CDS270: Optimization, Game and Layering in Communication Networks

Lecture 9: Random Access Games and Medium Access Control Design

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Agenda

- Contention-based medium access control (contention control)
- A game theoretic approach to contention control
  - Random access game
  - A case study
  - Utility and reverse-engineering
  - Conclusions

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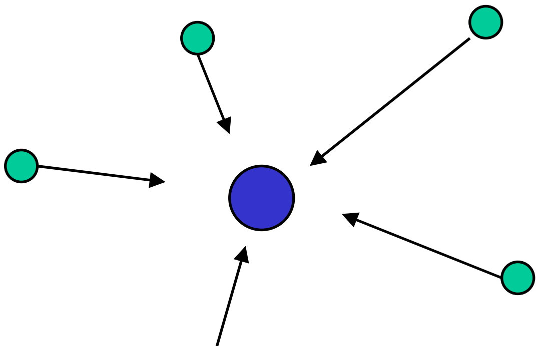
Medium access control (MAC)

- Wireless channel is shared medium and interference-limited
- Medium access control: coordinate channel access
  - Reduce/avoid interference/collision
  - Efficient utilization of wireless spectrum
  - Quality of Service control



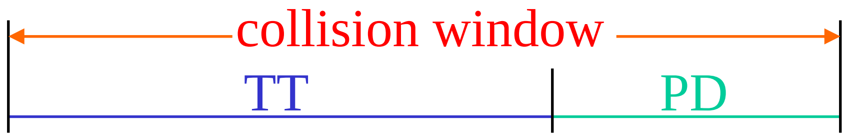
a multiple access network

Two kinds of methods

- Schedule-based
  - Establish transmission schedules *a priori* or dynamically
  - Usually requires centralized implementation
  - High complexity, not practical in real networks
- Contention-based
  - Wireless nodes contend for the channel
  - Simple, distributed implementation
  - High statistical multiplexing gain
  - Aloha, CSMA/CA, 802.11 DCF, …

Aloha

- Very simple: if a node has a packet to send, it just transmits
- Listen for an amount of time
  - If an ACK is received, done.
  - Otherwise, resend the packet
- Low-delay in light-load scenarios
- Low channel utilization (<=18%)
  - Collision window is equal to transmission time (TT) plus propagation delay (PD)



Slotted Aloha

- Time is slotted
  - slot duration is equal to transmission time plus maximum propagation delay
- Begin transmission at the slot boundaries
- Higher channel utilization (<=1/e)
  - Collision window is a point -- the slot boundary

Carrier Sensing multiple access (CAMA)

- Infer channel state through carrier sensing
  - Sense carrier before transmission
  - If idle, transmit the whole packet
  - Wait for ACK
- Higher channel utilization
  - Collision window is equal to maximum propagation delay
- When finding a busy channel
  - Non-persistent: sense the channel again after a random amount of time; if idle, send immediately
  - P-persistent: sense continuously; if idle, send with probability p

Contention/collision resolution

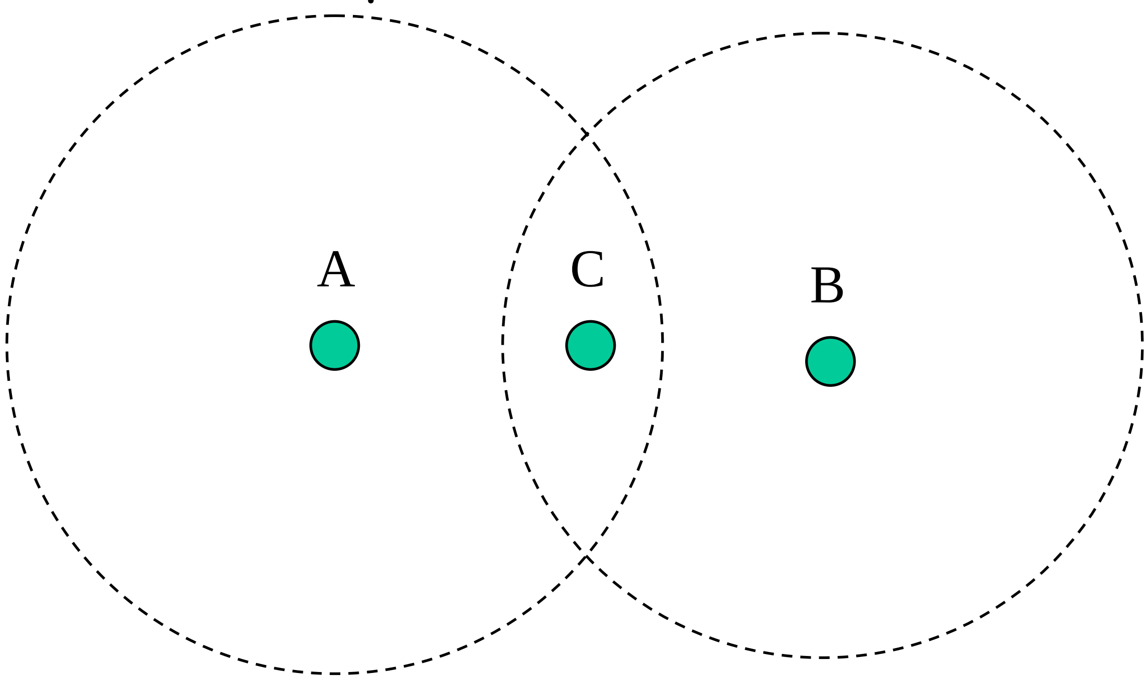
- What to do upon a collision
  - If the colliding nodes transmit immediately when the channel is idle after a collision, another collision is guaranteed
- Two collision resolution mechanisms
  - Persistence: transmit with a probability p
  - Backoff: wait for a random amount of time bounded by CW before retransmission
- Contention resolution algorithm (i.e., how to decide p and CW values dynamically in response to contention) is the key

