Interference-Aware Topology, Capacity, and Flow Assignment in Wireless Mesh Networks

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Thanks to: Vishwanath, Massimo, Sayeem, Prof. Mukherjee
Motivation

- Topology, Capacity, and Flow Assignment (TCFA) is a general network-design problem

- Design a cross-layer solution for TCFA That is:
  - Dynamically allocate resources
  - Self organized

- Design a realistic secondary-interference model
Why Topology Control?

- Wireless links are soft (no physical deployment is required)
- Network topology is not expected to be fixed for a long time
- A good topology design should follow the traffic demand and assign links as needed to serve as much users as possible within a short period of time
- Decreasing number of links on a topology $\Rightarrow$ decreases interference
- Decreasing number of links on a topology $\Rightarrow$ increases delay (increases number of hops)
- With minimum number of links, we can assign different channels to each links to achieve the best performance
In Wireless Mesh Network

- Each radio has a limited capacity
  - This can be used as a constraint instead of Cost Constraint

- Wireless Channel is a shared channel

- Interference limits the effective capacity

Gateway

Rest of the Internet

Router

Gateway

Router

Router

Gateway

Router

AP

End users

End users
## Why Topology CFA in WMN?

<table>
<thead>
<tr>
<th></th>
<th>Fully connected</th>
<th>Tree</th>
<th>Star</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of links</strong></td>
<td>high</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>high</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td><strong>Interference</strong></td>
<td>high</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>high</td>
<td>low</td>
<td>high</td>
</tr>
</tbody>
</table>
Wireless Constraints

- Primary Interference Constraint:

  - Self Interference
  - Collision
  - Multicast

- Signal-to-Interference-and-Noise Ratio (SINR) Constraint:

  \[
  \frac{G_{(i,j)} P_{(i,j)}}{N_o + \sum_{(p,q) \in L_t} I_{(p,q,i,j)} P_{(p,q)}} \geq \beta
  \]

Ref: Channel, Capacity, and Flow Assignment in Wireless Mesh Networks Presentation, by Vishwanath Ramamurthi
Wireless Constraints

- Secondary Interference Constraint:

\[
Link_I(J) = \begin{pmatrix}
    q_1 & q_2 \\
    1 & 1 \\
    1 & 1
\end{pmatrix}
\]
Secondary-Interference Approaches

1. Combined Interfering-links Constraint (1eq)

2. Separate Interfering-links Constraint (Aeq)

3. Multiple Interfering-links Constraint (M eq)
Combined Constraint

\[ \text{Link}_I(J) = \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} \begin{pmatrix} q_1 & q_2 \\ 1 & 1 \\ 1 & 1 \end{pmatrix} \]

\[ C_j + C_{p_1q_1} + C_{p_1q_2} + C_{p_2q_1} + C_{p_2q_2} \leq C \]
Separate Constraint

$$\text{Link}_I(J) = \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$

\[ p_1 q_1 + p_1 q_2 + p_2 q_1 + p_2 q_2 \leq C \]

\[ 4 \text{ equations} \]
Multiple Constraint

\[
\text{Link}_I(J) = \begin{pmatrix}
1 & 1 \\
1 & 1
\end{pmatrix}
\]

\[
S_1 = \{ L_{p_1q_1}, L_{p_2q_2} \}
\]

\[
S_2 = \{ L_{p_1q_2}, L_{p_2q_1} \}
\]

\[
C_j + C_{p_1q_1} + C_{p_2q_2} \leq C
\]

\[
C_j + C_{p_1q_2} + C_{p_2q_1} \leq C
\]

\[\Rightarrow \text{2 equations}\]
Secondary-Interference Approaches

- Our approach (Meq) provides more capacity compared to (1eq) approach (reduce Interference)

- Our approach reduces number of equations in the MILP compared to (Aeq) approach (increase processing speed)

- Meq is a More Realistic approach
TCFA Formulation

Given:
- Number of nodes and their locations
- Number of interfaces per node
- Source-destination traffic demands $D_{s,d}$

Minimize: (# of links) + $\varepsilon$ (delay)
- With respect to: $\{C_{i,j}\}$ and $\{\lambda_{i,j}\}$

