Robust Channel Assignment for Link-level Resource Provision in Multi-Radio Multi-Channel Wireless Networks

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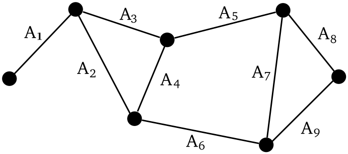
QoS-sensitive applications

- Wireless visual surveillance networks with quasi-static link-level traffic demand



Wireless Mesh Networks

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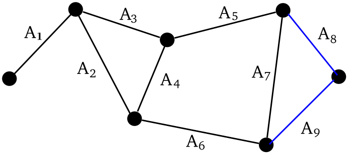
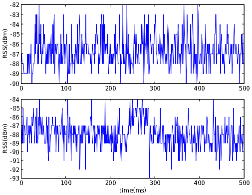


Challenges

- Dynamics of channel conditions
  - In both mobile and static scenarios



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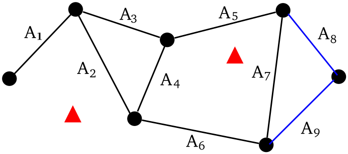
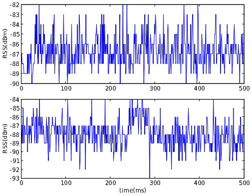


Challenges

- Dynamics of channel conditions
  - In both mobile and static scenarios
- Interference from co-existing networks
  - e.g., WiFi hotspots



Wireless Mesh Networks

QoS-sensitive applications

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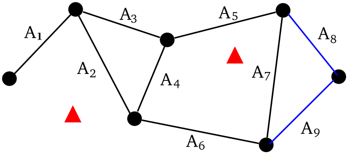
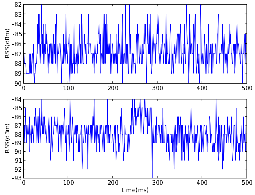


Challenges

- Dynamics of channel conditions
  - In both mobile and static scenarios
- Interference from co-existing networks
  - e.g., WiFi hotspots

$\Longrightarrow$ Varying channel capacity



Motivation

Q: can we provide predictable service in the dynamic wireless environment via resource provisioning?

- Radio
- Channel
- Link rate
- Scheduling
- Power

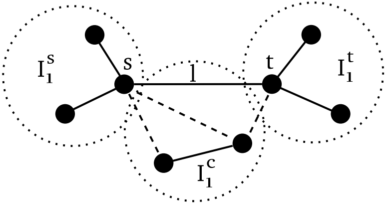
A: design a robust radio and channel assignment scheme for MR-MC wireless networks

- Explicitly accounting for link-level traffic demand
- Robust to external interference and channel variation
- Incorporating measurement-driven interference model
- Provable convergence to global optimality

Models and Notations

- Multi-radio multi-channel networks
  - Each node has multiple radios, each radio can switch between different channels
- Link-level traffic demand
  - Can be extended to end-to-end traffic demand
- Each link l is associated with a unique pair of radios at the transmitter and receiver node and a single channel:
  - x_l^i: equals 1 if radio i is assigned to link l at transmitter node s, and 0 otherwise.
  - y_l^j: equals 1 if radio j is assigned to link l at receiver node t, and 0 otherwise.
  - z_l^k: equals 1 if channel k is assgined to link l, and 0 otherwise.

Radio and Contention Constraints



- I_l^s : conflicting link set at transmitter node s
- I_l^t : conflicting link set at receiver node t
- I_l^c : conflicting link set in the same contention domain

Aggregate transmission time

$$T_l(x,y,z) = \frac{A_l}{C_l} + \sum_{l' \in I_l^s} \frac{x_{l'}^i A_{l'}}{C_{l'}} + \sum_{l' \in I_l^t} \frac{y_{l'}^j A_{l'}}{C_{l'}} + \sum_{l' \in I_l^c} \frac{z_{l'}^k A_{l'}}{C_{l'}} \leq 1$$

- A_l : link-level traffic demand
- C_l : effective link rate

Interference margin and effective link rate

Gaussian noise channel model

$$C_l \approx B \log\left(1 + \frac{P_s G_{st}}{\sigma_0 + \sigma_e + \sum_{s' \neq s} P_{s'} G_{s't}}\right)$$

