_4 & q_2 \end{pmatrix} \]

\[ \text{PER}_A = \frac{1-p_1}{2-p_1-p_2} \quad \text{and} \quad \text{PER}_B = \frac{1-q_1}{2-q_1-q_2} \]

\[ P = \begin{bmatrix} p_1 & p_4 & p_3 & p_4 & p_3 & 0 & 0 & 0 & 0 \\ p_1 & p_4 & p_3 & p_4 & p_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & p_4 & p_2 & p_4 & p_2 & p_4 \\ 0 & 0 & 0 & 0 & p_4 & p_2 & p_4 & p_2 & p_4 \\ 0 & 0 & 0 & 0 & p_4 & p_2 & p_4 & p_2 & p_4 \\ p_1 & p_4 & p_3 & p_4 & p_3 & 0 & 0 & 0 & 0 \\ p_1 & p_4 & p_3 & p_4 & p_3 & 0 & 0 & 0 & 0 \end{bmatrix} \]

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: \( \eta_{ARQ} = (1 - \text{PER}) = \frac{1-p_2}{2-p_1-p_2} \)

Throughput gain achieved with SSC-ARQ:
\[ \text{Gain} = \eta_{SSC-ARQ} - \eta_{ARQ} \]

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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:

- Initialization and network entry
- CINR of PBS < Threshold–1
- Yes: MOB_SCN–REQ, MOB_SCN–RSP
- No: Scanning
- Select best neighbor BS as SBS
- MS information
- Create service flow for MS
- Start splitting traffic for MS
- Execution of traffic splitting and handoff completion
- Management messages
- CINR of PBS < Threshold–2
- Yes: Change PBS
- No: CINR of PBS ≥ Threshold–2
- Change PBS
- Stop splitting traffic
- Add MS
- Remove MS
- Data + management
- Sub-carrier reassignment (optional)
- Data
- Local DL–MAP (Build DL–MAP)
- SBS CID for service flow
- MS done
- PBS done
- SBS done
- Create service flow for MS
- MS+MS information
- MS information
- SBS information
- SBS done
- PBS done
- Start splitting traffic for MS
- Universal DL–MAP
- Data + management
- Sub-carrier reassignment (optional)
- Data
- Build DL–MAP
- SBS CID for service flow
- MS done
- PBS done
- SBS done
- Create service flow for MS
- MS+MS information
- MS information
- SBS information
- SBS done
- PBS done
- Start splitting traffic for MS
- Universal DL–MAP
- Data + management
- Sub-carrier reassignment (optional)
- Data
- Build DL–MAP

Rate supported at the cell-edge:

- Distance from the left cell edge (m)
- Supported data rate (Mbps)
- Movement time elapsed (s)
- Packet drop rate (%)
- Packet delay (ms)

Differentiated QoS performance:

(a) Hard handoff
(b) Soft handoff (MDHO)
(c) Split handoff
Outage Probability

- **SINR**\( \gamma_{i,x} = \frac{P \cdot L_{i,x}}{I_{i,x}^0 + I_{i,x}^s + N_0 B} \) \( I_{i,x}^s \approx 0 \) and \( I_{i,x}^0 >> N_0 B \)

- 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 \( I_{i,x}^0 = \sum_{j=1}^{N_{oc}} P \cdot L_{j,x} \cdot \rho_j \)

- 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
  \[ P_{out,x}^{hard}(i) = \sum_{i}^{N_c} P_x(i) \cdot P_{out,x}(i). \]

For the proposed scheme:

\[ P_{out,x}^{prop}(i) = \sum_{i}^{N_c} P_x(i) \cdot P_{out,x}(i) \cdot \prod_{j}^{N_{oc}} P_{out,x}(j) \quad \forall \ i \neq j. \]
Analysis (Contd.)

Scheduling of Shared Users

- Effective capacity: $\bar{E}_C^u(\theta^u) = -\frac{1}{\theta^u S} \log E\{e^{-\theta^u \mu^u_i}\}$

- If the same user is scheduled from two BSs, $BS_i$ and $BS_j$

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

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

- Solution:

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

$$
S_{j,2}^u = \frac{S_i^u}{2} + \frac{S_i^u}{2 \theta^u r} \log \left[\frac{(1 - P_j)/P_j}{(1 - P_i)/P_i}\right]
$$
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 $\rho_2$. 
(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 $\alpha$ (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 $k$th 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 $C$ to a user is:

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

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

User’s utility $U$ depends on the traffic type requested:

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

where $d_{suc}$ and $d_{req}$ are the successful and requested data, respectively.