CSMA/CD

- Collision detection (CD): immediately stop the transmission when sensing a collision
  - Detect at the senders
  - Not wait for an ACK
- Contention resolution: Binary exponential backoff
  - Wait a random amount of time bounded by CW before retransmission
  - Double CW upon every collision
  - Packet collision is the feedback signal
- Invented for Ethernet

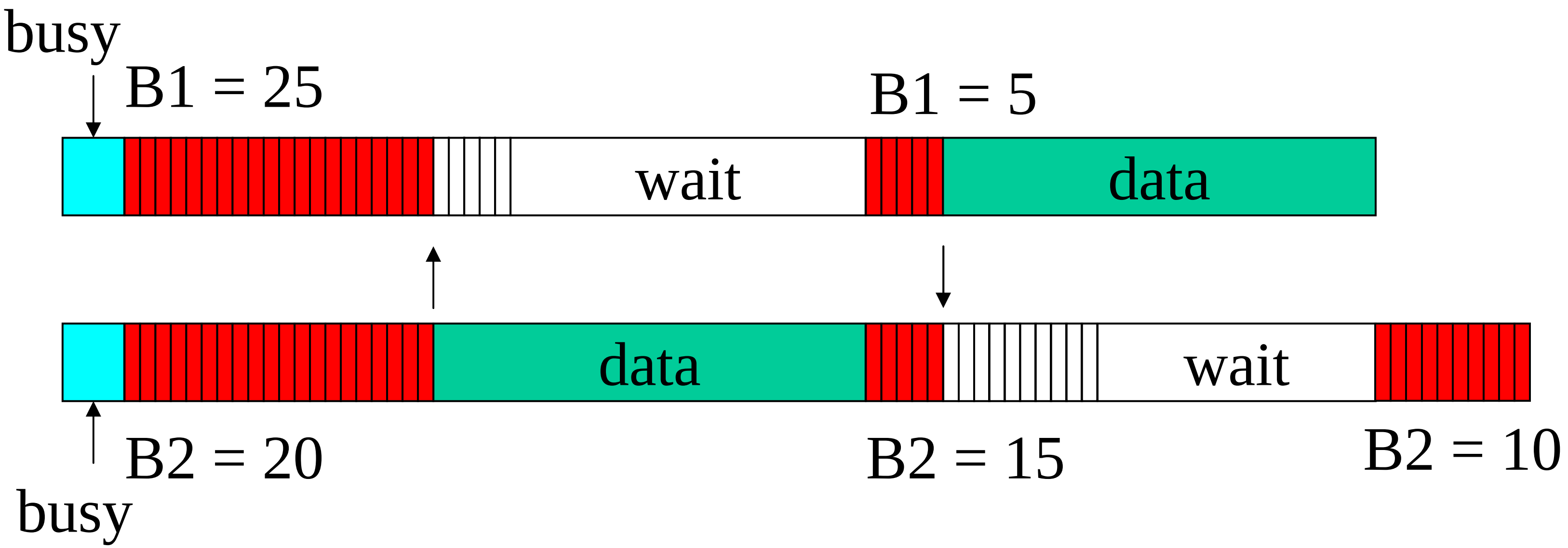
CSMA/CA

- Why collision avoidance (CA)?
  - CD is difficult in wireless networks: sender cannot effectively distinguish incoming weak signals from noise and the effects of its own transmission
  - Hidden terminal problem