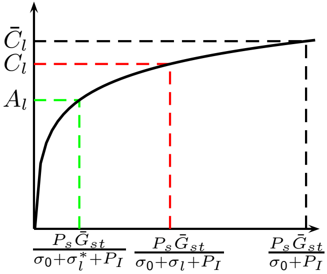
- P_s : transmission power of node s
- $P_{s'}$: transmission power of node s'
- G_{st} : channel gain between s and t
- $G_{s't}$: channel gain between s' and t
- σ_0 : noise floor
- σ_e : external interference

Interference margin and effective link rate

Gaussian noise channel model

$$C_l \approx B \log\left(1 + \frac{P_s \bar{G}_{st}}{\sigma_0 + \sigma_l + \sum_{s' \neq s} P_{s'} \bar{G}_{s't}}\right)$$

- P_s : transmission power of node s
- $P_{s'}$: transmission power of node s'
- $\bar{G}_{st}$: mean channel gain between s and t
- $\bar{G}_{s't}$: mean channel gain between s' and t
- σ_0 : noise floor
- σ_l : interference margin



Robust Radio & Channel Assignment Problem

Objective : To find a set of radio and channel assignment that maximizes the interference margin subject to certain fairness properties

- Utility function $U_l(\sigma_l)$ is increasing, additive, strictly concave and 2nd order differentiable

$$\begin{aligned} \max \quad & \sum_{l \in \mathcal{L}} U_l(\sigma_l) \\ \text{s.t.} \quad & T_l(x, y, z, \sigma) \leq 1, \forall l \in \mathcal{L}, \\ & x_l^i, y_l^j, z_l^k = \{0, 1\}, \forall l \in \mathcal{L}, \\ & \sigma_l \geq 0, \forall l \in \mathcal{L}. \end{aligned}$$

Solution

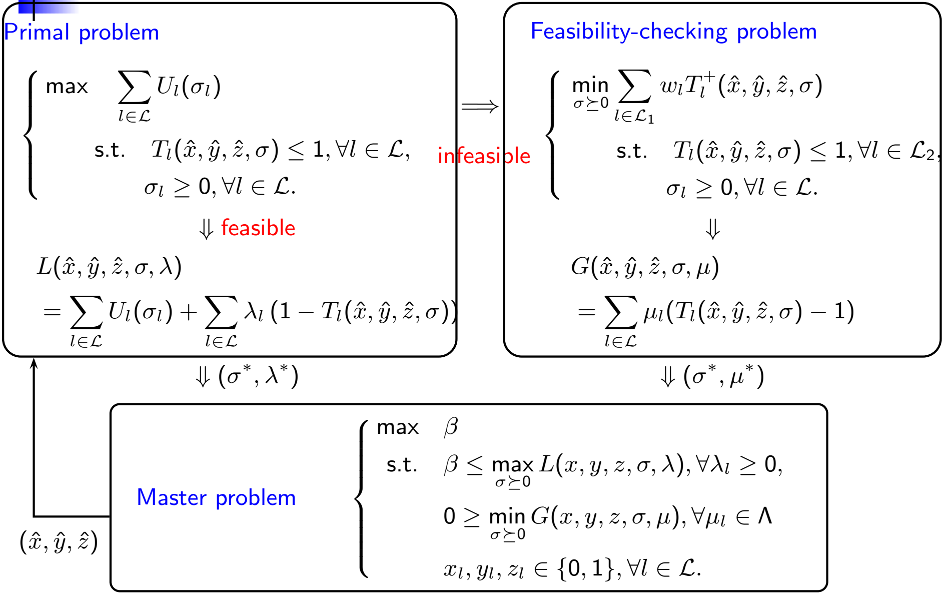
Challenge

- Mixed-integer Nonlinear Programming(MINLP) problem
    - σ is a vector of continuous variables
    - x, y, z are vectors of binary variables
- MINLP problem is NP-hard

Generalized Benders Decomposition[Geoffrion, 1972]

- The problem is not concave in σ and x, y, z jointly, but fixing x, y, z makes it so in σ.
- The nonconcavity can be treated separately from the concave portion by decomposing the original MINLP problem to a primal problem and a master problem and solve them iteratively.

