Leveraging the Trade-off Between Spatial Reuse and Channel Contention in Wireless Mesh Networks

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Content

Introduction

- Wireless Mesh Network

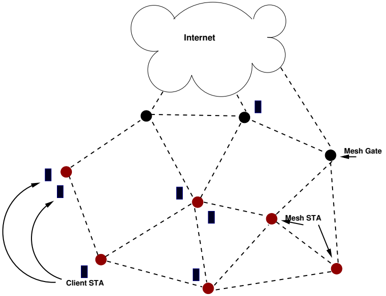

Figure: Wireless Mesh Architecture

- Multi-path communication
- Multi-hop communication
- Used as wireless backbone for providing Internet.

Introduction

- Wireless Mesh Network
- IEEE 802.11s [1] standard for channel access.
  - Distributed Coordination Function (DCF).
    - CSMA/CA with binary exponential back-off algorithm.
    - Can not provide Quality of Service (QoS)

- Wireless Mesh Network
- IEEE 802.11s [1] standard for channel access.
  - Distributed Coordination Function (DCF).
  - Point Coordination Function (PCF).
    - Polling based mechanism.
    - Can provide QoS
    - Hard to implement in multi-hop scenario.

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  - Point Coordination Function (PCF).
  - Mesh Coordination Function (MCF).

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  - Distributed Coordination Function (DCF).
  - Point Coordination Function (PCF).
  - Mesh Coordination Function (MCF).
    - Enhanced Distributed Channel Access. (EDCA)
      QoS by traffic priority class.

      No strict guarantee on QoS.
    - MCF Controlled Channel Access. (MCCA)
      Spatial-TDMA (STDMA)

      Distributed QoS ensuring channel access mechanism.

- Wireless Mesh Network
- IEEE 802.11s [1] standard for channel access.
- MCCA working principle

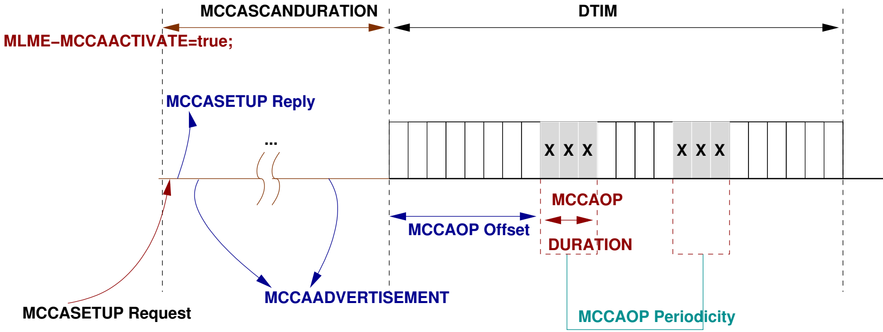

Figure: MCCA Standard

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- MCCA working principle

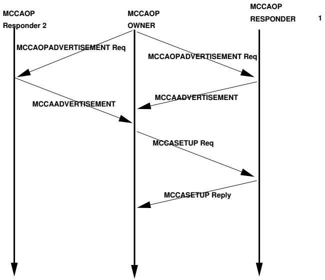

Figure: MCCA Setup procedure

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- Wireless Mesh Network
- IEEE 802.11s [1] standard for channel access.
- MCCA working principle
- Problems of MCCA standard.
  Increase spatial reuse by tuning SDR parameters

  Non-uniform distance between transmitter- receiver pair affects flow fairness

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  Distance between transmitter- receiver pair affects flow fairness
- This work tries to find a solution which ensures fairness in case of MCCA enabled Wireless Mesh Network by scheduling SDR parameters.

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  Distance between transmitter- receiver pair affects flow fairness
- This work tries to find a solution which ensures fairness in case of MCCA enabled Wireless Mesh Network by scheduling SDR parameters.
- Scheduling of SDR parameters have known trade-off issues.