Approaches for CA

- Randomized “backoff”
  - Slotted contention period
  - Operation
    - Each node selects a random backoff number
    - Waits that number of slots while sensing the channel
    - If channel stays idle and reaches zero then transmit
    - If channel becomes active wait until transmission is over then resumes backoff counter again



CW=32

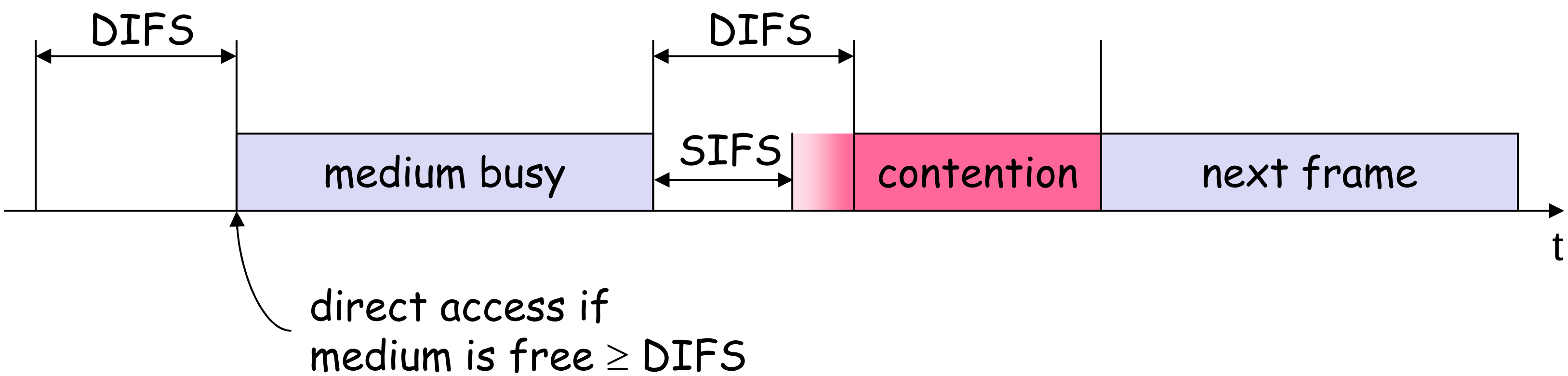
- Use of RTS (request-to-send) and CTS (clear-to-send) exchange
  - Before sending a packet, the sender first sends a RTS. The receiver responds with a CTS. Nodes hearing RTS or CTS then know that the channel will be busy for the duration of the request (indicated by Duration ID in the RTS and CTS)
  - Virtual carrier sensing: nodes will adjust their Network Allocation Vector (NAV) -- time that must elapse before a station can sense channel for idle status

Wireless 802.11 DCF (basic)

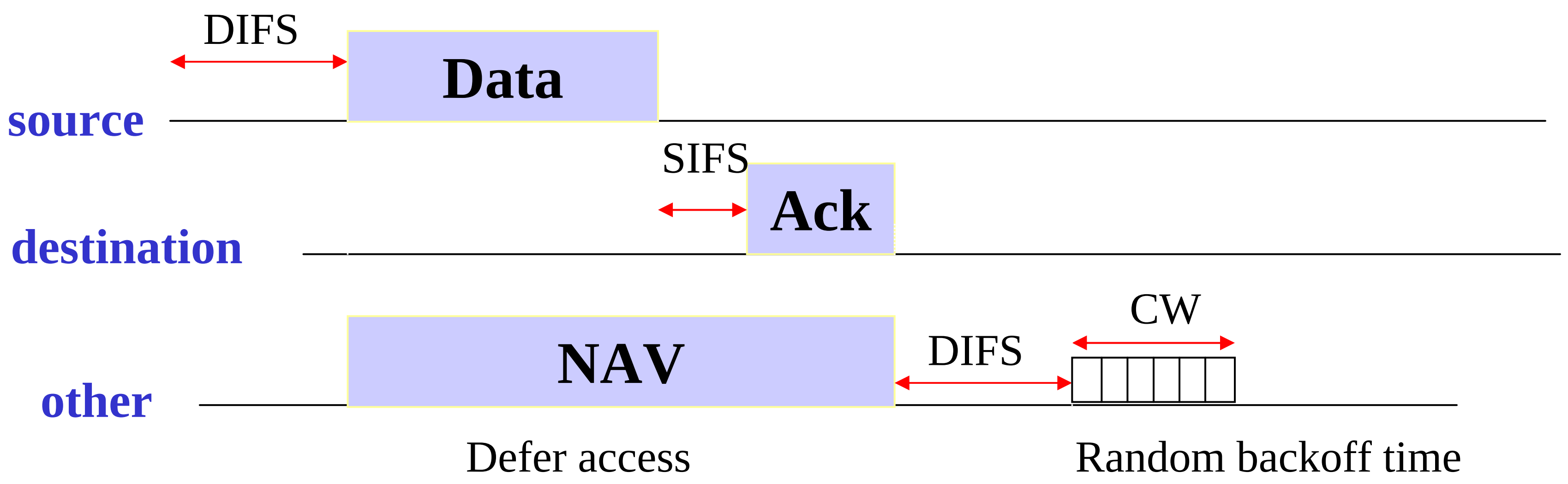
- DCF stands for distributed coordination function
- A CSMA/CA medium access protocol
  - CSMA: sense before transmission
  - CA: random backoff to reduce collision probability
    - when transmitting a packet, choose a backoff interval in the range [0, CW-1]
  - Count down the backoff interval when medium is idle
    - count-down is suspended if medium becomes busy
  - Transmit when backoff interval reaches 0