Generalized Benders Decomposition



Primal problem

$$\begin{cases} \max & \sum_{l\in\mathcal{L}} U_l(\sigma_l) \\ \text{s.t.} & T_l(\hat{x},\hat{y},\hat{z},\sigma) \le 1, \forall l \in \mathcal{L}, \\ & \sigma_l \ge 0, \forall l \in \mathcal{L}. \end{cases}$$

$\Downarrow$ feasible

$$L(\hat{x},\hat{y},\hat{z},\sigma,\lambda) = \sum_{l\in\mathcal{L}} U_l(\sigma_l) + \sum_{l\in\mathcal{L}} \lambda_l \left(1 - T_l(\hat{x},\hat{y},\hat{z},\sigma)\right)$$

$\Longrightarrow$ infeasible

Feasibility-checking problem

$$\begin{cases} \min_{\sigma\succeq 0} & \sum_{l\in\mathcal{L}_1} w_l T_l^+(\hat{x},\hat{y},\hat{z},\sigma) \\ \text{s.t.} & T_l(\hat{x},\hat{y},\hat{z},\sigma) \le 1, \forall l \in \mathcal{L}_2, \\ & \sigma_l \ge 0, \forall l \in \mathcal{L}. \end{cases}$$

$\Downarrow$

$$G(\hat{x},\hat{y},\hat{z},\sigma,\mu) = \sum_{l\in\mathcal{L}} \mu_l (T_l(\hat{x},\hat{y},\hat{z},\sigma) - 1)$$

$\Downarrow (\sigma^*, \lambda^*)$

$\Downarrow (\sigma^*, \mu^*)$

Master problem

$$\begin{cases} \max & \beta \\ \text{s.t.} & \beta \le \max_{\sigma\succeq 0} L(x,y,z,\sigma,\lambda), \forall \lambda_l \ge 0, \\ & 0 \ge \min_{\sigma\succeq 0} G(x,y,z,\sigma,\mu), \forall \mu_l \in \Lambda \\ & x_l, y_l, z_l \in \{0,1\}, \forall l \in \mathcal{L}. \end{cases}$$

$(\hat{x},\hat{y},\hat{z})$

GBD Algorithm

```
Set $m = 1$ and $x^{(m)}, y^{(m)}, z^{(m)} \in \{0,1\}, LB^0 \leftarrow -\infty, UB^0 \leftarrow \infty, P^0 \leftarrow \emptyset, F^0 \leftarrow \emptyset$.
while $LG^{m-1} < UB^{m-1}$ do
    if the primal problem is feasible then
        Solve the primal problem $P(x^{(m)}, y^{(m)}, z^{(m)})$ to obtain optimal solution $\sigma^{(m)}$ and $\lambda^{(m)}$;
        $P^m \leftarrow P^{m-1} \cup \{m\}$, $F^m \leftarrow F^{m-1}$;
        $LB^m \leftarrow \max(LB^{m-1}, v(x^{(m)}, y^{(m)}, z^{(m)}))$;
        if $LB^m = v(x^{(m)}, y^{(m)}, z^{(m)})$ then
            $(x^*, y^*, z^*, \sigma^*) \leftarrow (x^{(m)}, y^{(m)}, z^{(m)}, \sigma^{(m)})$;
        end
    else if the primal problem is infeasible then
        Solve the feasibility-check problem $F(x^{(m)}, y^{(m)}, z^{(m)})$ to obtain the optimal solution $\sigma^{(m)}$ and $\mu^{(m)}$;
        $P^m \leftarrow P^m$, $F^m \leftarrow F^{m-1} \cup \{m\}$;
    end
    Solve the master problem $M(\sigma^{(m)}, \lambda^{(m)}, \mu^{(m)})$ to obtain the optimal solution $(x^{(m+1)}, y^{(m+1)}, z^{(m+1)})$ and $\beta^{(m)}$; $UB^m \leftarrow \beta^{(m)}$, $m \leftarrow m + 1$;
end
return $(x^*, y^*, z^*)$ and $\sigma^*$.
```

Algorithm

Convergence

- The sequence of upper bounds(master problem) is nonincreasing and the set of lower bounds(primal problem) is nondecreasing
- The algorithm is guaranteed to converge to the optimal solution in a finite number iterations[Geoffrion'72, Li'06]

Implementation

- The primal problem can be solved distributively using dual decomposition
- The master problem have to be solved in centralized manner with constant communication costs

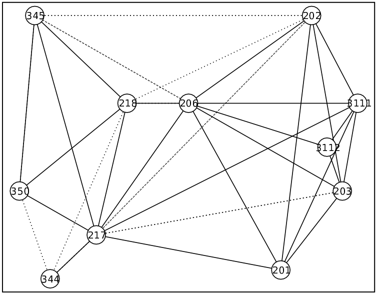
Scheduling

- A TDMA schedule algorithm based on the idea of maximal scheduling, can be implemented distributively.