Output:
- Optimal Network Topology
Input Notations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_A$</td>
<td>Number of routers</td>
</tr>
<tr>
<td>$N_G$</td>
<td>Number of Gateways</td>
</tr>
<tr>
<td>$N$</td>
<td>$N_A + N_G$</td>
</tr>
<tr>
<td>$C$</td>
<td>Maximum radio capacity</td>
</tr>
<tr>
<td>$D_{sd}$</td>
<td>Traffic demand of a source-destination pair</td>
</tr>
<tr>
<td>$F_j$</td>
<td>Number of radio interfaces at node $j$</td>
</tr>
<tr>
<td>$F_{jf}$</td>
<td>Channel assigned to the $f$-th radio at node $j$</td>
</tr>
<tr>
<td>$W$</td>
<td>Number of channels available</td>
</tr>
<tr>
<td>$E_{j,k}$</td>
<td>Set of non-overlapping interfering links at node $j$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Minimum traffic parameter on any link</td>
</tr>
<tr>
<td>$H_{\text{max}}$</td>
<td>Maximum allowed number of hops along a single $(s, d)$ flow</td>
</tr>
<tr>
<td>$k$</td>
<td>Maximum allowed congestion on any link</td>
</tr>
</tbody>
</table>
# Variable Notations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{ij,m}$</td>
<td>Capacity of $L_{ij}$ over channel $m$</td>
</tr>
<tr>
<td>$C_{ij}$</td>
<td>Aggregate link capacity of $L_{ij}$ over all channels</td>
</tr>
<tr>
<td>$Src_{i,sd}$</td>
<td>Up/downstream traffic sourced from node $i$ and issued by $(s, d)$ source-destination flow</td>
</tr>
<tr>
<td>$Snk_{isd}$</td>
<td>Up/downstream traffic sunk at node $i$ and issued by $(s, d)$ source-destination flow</td>
</tr>
<tr>
<td>$r_i$</td>
<td>Total up/downstream traffic that is sourced or sunk at node $i$</td>
</tr>
<tr>
<td>$\lambda_{ij,sd}$</td>
<td>Amount of traffic on $L_{ij}$ and belongs to $(s, d)$ flow</td>
</tr>
<tr>
<td>$\lambda_{ij}$</td>
<td>Total up/downstream flow on $L_{ij}$ over all $(s, d)$ pairs</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Total traffic on all links</td>
</tr>
<tr>
<td>$\gamma_{ij}$</td>
<td>$\text{(binary)} = 1$, when $L_{ij}$ carries traffic</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Number of links selected to represent the new topology</td>
</tr>
<tr>
<td>$h_{ij,sd}$</td>
<td>$\text{(binary)} = 1$, when $L_{ij}$ is selected to carry traffic along $(s, d)$ flow</td>
</tr>
</tbody>
</table>
TCFA Model

- **Demand constraints at routers**

\[
\begin{align*}
\text{Source node} & : s = i, \quad \text{and} \quad d = RI \\
\text{Destination node} & : s = RI, \quad \text{and} \quad d = i \\
\text{Intermediate node} & : s \neq i, \quad \text{and} \quad d \neq i
\end{align*}
\]

\(\forall i, \forall (s, d) \text{ pairs}\)
TCFA Model

- Total flow at a node

\[ \sum_v (s, a) \forall i \]

- Flow-conservation constraints

\[ \forall i, \forall (s, d) \text{ pairs} \]
TCFA Model

- **Link-flow constraints**

\[
\lambda_{ij} = \sum_{(s,d)} \lambda_{sd} \quad \forall (i, j)
\]

- **Delay constraints**

\[
\lambda = \sum_{(i,j) \in E} \lambda_{ij}
\]
TCFA Model

- **Capacity constraints**
  \[ C_{ij} = \sum_{w=1}^{W} B_{ij}^w \quad \forall (i, j) \]

- **Primary-interference constraints**
  \[ \sum_{\forall \text{links} \in E} B_{ij}^{F_j^f} + \sum_{\forall \text{links} \in E} B_{ji}^{F_j^f} \leq C \quad \forall j, \forall f \]

- **Secondary-interference constraints**
  \[ \sum_{\forall i \in A_j} B_{ij}^w + \sum_{\forall p, q \in E_{j}^{S_k}} B_{pq}^w \leq C \quad \forall j, \forall S_k \]
TCFA Model

- **Link constraints**
  \[ \gamma_{ij} \geq \frac{\lambda_{ij}}{G} \quad \forall (i, j) \]

- **Topology constraints**
  \[ \gamma = \sum_{\forall (i, j) \in E} \gamma_{ij} \]

- **Hops constraints**
  \[ h_{ij}^{sd} \geq \frac{\lambda_{ij}^{sd}}{G} \quad \forall (i, j), \forall (s, d) \text{ pairs} \]

  \[ \sum_{\forall (i, j) \in E} h_{ij}^{sd} \leq H_{max} \quad \forall (s, d) \text{ pairs} \]
Performance Evaluation: Assumptions