- **Utility Function**: $U = \left\{ \begin{array}{ll} 1 - e^{-c_1 d_{suc}/d_{req}}, & \text{NRT app.} \\ \frac{1}{1 + c_2 e^{-c_3 d_{suc}/d_{req}}}, & \text{RT app.} \end{array} \right.$

- **Sigmoid Utility**: $U = \left\{ \begin{array}{ll} 1 & \text{if } d_{suc} > d_{req} \\ \frac{1}{2} + \frac{1}{2} \tanh \left( \frac{d_{suc} - d_{req}}{d_{req}} \right) & \text{otherwise} \end{array} \right.$

- **Convex Approximation**: $U = \left\{ \begin{array}{ll} 1 & \text{if } d_{suc} > d_{req} \\ \frac{1}{2} + \frac{1}{2} \log \left( \frac{d_{suc}}{d_{req}} \right) & \text{otherwise} \end{array} \right.$

Maximize

$$\sum_{i=1}^{N} U^i$$

Subject to

- $C^i \leq c_{max}^i, \quad \forall i = 1, 2, \ldots, N,$

- $\frac{\left( \sum_{i=1}^{N} \sum_{k=1}^{N_{cr}} a^i_{cr,k} d_{cr,k} \right)^2}{N \sum_{i=1}^{N} \left( \sum_{k=1}^{N_{cr}} a^i_{cr,k} d_{cr,k} \right)^2} \geq \gamma,$

- $\sum_{i=1}^{N} a^i_{ce} \leq N_{ce},$

- $\sum_{i=1}^{N} a^i_{cr,k} \leq \frac{\tau}{\tau_{cr}}, \quad k = 1, \ldots, N_{cr}.$
Solution to the Optimization Problem

- Approximation to RT user’s utility function:
  \[ U_c = 1 - e^{-c_4(d_{suc} - d_{min})/d_{req}} \]

![Utility function graph](image)

- Algorithm for optimal resource allocation

1. **Optimal Resource Allocation Block**
   - Obtain optimal \( a_{ce}^i \) and \( a_{cr,k}^i \) iteratively
   - Obtain optimal Lagrange multipliers using subgradient method

2. **Call Admission Control Block**
   - Is there any user with \( U_i^t \) negative?
     - Yes: New optimization problem with the RT user having minimum \( U_c \) blocked
     - No: Solution to the original optimization problem

Cross-Layer Protocol Optimization for Green Wireless Network Systems

Swades De (IIT Delhi)
Results I

Users’ utility along with their cost constraint ($\alpha$) and average utility observed by successful users in different $\alpha$ 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 $\alpha$ users) along with high-paying users, while SNS can provide high QoS only to high-paying LCN users.
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 $\alpha$, 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

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\(^{10}\) S. Agarwal and S. De (IEEE Commun. Lett., 19(6), 2015)


\(^{12}\) S. Debroy, et al. (IEEE TMC, 13(12), 2014)
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, $\Phi_{sw}$ switching energy consumption per channel switch.

![Diagram of channel switching](image-url)
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

\[
P = \begin{bmatrix}
e^{-T/\lambda} & 1 - e^{-T/\lambda} \\
1 - e^{-T/\mu} & e^{-T/\mu}
\end{bmatrix}
\]
Computation of Optimal SU Packet Length

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

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

i.e.,

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

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

- $W(\cdot)$ is the Lambert-$W$ function and $r = \eta \mu (1 - e^{-T/\lambda})/T$
PMF of $\tau$, $G_{\tau}$ is given as:

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

PMF of $\tau_e$, $H_{\tau_e}$ is given as $H_{\tau_e} = G^{\bigstar(N-1)}(\tau_e - Nn_s)$
• Probability of channel 1 being in OFF state at time $n_4$ is

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

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

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

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

$v = p_0/P_{(1+1)}(1, 2)$ 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
  \[
  Pr(k_l = k) = (P_{l+1}(1, 1))^{k-1}P_{l+1}(1, 2)
  \]
  with mean \(\mathbb{E}[k_l] = 1/P_{l+1}(1, 2)\)

- Number of times \((k_s)\) SU senses the channel busy is distributed as
  \[
  Pr(k_s = k) = (P(2, 2))^{k-1}P(2, 1)
  \]
  with mean \(\mathbb{E}[k_s] = 1/P(2, 1)\)

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

\[
\mathcal{E}_{SC} = \frac{lTe[k_l] - \eta \mu}{\mathbb{E}[k_l]l\Phi_t + \Phi_{se} + \mathbb{E}[k_s]\Phi_{se}}
\]
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

\[
Pr(k_s = k) = (\text{Pr}_m(2, 2))^{(k-1)} \text{Pr}_m(2, 1)
\]

with mean \( \mathbb{E}[k_s] = 1/\text{Pr}_m(2, 1) \)

