A New Model for Packet Scheduling in Multihop Wireless Networks

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Design Goals

• Support **Communication Intensive** Applications in Multihop Wireless Networks
  – Fair Allocation of Channel Bandwidth
  – Maximization of Channel Utilization

• Tradeoff between **Fairness** and **Maximizing Aggregate System Throughput**

• **Distributed** Packet Scheduling Design
Outline

• Issues in Multihop Wireless Packet Scheduling
• Service Models for Multihop Wireless Packet Scheduling
• An Idealized Centralized Algorithm
• A Distributed Implementation
• Performance Evaluation
• Conclusion and Future Work
Network Model

- A **Single** Shared Physical Channel
- **Collision** – Receiver in Transmission Range of More than One Transmitting Node
- **Flow** – Stream of Packets from Source to Destination <Sender, Receiver, Flow_ID>
- **CSMA/CA** MAC Framework
Design Issues

- Location Dependent Contention & Channel Reuse
  - Spatial Reuse
  - Spatial Collision
  - F1
  - F2
  - F3
Design Issues

No Spatial Contention

No Spatial Reuse
Flow Contending Graph

Node Graph

Flow Graph
Design Issues (cont’d)

• Inherent Conflict between Achieving Fairness & Maximizing Channel Utilization

• To Maximize Channel Utilization
  • Schedule F3 & F5 always (MIS)
  • Starve F1, F2 & F4

Node Graph

Flow Graph
Design Issues (cont’d)

Inherent Conflict: Fairness, Throughput

Node Graph

Flow Graph

Fairness v.s. Aggregate Throughput
Design Issues (cont’d)

• **Distributed Nature** of Packet Scheduling in Generic Multihop Wireless Networks
  – Unlike **Wireline** or **Packet Cellular** Networks. NO Single Logical Entity for Scheduling
  – NO **Direct Access** to All Contending Flow Info

• Provide QoS at Finest Time Scale (Packet Level)
Solution Space

• One End – Ensure Fairness Always
  – At the Cost of Channel Utilization

• The Other End – Maximize Channel Utilization Always
  – Schedule Largest Number of Non-conflicting Flows
  – Starvation of Certain Flows
Tradeoff Between Fairness & Maximizing Channel Utilization

• Each Flow is Provided a Basic Fair Share
  – Global Topology-Independent Fairness
  – Local Topology-Dependent Fairness
• Further Maximize Channel Utilization
Global Topology-Independent Fairness Model

• Every Flow with Weight $r_i$ Receive a Proportional Basic Fair Share:
  \[
  \sum_{j \in B(t_1)} \frac{r_i}{r_j} C(t_1, t_2)
  \]

• Flow Set $B(t_1)$: All Backlogged Flows in Connected Flow Graph – Global Flow Information Propagation

• A Priori Fair Share Bounds

• Topology Independent
Local Topology-Dependent Fairness Model

• Every Flow with Weight $r_i$ Receive a Proportional Basic Fair Share:

$$\sum_{j \in B_i(t_1)} \frac{r_i}{r_j} C(t_1, t_2)$$

• Flow Set $B_i(t_1)$: Backlogged Flows in Flow’s Local Contending Flow Set – Only Local Flow Information Necessary

• Larger Basic Fair Share

• Topology Dependent

• Lower Spatial Channel Reuse
Maximize Spatial Channel Reuse

• Maximizing Spatial Reuse is Equivalent to *Maximum Independent Set* (MIS) Problem in Flow Contending Graph

• Solution to MIS Problem
  – NP Complete
  – *Greedy Approximation*: Minimum Degree First
An Example

Flow ID : F0  F1  F2  F3  F4  F5

Spatial Reuse :

Basic Fair Share :

Time :

Flow Graph :
An Example

Flow ID:  F0  F1  F2  F3  F4  F5

Spatial Reuse:  F2  F3  F4  F5

Basic Fair Share:  F0

Time:

Flow Graph:
An Example

Flow ID: F0 F1 F2 F3 F4 F5

Spatial Reuse: F2 F3 F5

Basic Fair Share: F0 F1

Time:

Flow Graph: F0 F1 F2 F3 F4 F5
An Example

Flow ID: F0 F1 F2 F3 F4 F5

Spatial Reuse: F2 F0 F4 F5
              F3 F5 F2

Basic Fair Share: F0 F1 F4

Time:

Flow Graph:
An Example

Flow ID: F0 F1 F2 F3 F4 F5

Spatial Reuse: F2 F3 F5 F0 F2 ...

Basic Fair Share: F0 F1 F4 ...