- Contention resolution: contention window CW is adapted dynamically depending on collision occurrence
  - binary exponential backoff: double CW upon every collision
  - Set to base value (CW=32) after a successful transmission
  - Packet collision is the feedback signal

- Slotted system: Inter Frame Spacing
  - SIFS (Short Inter Frame Spacing)
    - highest priority, for ACK, CTS
  - DIFS (Distributed Coordination Function IFS)
    - lowest priority, for asynchronous data service



DCF basic access method



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Contention control

- A distributed strategy to access/share wireless channel
- Control theoretic point of view
  - A contention resolution algorithm: dynamically adjusts persistence probability or contention window in response to the contention
  - A feedback mechanism: updates a contention measure and sends it back to wireless nodes

- Two contention resolution mechanisms
  - Persistence: access the channel with some persistence probability
  - Backoff: wait for a random amount of time bounded by the contention window before a transmission
- Different MAC methods differ in terms of
  - how they adjust persistence probability or contention window
  - What contention measure they use

IEEE 802.11 DCF (revisited)

- Uses a binary contention signal: packet collision or successful transmission
- Uses a backoff mechanism
  - Doubles contention window upon a collision (binary exponential backoff)
  - Sets it to the base value upon a successful transmission

Performance problems/limitations of 802.11 DCF

- Throughput degradation in high-load scenarios because of excessive collisions
  - Set to the base contention window is too drastic
- Short-term unfairness due to the oscillation in contention window
  - Directly caused by binary exponential backoff
  - Unavoidable because of binary contention signal
- Performance deterioration in adverse channel conditions
  - Cannot distinguish collisions from corrupted frames
- Not easy to adapt to channel variations

Observations

- For high efficiency and better fairness, need to stabilize the network into a steady state which sustains appropriate window sizes
  - Require continuous feedback signal
- Need to use a contention measure whose estimation is not based on packet collisions, and decouple contention control from handling failed transmissions

Objective

- To provide an analytical framework to study contention/interaction among wireless nodes
- To design medium access methods
  - Stabilize the network around a steady state with a target fairness (or service differentiation) and high efficiency (high throughput, low collision)
  - Decouple contention control from handling failed transmissions

Methodology

- Study the contention/interaction among wireless nodes in game theory framework
- Design MAC according to distributed strategy update algorithm achieving Nash equilibrium
  - Not intended to model selfish behaviors of wireless nodes
  - But to capture information and implementation constraints encountered in real networks
  - Design game to guide individual nodes to seek an equilibrium that achieves system-wide performance objectives

Random access game

- Consider a set N of greedy wireless nodes in a single-cell wireless LAN
- Each node i attains a utility $U_i(p_i)$ when it accesses the channel with probability p_i
  - $U_i(\cdot)$ is assumed to be a continuously differentiable, increasing, concave function with the curvatures bounded away from zero, i.e., $-1/U_i^{''}(p_i) \geq 1/\lambda > 0$
  - If persistence mechanism is used, p_i is just persistence probability.
  - If backoff mechanism is used, p_i is related to a constant contention window cw_i according to $p_i = 2/(cw_i + 1)$

- **Definition**: A random access game G is defined as a triple $G := \{N, (s_i)_{i \in N}, (u_i)_{i \in N}\}$
  - N is a set of players (wireless nodes)
  - Strategy $s_i := \{p_i \mid p_i \in [v_i, w_i]\}$ with $0 \le v_i \le w_i \le 1$
  - Payoff function $u_i(p) := U_i(p_i) - p_i q_i(p)$ with $q_i(p) := 1 - \Pi_{j \in N/\{i\}}(1 - p_j)$
- Wireless nodes interact through collisions
- **Homogeneous** users and **heterogeneous** users