- Optimal \( m \) is given by setting \( d\mathcal{E}_{SC}^{(m)}/dm = 0 \)

\[
m^{\text{opt}} = \left[ \frac{1}{\ln(\kappa)} \mathcal{W} \left( -e^{(\Phi_{se} - \Phi_i) \ln(\kappa) - \Phi_i} \right) - \frac{(\Phi_{se} - \Phi_i) \ln(\kappa) - \Phi_i}{\Phi_i \ln(\kappa)} \right]
\]

\( \kappa \triangleq 1 - e^{-T/\lambda} - e^{-T/\mu} \)
$\mathcal{U}$ and $\mathcal{E}$ at different PU channel activity for exponentially distributed PU idle and busy periods with slot duration $= 50 \mu s$, $\lambda = 5 ms$, $n_s = 4$, $\Phi_{se} = 40 mW$, $\Phi_i = 16.9 mW$, $\Phi_{tx} = 69.5 mW$, $\Phi_{sw} = 20 \mu J$
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 $\mu$ and $\lambda$ 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

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

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

\[
G_E = \frac{SU\ Goodput}{Energy\ consumption\ by\ SU}
\]

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

\[
R_c = \frac{Number\ of\ slots\ in\ which\ PU\ experienced\ collision}{Number\ of\ slots\ in\ which\ PU\ transmitted}
\]
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

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

- Expected number of PU slots occupied in \( n \) slot SU channel sensing phase
- ‘Start’ is 0/1

\[
E_l(n) = E[PU \text{ occupied Slots}] = \sum_{i=1}^{n-1} i \cdot P_{in}(start, i/0) + \sum_{i=1}^{n} i \cdot P_{in}(start, i/1)
\]

- Probability of packet success with \( k_e \) as allowable error ratio

\[
P_s(m) = Pr \{ \text{Packet success} \} = \sum_{i=0}^{[k_e \cdot m]} \{ P_{tm}(start, i/0) + P_{tm}(start, i/1) \}
\]
Analysis III

FSM representation eDSA V.1

FSM representation eDSA V.2

\[
P^V_1 = \begin{bmatrix}
A & B & C \\
A & 0 & 1 & 0 \\
B & P_c^{m+n}(0, 0) & 0 & P_c^{m+n}(0, 1) \\
C & P_c^n(1, 0) & 0 & P_c^n(1, 1)
\end{bmatrix}
\]

\[
P^V_2 = \begin{bmatrix}
A & B \\
A & P_c^m(0, 0) & P_c^m(0, 1) \\
B & P_c^n(1, 0) & P_c^n(1, 1)
\end{bmatrix}
\]
Analysis IV

eDSA V.1:

- **Goodput:**
  \[
  G^V_1(m, n) = \frac{\pi^V_1(A) \cdot (d_m \cdot k_c - H) \cdot P_s(m)}{T \cdot (\pi^V_1(A) \cdot m + \pi^V_1(B) \cdot n + \pi^V_1(C) \cdot n)}
  \]

- **PU collision ratio:**
  \[
  R_c^V_1(m, n) = \frac{\pi^V_1(A) \cdot E_c(m)}{\pi^V_1(A) \cdot E_c(m + n) + \pi^V_1(C) \cdot E_t(n)}
  \]

- **Energy consumption:**
  \[
  \Phi^V_1(m, n) = \frac{\pi^V_1(A) \cdot \Phi_t \cdot m + \pi^V_1(B) \cdot (\Phi_s + \Phi_i \cdot (n - 1)) + \pi^V_1(C) \cdot (\Phi_s + \Phi_i \cdot (n - 1))}{T \cdot (\pi^V_1(A) \cdot m + \pi^V_1(B) \cdot n + \pi^V_1(C) \cdot n)}
  \]

- **Energy efficiency:**
  \[
  G^V_E = \frac{G^V_i}{\Phi^V_i}
  \]

\(d_m = m \cdot b, b\) per slot bits transmission, \(m = (m)\) or \((m_1, m_2, m_3)\). Energy consumed per slot: \(\Phi_s\) for channel sensing, \(\Phi_t\) for packet transmission, and \(\Phi_i\) in SU idling state.
Analysis V

**eDSA V.2:**

- **Goodput:**
  
  \[
  G^V_2(m, n) = \frac{\pi^V_2(A) \cdot (d_{m-1} \cdot k_c - H) \cdot P_s(m - 1)}{T \cdot (\pi^V_2(A) \cdot m + \pi^V_2(B) \cdot n)}
  \]