Motivation

- Throughput - Transmit power level dependency.

$$\frac{G_{i_k j_k} P^{(t)}_{i_k j_k}}{\eta + \sum_{x \neq k} G_{i_x j_k} P^{(t)}_{i_x j_x}} \geq \gamma \tag{1}$$

Motivation

- Throughput - Transmit power level dependency.
- Throughput - Data rate dependency [2]

Data rate depends on Modulation and Coding Scheme (MCS)

Data Rate	Receive Sensitivity
1 Mbps	-101 dbm
2 Mbps	-98 dbm
5.5 Mbps	-92 dbm
11 Mbps	-89 dbm

Table: Data Sheet of Cisco Aironet 3600 Series

$$\frac{G_{i_k j_k} P_{i_k j_k}^{(t)}}{\eta + \sum_{x \neq k} G_{i_x j_k} P_{i_x j_x}^{(t)}} \geq \gamma(r_h) \quad (2)$$

Motivation

- Throughput - Transmit power level dependency.
- Throughput - Data rate dependency

Trade-off between Transmit power level and Data rate

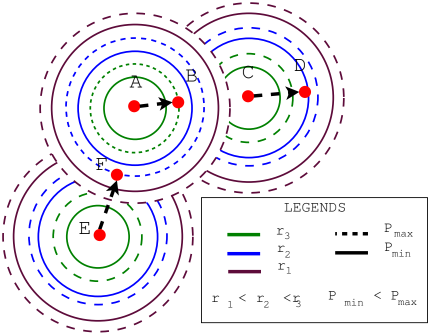

Figure: MCS and Transmit power level adjustment

Motivation

- Throughput - Transmit power level dependency.
- Throughput - Data rate dependency
- Throughput - Scheduling dependency

Non-conflicting flows can be scheduled simultaneously

Motivation

- Throughput - Transmit power level dependency.
- Throughput - Data rate dependency
- Throughput - Scheduling dependency
- Throughput - Fairness dependency [3]
- Fair allocation of throughput
  - Max-Min fairness
  - Proportional fairness
  - $(\mathfrak{P}, \alpha)$-proportionally fair[1] [4]

$$F_{\mathfrak{P}_{ij},\alpha}(\mathcal{R}) = \begin{cases} \mathfrak{P} \log(\mathcal{R}) & \alpha = 1 \\ \mathfrak{P}_{ij} \frac{\mathcal{R}^{(1-\alpha)}}{(1-\alpha)} & Otherwise \end{cases} \tag{3}$$

[1] $\log(\mathcal{R}) = \sum_i \log(\mathcal{R}_i)$

Motivation

- Throughput - Transmit power level dependency.
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  - Fair Joint Power and Rate Scheduling (Fair-JPRS)

Related Works

- Static Power Control
  - Uniform Range Power Control
    1. COMPOW

       Same power level for all nodes.
  - Variable Range Power Control
    1. MINPOW

       Use minimum power level to sustain communication.
    2. CLUSTERPOW

       Clusters transmitter receiver pairs based on required transmit power level.
    3. tunneled- CLUSTERPOW

Related Works

- Static Power Control
  - Uniform Range Power Control COMPOW
  - Variable Range Power Control

    MINPOW, CLUSTERPOW, tunneled- CLUSTERPOW
- Dynamic Power Control
  - PATE - Choose least congested node
  - PCMA,PCDC - Separate control channel
  - POWMAC - RTS/CTS packets for power adjustment

Related Works

- Static Power Control
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  - POWMAC - RTS/CTS packets for power adjustment
- Joint Design Challenge
  - Joint Power Control and Routing
  - Joint Power Control and Scheduling
  - Joint Power Control, Rate Control and Scheduling

Related Studies Contd...

- Joint Power Control, Rate Control and Scheduling
  - IPRS problem - Centralized optimization
  - DPRL Algorithm - Distributed heuristic

System Model

- Wireless Mesh Network
- IEEE 802.11 b/g/n physical layer support.
- Software Defined Radio (SDR) supported with multiple data rate and power levels.
- Single interface
- Single channel
- Omni-directional Antenna
- Time is slotted

$$X_{ijh}^{(t)} = \begin{cases} 1 & \text{If flow i} \rightarrow \text{j uses rate h at time t} \\ 0 & \text{Otherwise} \end{cases}$$