Nash equilibria

- Denote the strategies of all nodes other than i by p_{-i}. A vector of access probability p is a Nash equilibrium if, for all nodes i,

$$u_i(p_i, p_{-i}) \geq u_i(\bar{p}_i, p_{-i}) \text{ for all } \bar{p}_i \in s_i$$

- **Theorem**: There exists a Nash equilibrium for random access game G.
- Proof: strategy spaces s_i are compact convex sets, and the payoff functions u_i are continuous and concave in p_i.

- At Nash equilibrium, p_i either takes value at boundaries of the strategy space or satisfies

$$U_i^{'}(p_i) = q_i(p)$$

  - **Nontrivial** Nash equilibria: for all nodes i, p_i satisfies the above equality.
  - **Trivial** Nash equilibria, otherwise.

Nontrivial Nash equilibria

- **Theorem**: Random access game G has nontrivial Nash equilibrium if, for each node i, inverse function $(U_i^{'})^{-1}(q_i)$ maps any $q_i \in [0,1]$ into a point $p_i \in s_i$.
- Proof: define $p_i = B_i(p) := (U_i^{'})^{-1}(q_i(p))$, then $B(p) := (B_1(p), B_2(p), \cdots, B_{|N|}(p))$ maps the strategy space into itself. The theorem follows from the Brouwer's fixed point theorem.

- **Theorem**: if additionally $\Gamma_i(p_i)$ is a monotone function in s_i for all i, then random access game has a unique nontrivial Nash equilibrium.
  - Define idle probability $\gamma(p) = \Pi_{i \in N}(1 - p_i)$, and $\Gamma_i(p_i) := (1 - p_i)(1 - U_i'(p_i))$. At nontrivial Nash equilibrium, $\Gamma_i(p_i) = \gamma(p)$.
  - $\Gamma_i(p_i) = \Gamma_j(p_j)$ for any $i, j \in N$.
  - Proof by contradiction.

- **Definition**: A Nash equilibrium p is said to be a symmetric equilibrium if $p_i = p_j$ for all $i, j \in N$, and an asymmetric equilibrium otherwise.
  - If a system of homogeneous users has an asymmetric Nash equilibrium, all its permutations are Nash equilibria.
  - The symmetric equilibrium must be unique.

- **Corollary**: Random access game G has a unique nontrivial Nash equilibrium which is symmetric among each class of users.
  - Guarantees the uniqueness of nontrivial Nash equilibrium.
  - Guarantees fair sharing of wireless channel among the same class of wireless nodes.
  - Provides service differentiation among different classes of wireless nodes.

Dynamics

- Studies how interacting players (wireless node) could converge to a Nash equilibrium
- Difficult problem: "game theory lacks a general and convincing argument that a Nash outcome will occur"
- In the setting of random access
  - Players can observe the outcome of the action of others
  - Players do not have direct knowledge of other player actions or payoffs
- Consider repeated play of the random access game, and look for strategy update mechanism that achieves Nash equilibrium.

- Best response strategy

$$p_i(t+1) = B_i(p(t)) := \arg\max_{p \in s_i} (U_i(p) - pq_i(p(t)))$$

- **Theorem**: If function $B^{(2)}(p)$ has a unique fixed point in the strategy space, then best response strategy converges to unique nontrivial Nash equilibrium of random access game G.

- Gradient play

$$p_i(t+1) = [p_i(t) + f_i(p_i(t))(U_i^{'}(p_i(t)) - q_i(p(t)))]^{s_i}$$

- **Theorem**: Gradient play converges to the unique nontrivial Nash equilibrium of random access game G if stepsize $f_i(p_i) < 1/(\lambda + |N| - 1)$.
- Proof by Lyapunov method.

MAC design

- Random access games provide a general analytical framework to model a large class of system-wide quality-of-service models via the specification of per-node utility functions

- System-wide fairness or service differentiation can be achieved in a distributed manner as long as each node executes a contention resolution algorithm that is designed to achieve the Nash equilibrium.