- **PU collision ratio:**
  
  \[
  R^V_2(m, n) = \frac{\pi^V_2(A) \cdot E_c(m - 1)}{\pi^V_2(A) \cdot E_c(m) + \pi^V_2(B) \cdot E_t(n)}
  \]

- **Energy consumption:**
  
  \[
  \Phi^V_2(m, n) = \frac{\pi^V_2(A) \cdot (\Phi_t \cdot (m - 1) + \Phi_s) + \pi^V_2(B) \cdot (\Phi_s + \Phi_i \cdot (n - 1))}{T \cdot (\pi^V_2(A) \cdot m + \pi^V_2(B) \cdot n)}
  \]

- **Optimizing SU goodput and energy efficiency**

  \[
  (P1) \quad G_{opt}^V_i = \max_{m,n} G^V_i(m, n) \quad \quad (P2) \quad G_{\varepsilon opt}^V_i = \max_{m,n} G_{\varepsilon i}^V(m, n)
  \]

  \[
  \text{s.t. } R^V_c(m, n) < \eta \quad \quad \text{s.t. } R^V_c(m, n) < \eta
  \]

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

Relative goodput performance\textsuperscript{13,14}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{goodput_performance}
\caption{Comparison of maximum goodput across different systems.}
\end{figure}

Relative energy efficiency

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{energy_efficiency}
\caption{Comparison of maximum energy efficiency across different systems.}
\end{figure}

\[ \lambda = 20 - 160 \text{ ms}, \mu = 50 \text{ ms}, \eta = 0.05 \]


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 comprises 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 \( \lambda_s \) 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

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

\[
P_{PU}^{P \rightarrow Q} = 1 - \frac{\lambda_p e^{-\mu_p T_c} - \mu_p e^{-\lambda_p T_c}}{(\lambda_p - \mu_p)}
\]

\[
P_{PU}^{Q \rightarrow S} = 1 - \frac{\lambda_p e^{-\mu_p T_d} - \mu_p e^{-\lambda_p T_d}}{(\lambda_p - \mu_p)}
\]

\[
P_{SU} = \begin{cases} 
  p_s & \forall N_A > N_S \\
  \sum_{k=1}^{N_A} \frac{p_s}{N_S^k} \binom{N_A}{k} \left(1 - \frac{1}{N_S}\right)^{N_A-k} & \text{otherwise}
\end{cases}
\]

\[
D_{PU} = P_{SU} \left[ \left( \frac{T_C}{2} + T_D \right) P_{PU}^{P \rightarrow Q} + \frac{T_D}{2} P_{PU}^{Q \rightarrow S} \right]
\]
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 $N_S = 100$.

Multi-hop Forwarding Optimizations

- Relaying decision\textsuperscript{16}
- Greedy forwarding\textsuperscript{17}
- Multi-criteria optimality\textsuperscript{18,19,20}
- Lifetime-aware forwarding\textsuperscript{21,22,23}

\textsuperscript{16}K. Egoh and S. De (Proc. IEEE IWCMC 2006)
\textsuperscript{17}S. De (IEEE Commun. Lett., 9(11), 2005)
\textsuperscript{18}K. Egoh and S. De (Proc. IEEE MILCOM 2006)
\textsuperscript{20}K. Egoh, et al. (Book Chapter, CRC Press, 2012)
\textsuperscript{21}B. Panigrahi, et al. (Proc. IEEE Wksp. IAMCOM, 2009)
\textsuperscript{22}B. Panigrahi, et al. (Proc. IEEE VTC-Spring, 2010)
\textsuperscript{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: Distributed 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 node
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 $\alpha$**
  - For a given given density, there exists an optimum value $\alpha$ 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 $P_{\text{fail}} = \Pr \{ Y^* \leq Y + \beta | Y = y \}$
- $P_{\text{fail}} = 1 - \int_{t_1}^{t_2} h(y) S_Y (y + \beta) dy$
- $h$: failure rate and $S$ survival rate
- $\beta$: collision vulnerability window

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

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

Offers least remaining distance to destination, but also most error prone

Higher remaining distance to destination, but offers better link quality
Multi-Criteria Optimality

Basic notion
- Dominated zone
- Dominating zone
- Non-dominated zones

Multi-Criteria Mapping Function
- For a set of k criteria $\Omega_1, \Omega_2, \ldots, \Omega_k$:
  $$g_{\bar{\alpha}} (\Omega_i) = a (\bar{\alpha}) \Omega_1^{\alpha_1} \Omega_2^{\alpha_2} \cdots \Omega_k^{\alpha_k} + b (\bar{\alpha})$$
- Equivalent to cost metric $C_{\bar{\alpha}} (\bar{\Omega}_i) = \Omega_1^{\alpha_1} \Omega_2^{\alpha_2} \cdots \Omega_k^{\alpha_k}$
  mapped onto time $g_{\bar{\alpha}} (\bar{\Omega}_i) = a (\bar{\alpha}) \left[ C_{\frac{1}{\alpha_1}} (\bar{\Omega}) \right]^{\alpha_1} + b (\bar{\alpha})$
A Two Criteria Example