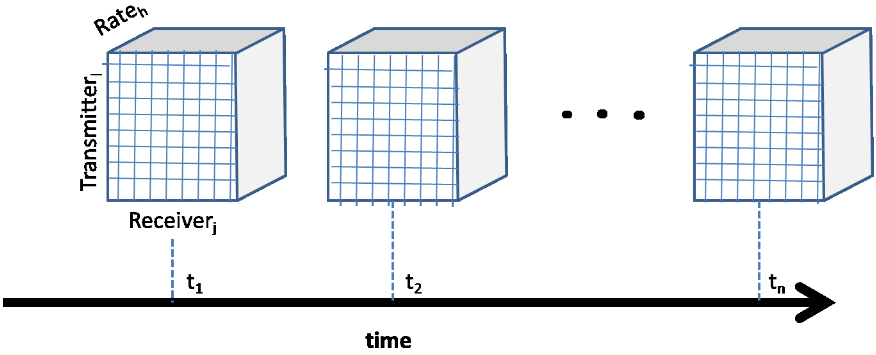

Figure: Interpretation of $X_{ijh}^{(t)}$

System Model Contd...

$$X_{ijh}^{(t)} = \begin{cases} 1 & \text{If flow i} \rightarrow \text{j uses rate h at time t} \\ 0 & \text{Otherwise} \end{cases}$$

Total transmitted data per *DTIM*

$$Tx_{ij} = \sum_{t}^{DTIM} \sum_{h} (X_{ijh}^{(t)} \times r_h \times \sigma)$$

Data rate for $h = r_h$
Slot duration σ

$$X_{ijh}^{(t)} = \begin{cases} 1 & \text{If flow i} \rightarrow \text{j uses rate h at time t} \\ 0 & \text{Otherwise} \end{cases}$$

$$Tx_{ij} = \sum_{t}^{DTIM} \sum_{h} (X_{ijh}^{(t)} \times r_h \times \sigma)$$

Indicator variable

$$\Gamma(\alpha) = \begin{cases} 1 & \alpha = 1 \\ 0 & Otherwise \end{cases}$$

$(\mathfrak{P}, \alpha)$-**Proportional fairness function**

$$F_\alpha(Tx) = \mathfrak{P}_{ij} \left(\Gamma(\alpha) \log(Tx) + (1 - \Gamma(\alpha)) \frac{Tx^{(1-\alpha)}}{(1-\alpha)} \right)$$

System Model Contd...

$$X_{ijh}^{(t)} = \begin{cases} 1 & \text{If flow i} \rightarrow \text{j uses rate h at time t} \\ 0 & \text{Otherwise} \end{cases}$$

$$Tx_{ij} = \sum_{t}^{DTIM} \sum_{h} (X_{ijh}^{(t)} \times r_h \times \sigma) \qquad \Gamma(\alpha) = \begin{cases} 1 & \alpha = 1 \\ 0 & Otherwise \end{cases}$$

$$F_\alpha(Tx) = \mathfrak{P}_{ij} \left(\Gamma(\alpha) \log(Tx) + (1 - \Gamma(\alpha)) \frac{Tx^{(1-\alpha)}}{(1-\alpha)} \right)$$

$$\mathscr{X}_{ij} = \{Tx_{ij}, P_{ij}\}$$

[2] $$Schedule(\mathscr{X}) = -\sum_{ij} (F_\alpha(Tx_{ij})) \qquad Power(\mathscr{X}) = \sum_{ij} \sum_{t} \left(P_{ij}^{(t)} \right)$$

[2]-ve sign in case of $Schedule(\mathscr{X})$ is used to ensure homogeneity of utility function(i.e. minimization)

$$X_{ijh}^{(t)} = \begin{cases} 1 & \text{If flow i} \rightarrow \text{j uses rate h at time t} \\ 0 & \text{Otherwise} \end{cases}$$

$$Tx_{ij} = \sum_{t}^{DTIM} \sum_{h} (X_{ijh}^{(t)} \times r_h \times \sigma) \quad \Gamma(\alpha) = \begin{cases} 1 & \alpha = 1 \\ 0 & Otherwise \end{cases}$$

