A Green Framework for Energy Efficient Management in TDMA-based Wireless Mesh Networks

Ahmed Amokrane\textsuperscript{1}, Rami Langar\textsuperscript{1}, Raouf Boutaba\textsuperscript{2}, Guy Pujolle\textsuperscript{1}

\textsuperscript{1} LIP6, Pierre and Marie Curie University, France

\textsuperscript{2} University of Waterloo, Canada

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Outline

1. Context
2. System Model
3. Proposed Methods
4. Performance Evaluation
5. Conclusion
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Wireless Mesh Networks
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- Energy efficient Wireless Mesh Network
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Network Topology

- The network is seen as a directed graph \( G(V, E) \)
- \( V = \{v_1, ..., v_n\} \): set of all the nodes
  - \( S = \{s_1, ..., s_m\} = \{v_{n-m+1}, ..., v_n\} \): set of nodes with internet connection \( \Rightarrow \) Gateways
- \( E = \{(i, j)/i, j \in \{1, ..., n\}, i \neq j\} \)
- Connectivity Matrix \( M \):

\[
M_{i,j} = \begin{cases} 
1 & \text{If there is a direct link between } v_i \text{ and } v_j \\
0 & \text{Else}
\end{cases}
\]
Interference Model

- Each node $i$: Transmission Range and Interference Range
- A link $(i, j)$ interferes with $(p, q)$ if:
  - $j \neq q$
  - $d_{i,q} \leq R_I(i)$
- Interference Matrix $I$

$$I(i,j),(p,q) = \begin{cases} 
  1 & \text{If the link } (i, j) \text{ interferes with the link } (p, q) \\
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Traffic model & Routing and Link Scheduling

- The Traffic: A set of flows L
- In TDMA: Time is divided into periods of $T$ units of time, each period = \{1..T\} slots
Traffic model & Routing and Link Scheduling

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Energy Efficiency & Throughput

- Energy Efficiency $= \text{Reduced number of used nodes (ON/OFF model)}$

- Higher throughput (Routed Traffic / Used slots) $= \text{Reduced number of used slots during } T$
Energy Efficiency & Throughput

- **Energy Efficiency** = Reduced number of used nodes (ON/OFF model)

  **Used node definition:**

  \[
  y_i = \begin{cases} 
  0 & \text{If } \sum_{t=1}^{T} \sum_{l \in L} \sum_{j=1}^{n} x_{ij}^{(t)}(l) + x_{ji}^{(t)}(l) = 0 \\
  1 & \text{Otherwise}
  \end{cases}
  \]

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  1 & \text{Otherwise} 
  \end{cases} \]

- Higher throughput (Routing Traffic / Used slots) = Reduced number of used slots during \( T \)

  Used slot definition:

  \[ z_t = \begin{cases} 
  0 & \text{If } \sum_{l\in L} \sum_{i,j=1}^{n} x^{(t)}_{ij}(l) = 0 \quad \forall t \in \{1, .., T\} \\
  1 & \text{Otherwise} 
  \end{cases} \]
Problem

**GIVEN:**
- A physical topology $G(V, E)$, connectivity and interference matrices $M$ and $I$
- A set of $m$ gateways
- A list $L$ of flows

**FIND:**
- The optimal routing and link scheduling of the $L$ flows
- Best tradeoff between network throughput and energy consumption
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The ILP

\[ \text{Minimize} \left( \alpha \sum_{i=1}^{n} y_i + (1 - \alpha) \sum_{t\in\{1,..,T\}} z_t \right), \quad \alpha \in [0, 1] \]

subject to:
No transmission over a non-existing link:
\[ x_{ij}^{(t)}(l) \leq M_{i,j} \quad \forall i, j \in \{1, ..., n\}, \forall t \in \{1, .., T\} \]

Two interfering links are not scheduled during the same slot:
\[ x_{ij}^{(t)}(l) + x_{pq}^{(t)}(l') I_{(i,j),(p,q)} \leq 1 \quad \forall i, j, p, q \in \{1, ..., n\}, \forall t \in \{1, .., T\} \]
The ILP

Flow conservation:

\[
\sum_{l \in L} \sum_{t \in \{1, \ldots, T\}} \sum_{j=1}^{n} x_{ij}^{(t)}(l) = \sum_{l \in L} \sum_{t \in \{1, \ldots, T\}} \sum_{k=1}^{n} x_{ki}^{(t)}(l) + \sum_{l \in L, s(l) = i} \sum_{t \in \{1, \ldots, T\}} \sum_{j=1}^{n} x_{ij}^{(t)}(l) \quad \forall i \in \{1, \ldots, n - m\}
\]