Forward progress $d$ and link quality $p$: $C(\alpha_1, \alpha_2)(d,p) = d^{\alpha_1}p^{\alpha_1}$
Motivation  
Link-layer Performance  
Cross-layer Cooperation  
Network-level Optimizations  
Green C

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, $E_c$

![Graph showing the energy/success/unit distance progress.}

- 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

Cross-Layer Protocol Optimization for Green Wireless Network Systems

Swades De (IIT Delhi)
A static WSN modeled as a weighted graph $G(\mathcal{V}, \mathcal{A}, \mathcal{W})$ 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* $S^{(i)}(s^{(i)}, t^{(i)}, k^{(i)})$ 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 $\xi$.

*Active transmission* $a^{(i)}_j(l, m)$: states whether there is an ongoing transmission between two neighbour nodes $l$ and $m$ for the $j$th packet in session $S^{(i)}$, i.e.,

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

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:**
  \[ \rho_j^{(i)}(l, m) = 1 - \sum_{e=0}^{b} \left( \frac{L}{e} \right) \left( \beta_j^{(i)}(l, m) \right)^e \left( 1 - \beta_j^{(i)}(l, m) \right)^{L-e} \]

- **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:**
  \[ E_{s_j}^{(i)}(l, m) = (e_t + e_r) \cdot R_j^{(i)}(l, m) \]

- **Energy consumption per successful packet per unit Euclidean distance progress:**
  \[ E_{c_j}^{(i)}(l, m) = \frac{E_{s_j}^{(i)}(l, m)}{d_{p_j}^{(i)}(l, m)} \]

- **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**: \( C_j^{(i)}(l, m, PEAR) = \frac{E_{s_j}^{(i)}(l,m)}{E(r)(m)} \)

- **GMPF**: \( C_j^{(i)}(l, m, 1) = Ec_j^{(i)}(l, m) \)

- **LM-GMFP**: \( C_j^{(i)}(l, m, 2) = \frac{Ec_j^{(i)}(l,m)}{E(r)(m)} \)

- **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 \( l \)
  \( m^* = \arg\min_m C_j^{(i)}(l, m, 1) \)
Optimization Problem Formulation

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

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

- If node \( l \) actively participates in \( \Pi \) 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

\[
n(\Psi) = \sum_{i=1}^{\left|\Psi\right|} k^{(i)}
\]
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

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 $G'(\mathcal{V}',\mathcal{A}',\mathcal{W}')$ can be stated as:

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

subject to

$$f(l, m) \geq 0 : (l, m) \in \mathcal{A'},$$
$$f(l, m) \leq C(l, m) : (l, m) \in \mathcal{A'},$$

$$\sum_{\{m:(l,m) \in \mathcal{A}'\}} f(l, m) - \sum_{\{m:(m,l) \in \mathcal{A}'\}} f(m, l) = 0 : l \in \mathcal{V'} - \{S^v\}, l \neq t_2.$$
Practical Network Lifetime

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

a packet to be transmitted successfully

subject to

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

$$\bar{e}_{ij}^{(i)}(l) \leq \mathcal{E} - \left( \sum_{i'=1}^{i-1} \sum_{j'=1}^{j-1} e_{ij'}^{(i')} - \sum_{j'=1}^{j-1} e_{ij'}^{(i')} \right), \quad \forall j, \forall l \in \Phi_{j}^{(i)},$$

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

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

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\textsuperscript{24,25}
- Effective communication range with distributed power control
- Forwarding protocols with power control\textsuperscript{26,27}
- Implementation of automatic transmit power control\textsuperscript{28,29}

\textsuperscript{25} B. Panigrahi, et al. (IET Wireless Sensor Systems, 2(1), 2012)
\textsuperscript{26} S. De, et al. (Proc. IEEE Sarnoff Symp. 2007)
\textsuperscript{27} B. Panigrahi, et al. (Proc. IEEE CSNT 2014)
\textsuperscript{28} R. K. Reddy, et al. (Proc. IEEE WMPC 2009)
\textsuperscript{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
  \[ n_i = \left\lceil \frac{2 \left( \pi - \arccos \frac{d}{2R_i} \right)}{\pi / 3} \right\rceil + 1. \]
- 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