Medium access method via gradient play

```
After each transmission
{
 /* Wireless node observes n idle slots before a transmission*/
 isum ← isum + n
 ntrans ← ntrans + 1
 if ( ntrans ≥ maxtrans ){
     /*compute the estimator*/
     n̄ ← isum / ntrans
     q_i ← (1 − (n̄ + 1) p_i ) /((n̄ + 1)(1 − p_i ))

     /*update access probability*/
     p_i ← p_i + f_i ( p_i )(U'_i ( p_i ) − q_i )
     /*update contention window*/
     cw_i ← (2 − p_i ) / p_i
     /*reset variables*/
     isum ← 0
     ntrans ← 0
     }
}
```

$$\bar{n} \leftarrow isum / ntrans$$

$$q_i \leftarrow (1 - (\bar{n} + 1) p_i) / ((\bar{n} + 1)(1 - p_i))$$

$$p_i \leftarrow p_i + f_i(p_i)(U_i'(p_i) - q_i)$$

$$cw_i \leftarrow (2 - p_i) / p_i$$

- Adapt to continuous feedback signal, and stabilize the network around a steady state specified by Nash equilibrium
  - controllable performance objective and better short-term fairness
- Equation-based control, adjust contention window according to how far the current state to the equilibrium
  - Result in simpler dynamics, achieve better contention control and higher throughput
- Can decouple contention control from handling failed transmissions

A case study

- Define random access game G_1 with the following utility

$$U_i(p_i) = \frac{1}{a_i}\left(\frac{(a_i - 1)w_i}{a_i}\ln(a_i p_i - w_i) - p_i\right),$$

where $0 < w_i < 1$ and $p_i \in [2w_i/(1+a_i), w_i]$.

Nash equilibrium and dynamics

- **Theorem**: if $a_i w_i < 1$, random access game G_1 has unique nontrivial Nash equilibrium. Moreover, the unique nontrivial Nash equilibrium of G_1 is symmetric among each class of users.
- Gradient play

$$p_i(t+1) = [p_i(t) + f_i(p_i(t))(\frac{w_i - p_i(t)}{a_i p_i(t) - w_i} - q_i(p(t)))]^{s_i}$$

$$cw_i(t) = \frac{2 - p_i(t)}{p_i(t)}$$

- **Theorem**: Suppose $a_i w_i < 1$, the system described by the above equations converges to the unique nontrivial Nash equilibrium of random access game G if $f_i(p_i) < 1/(\lambda + |N| - 1)$.

MAC design

- Make two key modifications to 802.11 DCF
  - Each node i estimates its conditional collision probability q_i

$$\bar{n} \leftarrow \beta\bar{n} + (1-\beta)\frac{isum}{ntrans}$$

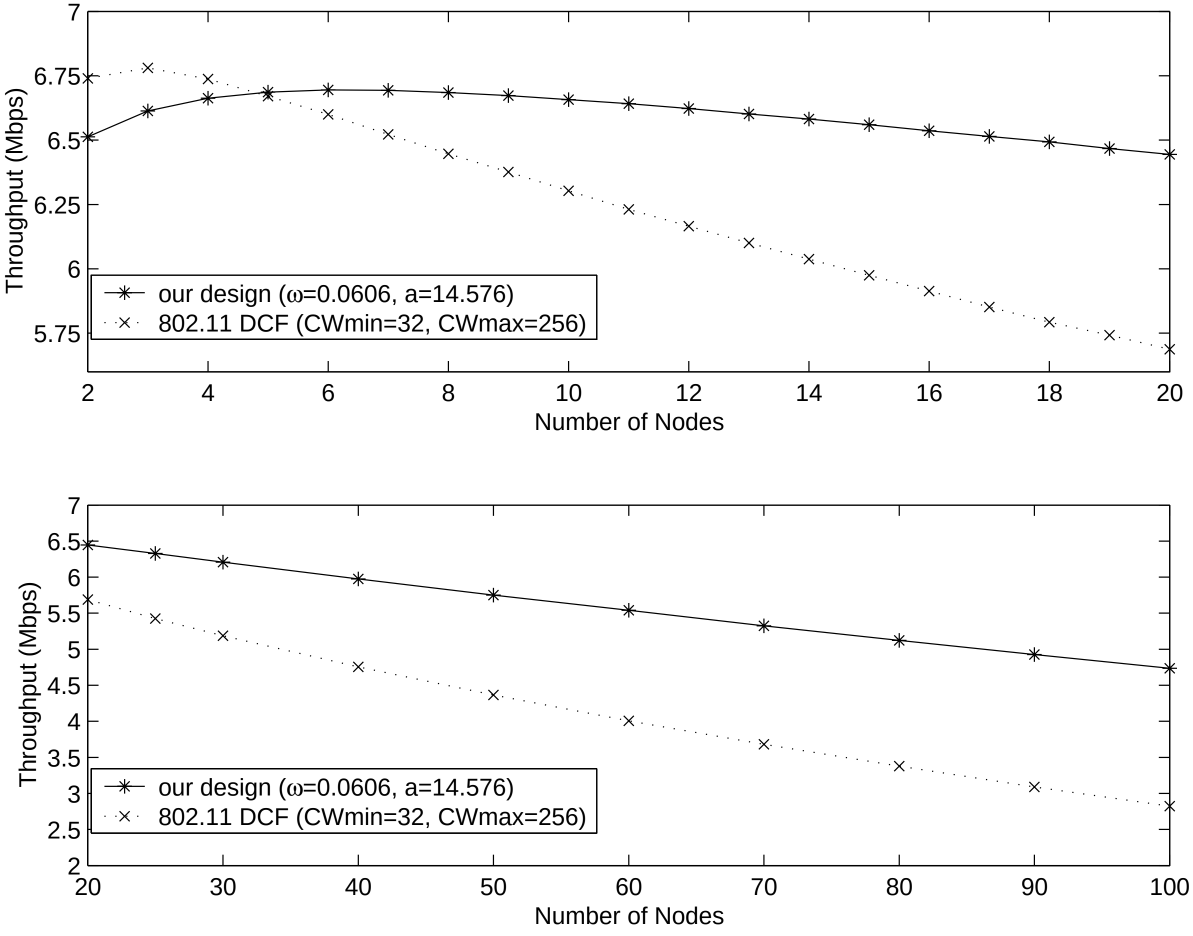
$$q_i \leftarrow \frac{1-(\bar{n}+1)p_i}{(\bar{n}+1)(1-p_i)}$$