Time:

Flow Graph:
Centralized Algorithms

- Ensure Per-flow Basic Fair Share
  - Fair Queuing

- Maximize Spatial Reuse
  - Simultaneously Schedule MIS of other Non-conflicting Flows

- Analytical Performance Bounds
  - Basic Fair Share Service Bound
  - Optimal Aggregate Channel Utilization
Distributed Implementation

• Two Key Issues
  – How to **Ensure** Fair Share to Every Flow
  – How to **Maximize** Spatial Reuse Distributedly

• Solution
  – Within CSMA/CA MAC Framework
  – Basic Fair Share: Approximate **WFQ** with Modified **WRR**
  – Maximizing Spatial Reuse: Backoff Based Implementation of **MIS** Greedy Algorithm
Distributed Implementation

• Backoff Based Implementation of $\textit{MIS}$ Greedy Approximation
  – Smaller-Degree Flow Transmits First
  – For Potential Spatial Reuse, Set $\textit{Backoff} = \textit{Flow\_Degree}$

• Integration
  – Basic Fair Share has Priority Over Spatial Reuse
  – For Basic Fair Share, Set $\textit{Backoff} = \textit{Zero}$
An Example

- Set $\text{Backoff} = \text{Zero}$ or $\text{Flow}_{\text{Degree}}$

- $F0$ Contends for Fair Share According to WRR
- $F1, F2, F3, F4 \& F5$ Contend for Spatial Reuse
An Example

• Set \textit{Backoff} = Zero or \textit{Flow\_Degree}
An Example

- Set \( \text{Backoff} = \text{Zero or Flow\_Degree} \)
An Example

- Set **Backoff = Zero or Flow_Degree**
An Example

- Set $\text{Backoff} = \text{Zero}$ or $\text{Flow\_Degree}$
An Example

• Set \textit{Backoff} = \textit{Zero} or \textit{Flow\_Degree}

• \textit{F0} is Provided its Fair Share Service Bound

• \textit{F2, F3 & F5} Maximize Spatial Reuse – \textit{Maximum Independent Set}
Other Issues

- Detailed MAC Layer Design
  - CSMA/CA Paradigm
- Global Flow Information (i.e. Flow Weights) Propagation for Global Fairness Model
  - Conflict-free Multicast Tree
Simulation Example

Node Graph

Flow Graph
Simulation Example (cont’d)

Per-Flow Throughput Comparison
Simulation Example (cont’d)

Minimal Per-flow Throughput Comparison

Aggregate Throughput Comparison
Summary of Simulation Findings

• Comparison of
  – Minimum Per-Flow Throughput
  – Aggregate System Throughput

• Four Approaches
  – Always Maximize Channel Utilization
  – Global Topology-Independent Fairness Model
  – Local Topology-Dependent Fairness Model
  – Always Ensure Fair Allocation of Communication Bandwidth
Minimal Per-Flow Throughput

Maximal Channel Utilization

0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2

Min Per-flow Throughput

21 Flows
33 Flows
50 Flows
80 Flows

Global Fairness Model
Local Fairness Model

Ensure Absolute Fairness

Maximal Channel Utilization

21 Flows
33 Flows
50 Flows
80 Flows

Global Fairness Model
Local Fairness Model

Ensure Absolute Fairness
Aggregate System Throughput

![Graph showing Aggregate System Throughput with lines for different numbers of flows: 21, 33, 50, and 80 flows. The graph compares Global Fairness Model and Local Fairness Model across Maximal Channel Utilization and Ensure Absolute Fairness dimensions. Each model shows a decrease in aggregate total throughput with increasing utilization.]
Related Work

• Distributed Fair Queuing
  – Adapt Fair Queuing Algorithm to Wireless LAN
  – Distributed Fair Scheduling
  – Backoff Based on Virtual Time
  – No Explicit Effort to Maximize Spatial Channel Reuse
Related Work (cont’d)

- MAC Layer Approach
  - Arbitrate Medium Access Control
  - Seek to Maximize Spatial Reuse of Bandwidth
  - Fairness on Wireless Links (not Packet Flows)
  - Work with TDMA Cycle
  - No Tradeoff between Fairness & Maximal Channel Utilization

Summary & Future Works

• Two-tier Service Models for Multihop Wireless Packet Scheduling
  – Ensure Basic Fair Share to Individual Flows
  – Maximize Further Spatial Reuse

• A Backoff-based Distributed Algorithm Closely Realize Ideal Models

• Improve the Design of the Distributed implementation
  – Interaction with underlying MAC Layer Protocols
  – Frequent Node Mobility

• More Extensive Simulation Evaluation