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3 4

$$Schedule(\mathscr{X}) = -\sum_{ij} (F_\alpha(Tx_{ij})) Power(\mathscr{X}) = \sum_{ij} \sum_{t} \left(P_{ij}^{(t)} \right)$$

[3] Minimization of *Schedule*($\mathscr{X}$) increases fairness

[4] Minimize *Power*($\mathscr{X}$) to reduce transmit power level

Formulation of Optimization Problem

INPUT:

1. Connectivity matrix (X)
2. Antenna and channel gain matrix (G)
3. Available MCSs
4. Available transmit power levels
5. Slot duration (σ)

Constraints:

1. Hidden node constraint
2. SINR constraint

OUTPUT:

Schedule of rate and available power levels ($\mathscr{X}$)

Formulation of Optimization Problem

Problem (Vector Optimization Problem)

$$Minimize \mathcal{Q}(\mathscr{X}) = \{Schedule(\mathscr{X}), Power(\mathscr{X})\} \quad (5)$$

S.T.

$$0 \leq P_{ij}^{(t)} \leq P_{max} \qquad h \in \{1, 2...m\} \qquad t \in \{1, 2...DTIM\} \quad (6)$$

$$\sum_{h} \left[\sum_{ij} X_{ijh}^{(t)} + \sum_{jf} X_{jfh}^{(t)} \right] \leq 1 \quad (7)$$

$$\Phi[X_{ijh}^{(t)} - 1] - G_{ij} P_{ij}^{(t)} + \gamma(r_h) \sum_{fs} G_{fj} P_{fs}^{(t)} + \gamma(r_h)\eta \leq 0 \quad (8)$$

Proof: Correctness

Definition

Pareto optimality: A solution of vector optimization problem is called Pareto optimal solution of Eqn. 9, if individual component of the vector can not optimized without affecting some other component.

$$min(f_1(x), f_2(x), \ldots, f_n(x)) \tag{9}$$

$$\text{S.T.:} x \in X \tag{10}$$

Say, S^* is the Pareto optimal solution of Eqn. 9, and $\mathscr{S}$ be the set of feasible solutions, then

$$\forall j \in \{1, 2, \ldots n\}, i \in \mathscr{S} : f_j(x^*) \leq f_j(x^i)$$
$$and$$
$$\exists i \in \mathscr{S} : f_j(x^*) < f_j(x^i)$$

Proof: Correctness

Lemma (1)

Every solution of the Problem 1 formulation yields a feasible transmission scenario at each time slot.

Proof Idea: Each solution maintains SINR constraints along with hidden node constraints. Therefore, yealds feasible transmission scenario.

Theorem (1)

All optimum solutions of Problem 1 generates a Pareto optimal power vector allocation based on the transmissions scheduled in each time slot.

Proof Idea: As the vector optimization uses no preference method, from the definition of Pareto optimality allocated power vectors are also Pareto optimal.

Proof: Convexity

Lemma (2)

Schedule($\mathscr{X}$) is differentiable under $\mathscr{X}_{uv}$ and a convex function.

Lemma (3)

Power($\mathscr{X}$) is differentiable under $\mathscr{X}_{uv}$ and is a convex function.

Lemma (4)

For a feasible transmission scenario constraints in Eq. (8) is differentiable under $\mathscr{X}_{uv}$ and convex.

Proof Idea: For all Lemma 2,3 and 4 the Hessian matrix of the given functions are positive semi-definite.

Theorem (2)

Problem 1 is a convex vector optimization problem.

Solution method: Using KKT condition

According to Theorem 1, Problem 1 is proven to be convex optimization,. Therefore, it can further be simplified using KKT condition as following. [5]

Problem (2)

$$\lambda_1 \mathfrak{P}_{uv} \left(\frac{\Gamma(\alpha)}{Tx_{uv}} + \frac{1-\Gamma(\alpha)}{Tx_{uv}^{\alpha}} \right) = \lambda_3 \frac{\Phi}{r_h \sigma} \tag{11}$$

$$\lambda_2 + \gamma(r_h)\lambda_4' \sum_q G_{uq} = \lambda_3 G_{uv} \tag{12}$$

$$\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 = 1 \tag{13}$$

However, the centralized solution requires global antenna and channel gain matrix (G) and communication matrix (X) for calculating SINR and hidden node constraints. These information are not available in case of WMN and MCCA suitable distributed implementation. Therefore, by exploiting the properties of Problem 2, a distributed heuristic can be formulated by approximating the local gain and local communication information.