  - Adjusts its contention window cw_i according to gradient play

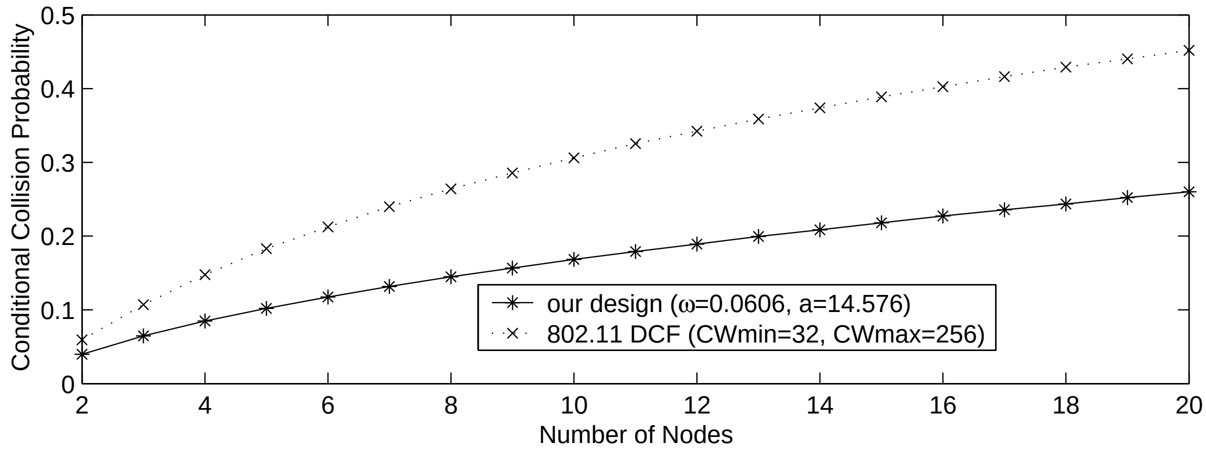
$$p_i \leftarrow p_i + f_i(p_i)(U_i^{'}(p_i) - q_i)$$