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

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

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

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

(1)

(2)
Interference Analysis II

**Interference due to different number of interferes**

\[ I_1(d) = \sum_{r=R_i-d}^{R_i} \sum_{\Theta(r)} p_e F(A) P_i(r) F^C(A_1^C). \]  

(3)

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

(4)

\[ I_3(d) = \sum_{r=R_i-d}^{R_i} \sum_{\Theta(r)} p_e F(A) \cdot \sum_{(r_2, \theta_2) \in A_1^C} \sum_{(r_3, \theta_3) \in A_{12}^C} p_e F(A_{12}^C) \cdot [P_i(r_1) + P_i(r_2) + P_i(r_3)] F^C(A_{123}^C), \]  

(5)

and

\[ I_4(d) = \sum_{r=R_i-d}^{R_i} \sum_{\Theta(r)} p_e F(A) \sum_{(r_2, \theta_2) \in A_1^C} \sum_{(r_3, \theta_3) \in A_{12}^C} p_e F(A_{12}^C) \cdot \sum_{(r_4, \theta_4) \in A_{123}^C} p_e F(A_{123}^C) [P_i(r_1) + P_i(r_2) + P_i(r_3) + P_i(r_4)]. \]  

(6)

**The total interference power at Y is:**  
\[ I(d) = \sum_{k=1}^{4} I_k(d) \]
Motivation Link-layer Performance Cross-layer Cooperation Network-level Optimizations Green Communications

Forwarding Protocols with Power Control

- $f_{d|PCN}(d) = \frac{\rho \pi d e^{-\rho \pi d^2/2}}{1 - e^{-\rho \pi (R^2 - r_0^2)/2}}$
- $f_{d|PCG}(d) = \frac{2\rho \sqrt{R^2 - r_0^2 - d^2}}{1 - e^{-\rho \pi (R^2 - r_0^2)/2}} e^{-\rho Q(d)}$

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 $A_1, A_2, \ldots, A_k$ with $A_1 \cup A_2 \cup \ldots \cup A_k = A(d)$,

$$I_k(d) = \sum_{r=R_i^x}^{R_i^y} \Theta(r) \sum_{r=R_i^x}^{R_i^y} \sum_{\theta=-\Theta(r)}^{\Theta(r)} p_e F(A) \sum_{(r_2, \theta_2) \in A_1^C} \sum_{(r_3, \theta_3) \in A_{12}^C} p_e F(A_{12}^C) \cdots \sum_{(r_k, \theta_k) \in A_{12\ldots(k-1)}^C} p_e F(A_{12\ldots(k-1)}^C) \cdots \left[ P_i(r_1) + P_i(r_2) + \cdots + P_i(r_k) \right] F^C(A_{12\ldots(k-1)}^C),$$

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:

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

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

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

(7)
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

PC with TinyOS (listen tool on Windows XP)  Mica2 Tx
MIB 510  Wireless link
Mica2 Rx

Experimental setup

Listen tool on Windows XP
RS-232 cable
MIB510 gateway
51 pin expansion connector
MICA2 mote
Wireless link

Swades De (IIT Delhi)
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\textsuperscript{30,31}
- Integrated data and energy mule\textsuperscript{32}
- Multi-hop and multi-path RF energy transfer\textsuperscript{33,34,35,36}
- Optimum relay placement\textsuperscript{37}
- Charging time characterization\textsuperscript{38}

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

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.

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

**Corollary (1)**

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

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

\[ T_{sleep} = \frac{E_{on}}{P_{s}(scv) - P_{leak}} \]

\[ P_{s}(scv) = \eta p_{tr} \sum d_{s}^{(u)} \text{Pr}(d_{s})P_{s}|X(d_{s}) \]

Condition on duty cycle

- Limit on sustainable transmission duty cycle for a given transmitter-to-scavenger distance at various rectification efficiency for \( p_{tr} = 0.3 \) and \( P_{leak} = 30 \text{ pW} \).