Evaluation I: Numerical Results

Wireless mesh network testbed

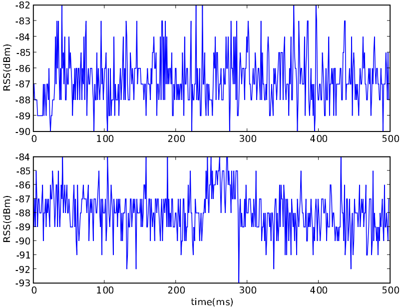
- 11 nodes
- 802.11 a/b/g
- No. of radios(1–3)
- No. of channels(1–4)

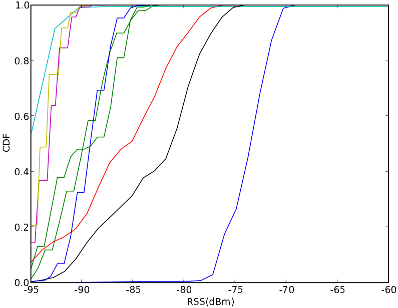


Algorithm comparison

- Robust algorithm
- MinInt algorithm[Mhatre'07]
- Random algorithm

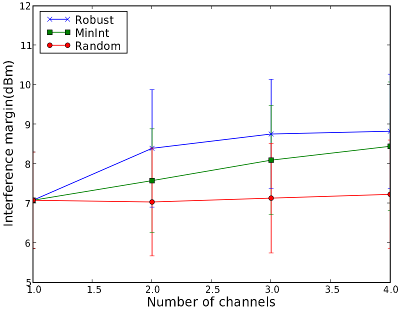
RSS Trace



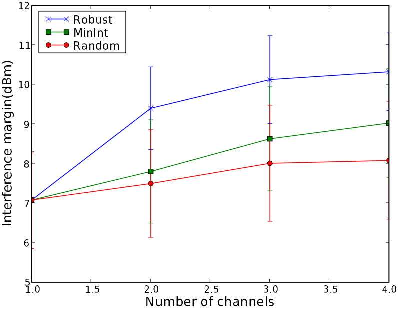


- Significant variations of RSS in short timescale
- RSS variation is link dependent

Numerical Results – Interference Margin



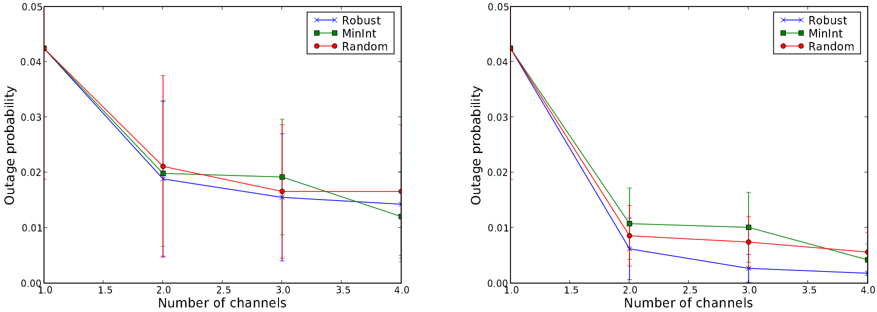
(a) One radio



(b) Two radios

- As the number of radios and channels increases, the interference margin increases
- Robust algorithm outperforms other two schemes