[5] Here λ_i denotes KKT variable and $\lambda_i > 0$

Distributed Heuristic Proposal

Augmentation of MCCA

- Each mesh STA v sends a beacon frame using P_{max} and SINR for that frame is captured in $\mathcal{S}_{uv}$. Each mesh STA broadcasts its $\mathcal{S}_{uv}$ with MCCAOP advertisement req message.
- Data rate r_h is decided such that $\gamma(r_{h+1}) > \mathcal{S}_{uv}$ and $\gamma(r_h) \leq \mathcal{S}_{uv}$
- Transmit power level is calculated using $P_{uv}^{(h)} \geq \frac{\gamma(r_h)\, P_{max}}{\mathcal{S}_{uv}}$.
- A winner is decided based on the highest $\mathcal{S}_{uv}$.
- Winner node decides
    - For the winner if no prior schedule is available the it assigns MCCAOP duration= Tx_{max}. Otherwise it estimates the value of $\mathfrak{P}_{ij}$ based on the available schedule information. Based on the estimated $\mathfrak{P}_{ij}$ solves Problem 2 by assuming $\sum_q G_{qv} = \frac{1}{P_{max}} \left(\frac{G_{uv} P_{max}}{\mathcal{S}_{uv}} - \eta \right)$ for finding Tx_{uv}.
    - MCCAOP offset= First available slot
    - MCCAOP periodicity = no. of contending neighbour (Δ).
    - MCAOP duration= $\frac{Tx_{uv}}{\Delta}$

Simulation Results in NS-3.19

Frame Size	512 B	
Traffic Generation rate	15Mb/s	
MCS	Data Rate	Receive Sensitivity
6.5OFDM	6.5Mbps	-87dBm
26OFDM	26Mbps	-81dBm
39OFDM	39Mbps	-78dBm
54OFDM	54Mbps	-73dBm
Min Power Level	2dbm	
Max Power Level	17dbm	
Power Levels	9	
Slot Time σ	0.80ms	
DTIM	1s	
Slots/DTIM	1000	
Scan Duration	32ms	

Table: Simulation Parameters

The proposed protocol is compared with the standard MCCA and DPRL [5].

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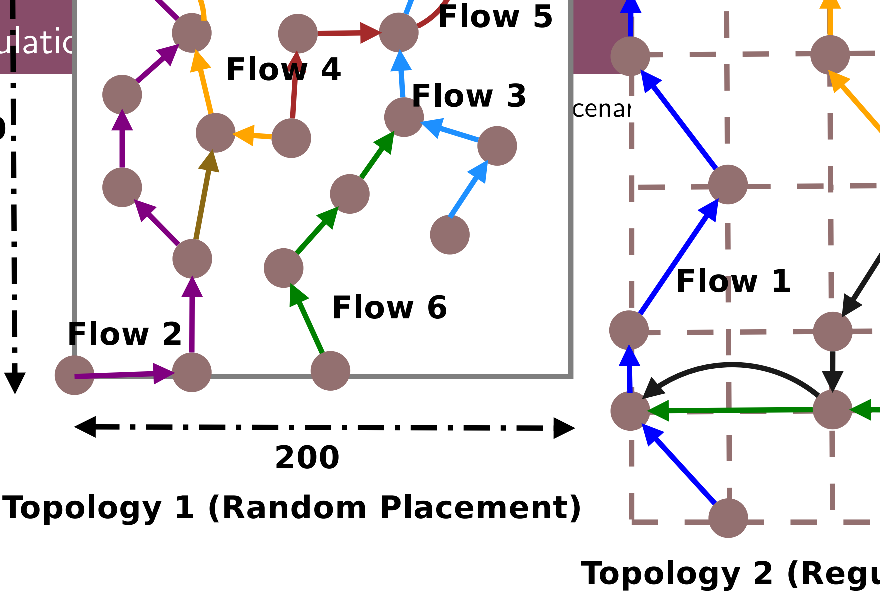