<table>
<thead>
<tr>
<th>Rectification effy. at 30pW leakage (%)</th>
<th>Avg. sleep duration (min)</th>
<th>Leakage power at rect. effy. of 1% (pW)</th>
<th>Avg. sleep duration (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>142</td>
<td>0</td>
<td>13.36</td>
</tr>
<tr>
<td>2</td>
<td>69</td>
<td>30</td>
<td>13.44</td>
</tr>
<tr>
<td>5</td>
<td>27</td>
<td>1</td>
<td>16.55</td>
</tr>
<tr>
<td>10</td>
<td>13.44</td>
<td>10,000</td>
<td>infeasible</td>
</tr>
</tbody>
</table>

Table 2: Energy scavenging gain at \( \eta = 0.06\% \)
Motivation

- **Energy capacity** of a miniature node’s battery is very limited
- 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

1. Maximum permissible power limits
2. Wide angled radiation pattern
3. Propagation losses
4. Low RF energy reception sensitivity
5. Low RF-DC conversion efficiency

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

Multi-Path Energy Routing (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

---

Three-tier architecture

Fig. 3: Three-tier architecture in MPER

- Hameg RF synthesizer
- Powercast P1110 EVB
- Powercast +6dBi patch antenna
- Powercast +6dBi patch antenna
- Mica2 mote
- Powercast +6dBi patch antenna
- Powercast +1dBi dipole antenna
- 50 mF supercapacitor
- 50 mF supercapacitor

RF source

Relay node

End node
## Hardware Specifications

**Table 3: Hardware specifications**

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

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

(b) Time Gains

<table>
<thead>
<tr>
<th>Voltage Level (V)</th>
<th>Average left-direct gain (%)</th>
<th>Average right-direct gain (%)</th>
<th>Average 3-path gain(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.17</td>
<td>4.32</td>
<td>10.95</td>
</tr>
<tr>
<td>2</td>
<td>8.29</td>
<td>7.96</td>
<td>14.83</td>
</tr>
<tr>
<td>3</td>
<td>19.72</td>
<td>18.13</td>
<td>28.84</td>
</tr>
</tbody>
</table>
Implementation of MPER in Dense network deployment

Fig. 5: Experimental set-up

![Experimental set-up image]

Table II: Time gains

<table>
<thead>
<tr>
<th>Voltage Level (V)</th>
<th>Average 2-path gain(%)</th>
<th>Average 3-path gain(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.4</td>
<td>12.2</td>
</tr>
<tr>
<td>2</td>
<td>6.9</td>
<td>13.5</td>
</tr>
<tr>
<td>3</td>
<td>12.1</td>
<td>17.4</td>
</tr>
</tbody>
</table>

Fig. 6: Feasibility of 3-hop

![Graph showing time gains]
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

- Intermediate node placed at Left position
- Intermediate node placed at Center position
- Intermediate node placed at Right position

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

- Case A
- Case B
- Case C

Fig. 9: Blocking characterization ($P_r$ in dBm)

- No blocking region
- Reflection gain
- Blocking loss
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 $\alpha$-BB algorithm to find $\epsilon$-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 $V_f$:

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

Problem Formulation I

- **ORP on 2-D Euclidean plane**

\[
(P0) : \max_{x_r, y_r} \quad \langle P_T \rangle = P_{2HET}(x_r, y_r)
\]

s.t.  
\[C1 : 0 \leq x_r \leq x_0 - x_d\]

\[C2 : y_0 \leq y_r \leq y_u(x_r)\]  

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

\[P_{2HET}(x_r, y_r) = P_{r1} + P_{r2}(x_r, y_r) + \sqrt{P_{r1} P_{r2}(x_r, y_r)} \times 2e^{-\psi^2} \cos \{k [r_1 - r_2(x_r, y_r)]\}\]  

\[P_{r2}(x_r, y_r) = \frac{D_c(x_r, y_r) P_{t2} G_{t2}(0^\circ) G_{rT}(\phi_2) \lambda^2}{(4\pi r_2(x_r, y_r))^2}, \quad r_2(x_r, y_r) = \sqrt{[x_0 - (x_r + x_d)]^2 + y_r^2}, \quad k = \frac{2\pi}{\lambda}\]

\[D_c(x_r, y_r) = \frac{T_{ON}(x_r, y_r)}{T_{ON}(x_r, y_r) + T_{OFF}(x_r, y_r)} = \frac{T(x_r, y_r, R_{ch}, V_i, V_f)}{T(x_r, y_r, R_{ch}, V_i, V_f) + T(x_r, y_r, R_{ch}, V_f, V_i)}\]  

- **Convex relaxation**

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

where \(\alpha \geq \max \left\{ 0, \max_{x_i \leq x_i \leq x_i^U} \left( -\frac{1}{2} \lambda_i P_{2HET} \right) \right\}\]  

\[\mathcal{L}(x_r, y_r) = -P_{2HET}(x_r, y_r) + \alpha \{[0 - x_r] [x_0 - x_d - x_r] [y_0 - y_r] [y_u(x_r) - x_r]\}\]
Problem Formulation II

- ORP with distributed beamforming

\[
(P2) : \quad \max_{x_r} P_{2HET}^{DB} = P_{r1} + P_{r2}(x_r, y_0) + 2\sqrt{P_{r1} P_{r2}(x_r, y_0)} \\
\text{s.t.} \quad C1 : 0 \leq x_r \leq x_0 - x_d
\]  