All flows have to be routed:

\[
Success(l) = 1 \quad \forall l \in L
\]
Optimal-based method: Optimal Green Routing and Link Scheduling (O-GRLS)
- Both Routing and link scheduling
- Optimal solution using a solver
Solving methods

- **Optimal-based method: Optimal Green Routing and Link Scheduling (O-GRLS)**
  - Both Routing an link scheduling
  - Optimal solution using a solver

- **Meta-heuristic-based method: Ant Colony Green Routing and Link Scheduling (AC-GRLS)**
  - Based on Ant Colony meta-heuristic
  - Near optimal solution
  - Reduced computational complexity
  - Path Formulation
AC-GRLS

- **Path formulation:**
  - Reduces the complexity of link formulation
  - Each flow (among $L$ flows) is provided with $K$ different paths toward a gateway
  - A solution: One path for each flow $\Rightarrow K^{|L|}$ possible solutions
  - Ant Colony meta-heuristic for efficient exploration of solution space

- Scheduling is done using a proposed Greedy Link Scheduling algorithm
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Test Settings

The objective function:

\[
Minimize \left( \alpha \sum_{i=1}^{n} y_i + (1 - \alpha) \sum_{t \in \{1,\ldots,T\}} z_t \right)
\]

\(\alpha \in [0, 1]\)

Performance metrics:
- Objective Function Value
- Proportion of non-source used nodes
- Achieved throughput
- Average path length

Network settings:
- Grid and Random Topologies
- Uplink traffic

<table>
<thead>
<tr>
<th>Scale</th>
<th>Nodes</th>
<th>Gateways</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>25</td>
<td>4</td>
<td>25%, 50% and 75%</td>
</tr>
<tr>
<td>Large</td>
<td>100</td>
<td>9</td>
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</tr>
</tbody>
</table>
Results: Small Scale Networks (25 nodes)

- AC-GRLS and O-GRLS Vs SP: Objective function value 30% better
- AC-GRLS Vs O-GRLS: Near optimal solution in a short computation time (0.5s Vs 550s)
Results: Small Scale Networks (25 nodes), 75% load

- Achieved throughput and Energy consumption:
  - The same energy budget, achieved throughput is 30% better ($\alpha = 0.4$)
  - The same throughput with 30% fewer used nodes ($\alpha = 0.7$)
Results: Small Scale Networks (25 nodes), 75% load

- **Tuning $\alpha$:**
  - A desired throughput $\Rightarrow$ a certain value of $\alpha$
  - Desired Throughput = 1.8 flow/slot $\Rightarrow$ $\alpha = 0.5$
Results: Small Scale Networks (25 nodes), 75% load

- Average path length:
  - Relatively short paths ($\alpha \in [0.4, 0.7]$)
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Conclusion

- Energy efficient management in TDMA-based WMNs
  - Routing and link scheduling
  - Optimal formulation and efficient approximation
  - Parametrized objective function: Energy-Throughput tradeoff
  - Better than Shortest Path strategies

- Future work:
  - Fine-grain energy consumption model
  - Switch ON/OFF costs
The ILP

\[
\text{Minimize} \left( \alpha \sum_{i=1}^{n} y_i + (1 - \alpha) \sum_{t \in [1, T]} z_t \right), \quad \alpha \in [0, 1]
\]

subject to:

No transmission over a non existing link:

\[
x_{ij}^{(t)}(l) \leq M_{i,j} \quad \forall i, j \in \{1, \ldots, n\}, \forall t \in [1, T]
\]

Two interfering links are not scheduled during the same slot:

\[
x_{ij}^{(t)}(l) + x_{pq}^{(t)}(l') I_{ij}, (p,q) \leq 1 \quad \forall i, j, p, q \in \{1, \ldots, n\}, \forall t \in [1, T]
\]
The ILP

No routing when reaching a Gateway

\[ x_{ij}^{(t)}(l) = 0 \quad \forall i \in \{n-m+1,...,n\}, j \in \{1,...,n\}, \forall l \in L, \forall t \in [1,T] \]

No loops when routing

\[
\sum_{t=1}^{T} \sum_{j=1}^{n} x_{ji}^{(t)}(l) \leq 1, \quad \sum_{t=1}^{T} \sum_{j=1}^{n} x_{ij}^{(t)}(l) \leq 1, \quad \forall i \in \{1,...,n\}, \forall l \in L
\]
The ILP