Figure: Simulation scenario

Simulation Results in NS-3.19

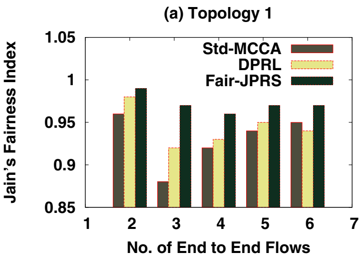

Figure: Effect on Jains Fairness Index

Simulation Results in NS-3.19

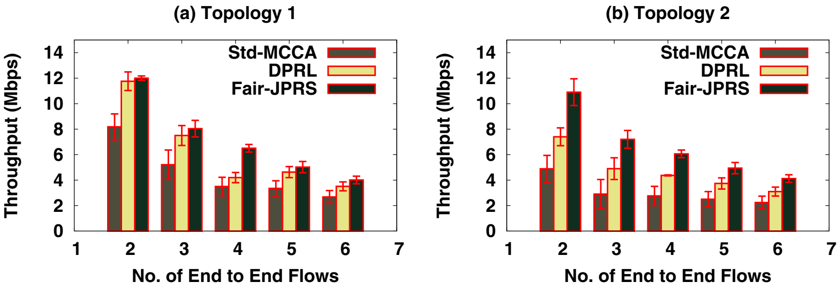

Figure: Effect on End To End Throughput

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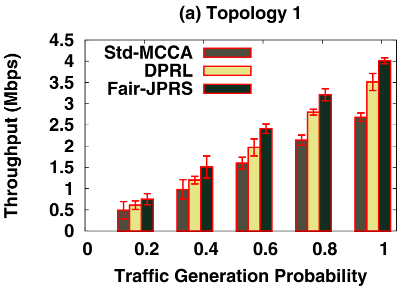

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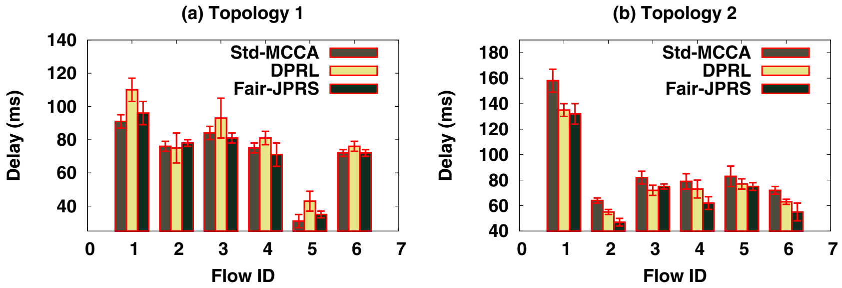

Figure: Effect on End To End Delay

Simulation Results in NS-3.19

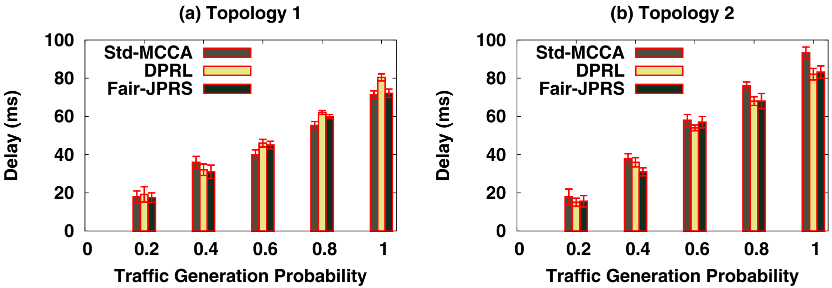

Figure: Effect on End To End Delay

Conclusion and Future Work

- Proposed Fair-JPRS improves performance in terms of fairness.
- The required average power level and throughput remains almost similar.

- Extension of the work:
  - For multiple interface with multiple channel case
  - Directional antenna support
  - Effect of end to end throughput and delay
  - Theoretical performance modelling of the proposed scheme

Thank You

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