- Single channel
- Single radio per node
- Upstream Traffic (40%)
- Downstream Traffic (60%)
- At least ½ of the traffic served (feasible solution $\alpha = 0.5$)
Performance Evaluation

- We study different cases

- We vary:
  - Number of hops
  - Number of gateways
  - Traffic load (per router)
  - Two objective functions
  - The value of $\alpha$ (Min traffic on each link)
Input Topology (mesh)
Result: Interference approaches

Number of Links on Topology

Traffic Load (Mbps)

Gamma

A_{eq}, \gamma+\lambda
M_{eq}, \gamma+\lambda
1_{eq}, \gamma+\lambda
A_{eq}, \lambda+\gamma
M_{eq}, \lambda+\gamma
1_{eq}, \lambda+\gamma
Result: Interference approaches
Result: Interference approaches network throughput.
Result: Multi-hop

Number of Links on Topology (6 Mbps)
Result: Multi-hop

Normalized Network Delay (6 Mbps)

Normalized Delay

No. of Hops

Aeq
Meq
1eq
Result: Multi-GW
Result: Multi-GW

![Normalized Network Delay Graph]

- Normalized Delay vs Traffic Load (Mbps)
- 2-GW and 1-GW networks
- Aeq, Meq, 1eq markers for comparison
Result: The value of $\alpha$
Result: TCFA Efficiency

Aggregate Network Throughput

Throughput (Mbps) vs. Traffic Load (Mbps)

TCFA
Mesh Topology
Max-throughput
Conclusion

- Design a Dynamic and self-organize TCFA solution for WMN
- Deploy realistically the impact of the interference on the link capacity
- TCFA dramatically improves the performance of WMN
- The selection of no. of hops is essential
Thank you
Backup Slides
Cross-Layer Design

- CA in wireless network should also take into account Interference

- Interference depends on
  - Topology
  - PHY Layer technology
  - Antenna Beam pattern

- Benefits of Cross Layer Design
  - PHY layer limitations are considered
  - Network resources are utilized to the best possible extent

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Network Design Problems

<table>
<thead>
<tr>
<th>Problem</th>
<th>Given</th>
<th>Minimize</th>
<th>w.r.t</th>
<th>s.t</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA</td>
<td>$\tau, \lambda_{i,j}$</td>
<td>$T$</td>
<td>$C_{i,j}$</td>
<td>$D$</td>
</tr>
<tr>
<td>FA</td>
<td>$\tau, C_{i,j}$</td>
<td>$T$</td>
<td>$\lambda_{i,j}$</td>
<td>$0 \leq \lambda_{i,j} \leq \mu C_{i,j}$</td>
</tr>
<tr>
<td>CFA</td>
<td>$\tau$</td>
<td>$T$</td>
<td>$C_{i,j}, \lambda_{i,j}$</td>
<td>$D$</td>
</tr>
<tr>
<td>TCFA</td>
<td>-</td>
<td>$T$</td>
<td>$\tau, C_{i,j}, \lambda_{i,j}$</td>
<td>$D$</td>
</tr>
</tbody>
</table>

- $\tau =$ Network Topology
- $\lambda_{i,j} =$ flow on link $(i,j)$
- $\mu =$ average packet size
- $C_{i,j} =$ capacity of link $(i,j)$
- $T =$ Average System Delay
- $D =$ Maximum cost

$$\sum_{(i,j) \in E} d_{i,j} \left( C_{i,j} \right) = D$$

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Channel, Capacity, and Flow Assignment (CCFA)

- Given:
  - Network Topology, source-destination demands $\gamma_{s,d}$
  - Number of non-overlapping channels $K$
  - Number of Network Interface Cards (NICs) on each node $q_i$

- Minimize: $T$

- With respect to: $\{C_{i,j}\}$, $\{\lambda_{i,j}\}$, and $H_{i,j} \in \{1, \ldots, K\}$
Network Utility

- Efficiency of a WMN

$$\eta = \frac{\text{Total Throughput}}{\text{Total Demand}} = \gamma = \frac{\sum \gamma_{s,d}}{D} = \frac{D}{\sum D_{s,d}}$$

- Utility U is defined to include both throughput and delay

$$U = \frac{\eta^{Em}}{T}$$

- Em = “Throughput emphasis factor”
  - How much is throughput emphasized over delay

- Generalized version of Kleinrock’s “Power” of a network
Overall CCFA Algorithm

Traffic Profiling

Channel Assignment

Multichannel Capacity and Flow Assignment (MCFA)

U^n - U^(n-1) ≤ ε

Yes

Channels, Capacities, and Flows

Link Flows

No

Channels

Capacities and Flows