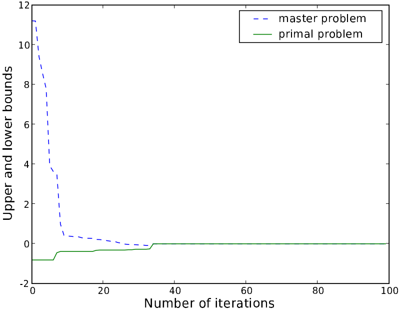
Numerical Results – Outage Probability



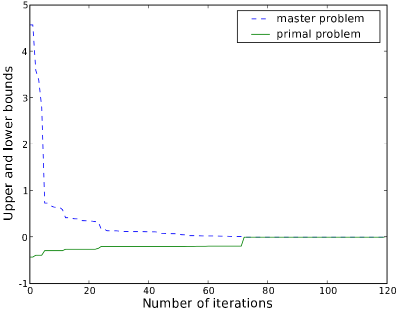
(a) One radio (b) Two radios

- Outage probabiltiy: percentage of violated constraints due to channel variations
- The outage probabiltiy is significantly reduced as the number of radios and channels increases
- Robust algorithm incurs less outage probability

Numerical Results – Convergence



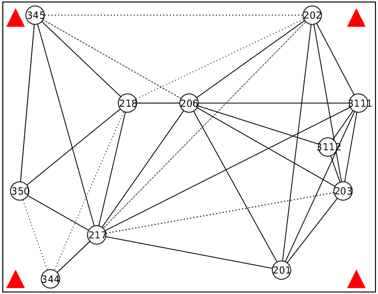
2 radios, 3 channels



3 radios, 4 channels

- The algorithm is guaranteed to converge to the optimal solution
- Convergence rate is affected by problem size (number of nodes, links, radios, channels etc.)

Evaluation II: Simulation Results



Qualnet simulations

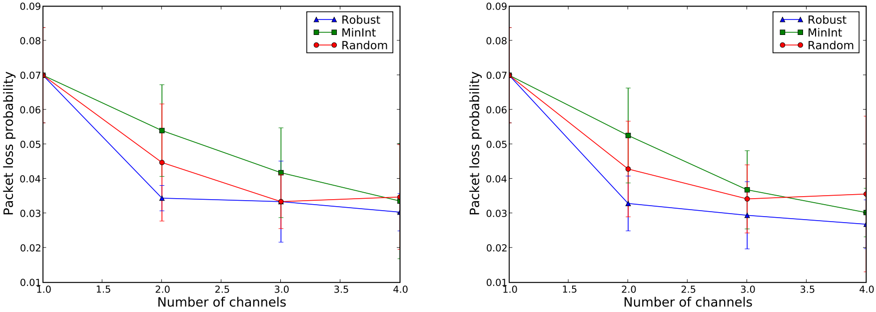
- Same topology as testbed
- Four external interference sources
- Inputs of propagation model from testbed measurement
- 802.11a PHY, TDMA

Interference source configuration

- No interference : none of these interference sources is activated
- Random interference : only one of the randomly selected interference sources is activated
- Persistent interference: all interference sources are activated

Simulation Results: Packet Loss Probability

No interference



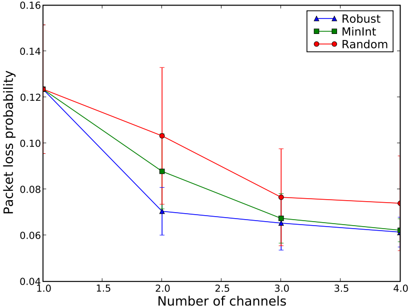
(a) One radio

(b) Two radios

- The robustness is improved as the number of radios and channels increases
- Robust algorithm incurs less packet losses than other two schemes

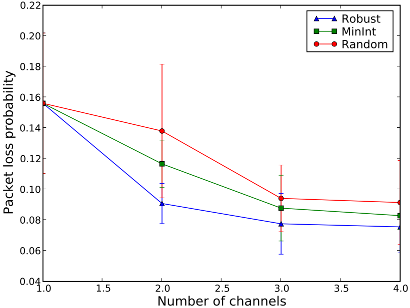
Simulation Results: Packet Loss Probability

Random interference



Two radio

Persistent interference



Two radios

- Higher packet losses as the no. of interference sources increases
- Robust algorithm handles channel variations and external interference better

Conclusions

- Wireless networks are generally unreliable, but we can contain the dynamics with robust resource provision
  - Radio, channel, link rate, schedule
- Design a robust radio and channel assignment algorithm for MR-MC wireless mesh networks
  - Explicitly accounting for link-level traffic demand
  - Robustness to channel variation and external interference
  - Guaranteed convergence to global optimality
- Future work
  - Power control
  - Routing
  - End-to-end traffic demand
  - Schedule

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Thank you!