(14)

- Constructive and destructive interference regions

\[
\mathcal{D}_I = \{(x_r, y_r) \mid P_{2HET}(x_r, y_r) < P_{DET}\} \\
= \{(x_r, y_r) \mid P_{r2}(x_r, y_r) + P_{r12}(x_r, y_r) < 0\}
\]  

(15)

where

\[
P_{r12}(x_r, y_r) = 2\sqrt{P_{r1} P_{r2}(x_r, y_r)} e^{-\psi^2} \cos \{k [r_1 - r_2(x_r, y_r)]\}.
\]

- Tradeoff at the relay: Energy scavenged versus energy delivered

\[
P_{t2}^{\text{eff}}(x_r, y_r) = D_c(x_r, y_r) P_{t2}.
\]  

(16)

\[
P_{r2}^{\text{cont}}(x_r, y_r) = \frac{P_{t2} G_{t2}(\phi_2) G_{rT}(\phi_2) \lambda^2}{(4\pi r_2(x_r, y_r))^2}
\]  

(17)

- Modified $\alpha$-BB based global optimization algorithm
Numerical Results I

Fig. 12: Norm. radiation pattern

![Radiation Pattern](image1)

Fig. 13: RF-DC efficiency

![Efficiency Graph](image2)

Fig. 14: On-off cycle

![On-off Cycle Graph](image3)

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

![2D Power Graph](image4)

Fig. 16: Convergence results

![Convergence Graph](image5)

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

![1D Power Graph](image6)
Numerical Results II

**Fig. 18:** Pseudo-concavity

**Fig. 19:** Gradient for P2

**Fig. 20:** Energy saved

<table>
<thead>
<tr>
<th>Case</th>
<th>Optimal Position $(x_r, y_r)$ (cm)</th>
<th>$P_{DET}$ (mW)</th>
<th>Maximum $P_{2HET}$ (mW)</th>
<th>Efficiency $\eta_E$ (%)</th>
<th>Energy saved (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$P_1$ $(61.08, 4.7 \times 10^{-10})$</td>
<td>0.4190</td>
<td>0.4690</td>
<td>11.94</td>
<td>4252.10</td>
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<tr>
<td></td>
<td>$P_2$ $(76.41, 0)$</td>
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<td></td>
<td></td>
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<tr>
<td>B</td>
<td>$P_1$ $(34.49, 8.9 \times 10^{-11})$</td>
<td>0.7342</td>
<td>0.7977</td>
<td>8.65</td>
<td>1808.70</td>
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<td>$P_2$ $(45.70, 0)$</td>
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</tr>
<tr>
<td>C</td>
<td>$P_1$ $(3.86, 4.9 \times 10^{-12})$</td>
<td>1.6188</td>
<td>1.6799</td>
<td>3.77</td>
<td>374.62</td>
</tr>
<tr>
<td></td>
<td>$P_2$ $(29.05, 0)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Node level strategies for improving RFET: summary of current work

Motivation
Link-layer Performance
Cross-layer Cooperation
Network-level Optimizations
Green Communications

RF source → Single hop path / DET → End node

Intermediate node 1a
Intermediate node 1b
Intermediate node 2

Three hop path
Two hop path

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

Data Transfer
Energy Flow

Sensor node
Energy beamforming using antenna array

Sensor node
Sensor node

Transmission range D+d

RF source
Relay node
Distributed beamforming

Distributed beamforming
Discontinuous 2-hop transmission
Continuous 1-hop transmission

Cooperative relaying

Swades De (IIT Delhi)
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:

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

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:

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

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 $\rightarrow$ function of residual voltage $V'$ across capacitor: a random variable

CDF of $T_C$, $F_{T_C}(t) = P(T_C \leq t) = P\left[T(V_H) - T(V') \leq t\right]$

$= P[T(V') > T(V_H) - t]$

$= 1 - F_{V'}(v)$

where $v$ is the initial residual voltage,

$$v = \frac{2\sqrt{RP} \left(1 - \frac{1}{Z'}\right)}{\sqrt{1 - (1 - \frac{1}{Z'})^2}}$$

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

PDF of $T_C$, $f_{T_C}(t) = \frac{dF_{T_C}}{dt} = -f_{V'}(v) \frac{dv}{dt}$

$= f_{V'}(v) \left\{ \frac{1}{C} \sqrt{\frac{P}{RZ''}} \right\}$

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

- **HAP**: Hybrid Access Point
- **AN**: Application node

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).

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

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

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