Flow conservation:

\[
\sum_{t=1}^{T} \sum_{j=1}^{n} \sum_{l \in L} x_{ij}^{(t)} (l) = \sum_{t \in \{1, \ldots, T\}} \sum_{k=1}^{n} x_{ki}^{(t)} (l) + \sum_{l \in L, s(l) = i} \left( \sum_{t=1}^{T} \sum_{j=1}^{n} x_{ij}^{(t)} (l) \right) \quad \forall i \in \{1, \ldots, n - m\}
\]

All flows have to be routed:

\[
Success(l) = 1 \quad \forall l \in L
\]
Algorithm 1 AC-GRLS pseudo code

1: Set Parameters
2: Initialize pheromone trails
3: for $i = 1 \rightarrow$ Number of Iterations do
4:   Construct Ant Solutions
5:   for all Ants do
6:     Build a solution step by step
7:   end for
8: end for
9: Update Pheromones
10: end for
AC-GRLS

Building a solution step by step:

1: for $l = 1 \rightarrow$ Number of flows do
2: \hspace{1em} $p \leftarrow Random(0..1)$
3: \hspace{1em} if $p < q_0$ then
4: \hspace{2em} Choose path $j$ where $j = \text{Argmax}_{k \in N_l} \left( \tau_{lk}^{\alpha_{\text{ANT}}} \times \eta_{lk}^{\beta_{\text{ANT}}} \right)$
5: \hspace{1em} else
6: \hspace{2em} Choose path $j$ according to $P_{lj}$ probability
7: \hspace{1em} $P_{lj} = \frac{\tau_{lj}^{\alpha_{\text{ANT}}} \eta_{lj}^{\beta_{\text{ANT}}}}{\sum_{k \in N_i} \tau_{lk}^{\alpha_{\text{ANT}}} \eta_{lk}^{\beta_{\text{ANT}}}}$
8: \hspace{1em} end if
9: \hspace{1em} Add the $j^{th}$ path for flow $l$ to current_solution
10: end for
AC-GRLS

Pheromone Trail Update:

1: //Update Pheromones for all flows $l$
2: for $l = 1 \rightarrow \text{Number of flows}$ do
3: \hspace{1em} for $j = 1 \rightarrow K$ do
4: \hspace{2em} $\tau_{lj} \leftarrow (1 - \rho)\tau_{lj}$ //Evaporation
5: \hspace{2em} if current solution is the best solution for the current iteration And $j^{th}$ path is selected for flow $l$ then
6: \hspace{3em} $\tau_{lj} \leftarrow \tau_{lj} + \Delta_{lj}^{best}$ //Reinforce the pheromone for the best solution of the current iteration
7: \hspace{2em} end if
8: end for
9: end for
Greedy Link Scheduling
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**Greedy Link Scheduling**

**Algorithm 2 Greedy Link Scheduling**

1. **IN:** $LS$: List of links to schedule, The conflict graph.
2. **OUT:** $Sched$: List of Slots with the corresponding scheduled links in each slot.
3. $Sched \leftarrow \{\};$ $i \leftarrow 0$ // $i$ is the current slot
4. **while** $LS \neq \emptyset$ **do**
5.    // Extend $Sched$ by one slot
6.    $i \leftarrow i + 1; Sched[i] \leftarrow \{\}$
7.    **for all** $ls \in LS$ **do**
8.        **if** $ls$ is not interfering with any link in $Sched[i]$ **then**
9.            $Sched[i] \leftarrow Sched[i] \cup \{ls\};$ Remove $ls$ from $LS$
10.        **end if**
11.    **end for**
12. **end while**
13. **Return** $Sched$
Results

Large Scale Networks (100 nodes), 75% network load

Achieved Throughput (flow/slot) Non-source used nodes (%)

AC-GRLS Beam Search Shortest Path Routing
Large Scale Networks (100 nodes), 75% network load

**Results**

- **Used gateways (%)**
  - AC-GRLS
  - Beam Search
  - Shortest Path Routing

- **Average path Length**
  - AC-GRLS
  - Beam Search
  - Shortest Path Routing
Energy Consumption & Traffic Model

- ON/OFF Energy consumption model model:
  - ON: node consumes energy
  - OFF: no energy consumed

- The Traffic: A set of flows $L$:
  - Each flow $l \in L$: from a source $s(l)$ toward a gateway $s \in S$
  - Multi-hop routing