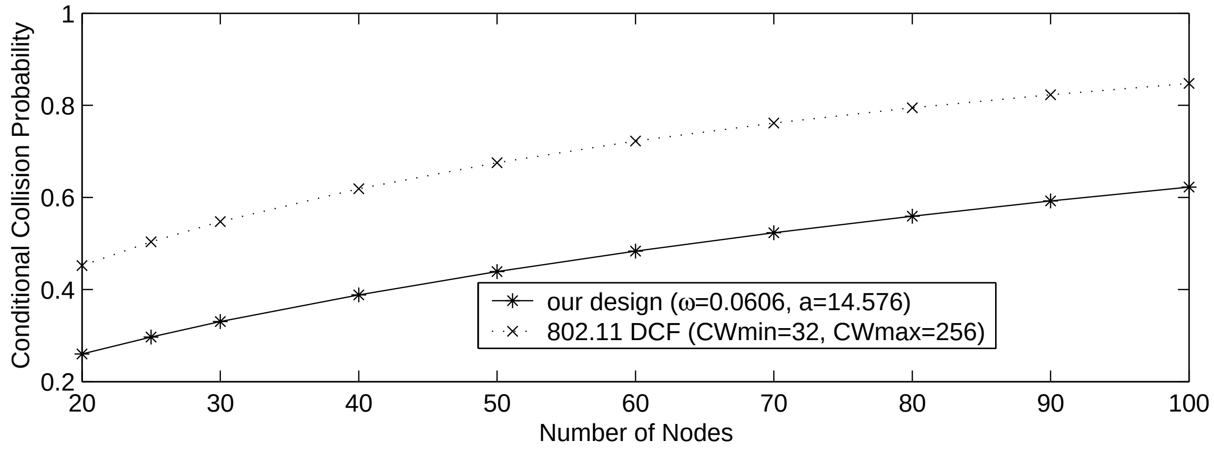
$$cw_i \leftarrow \frac{2-p_i}{p_i}$$

Throughput comparison

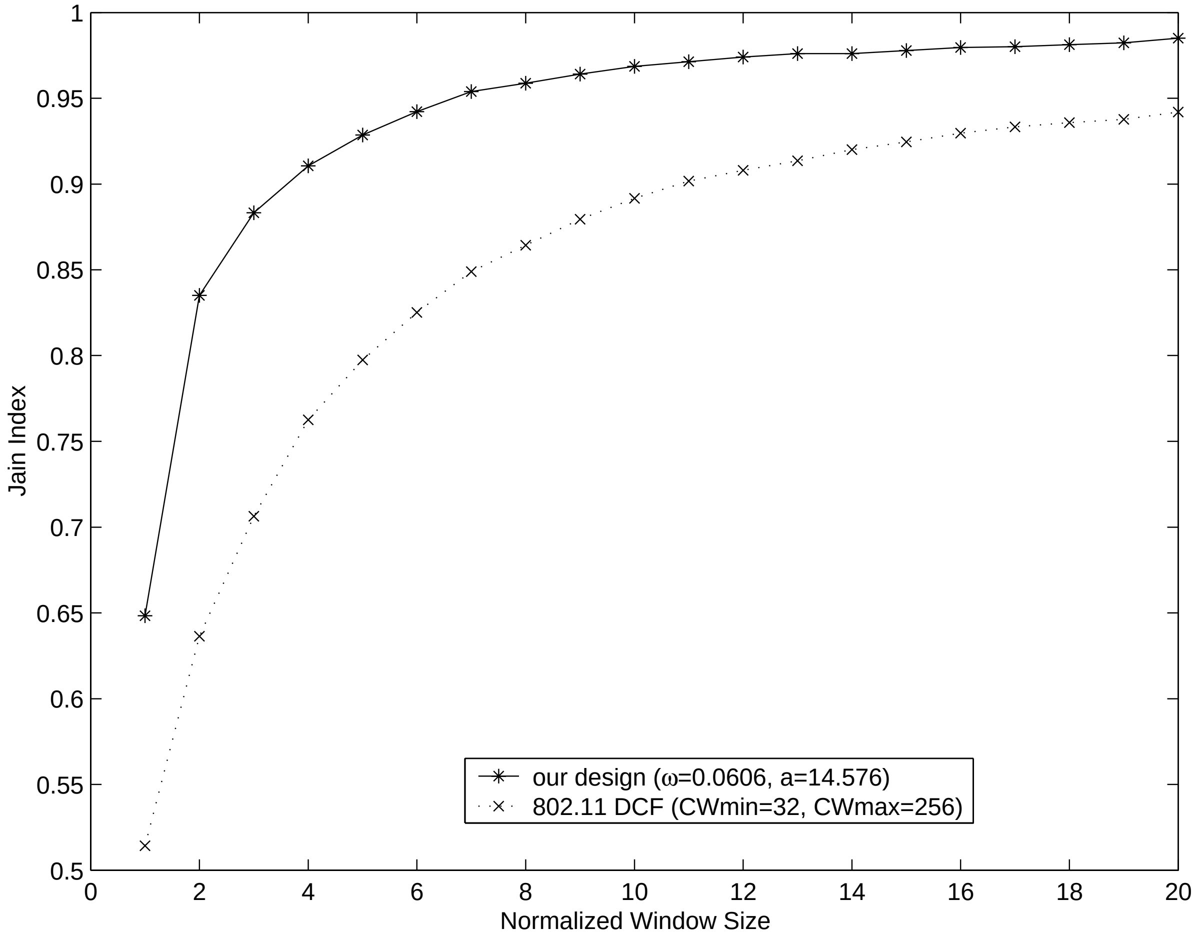


Collision overhead comparison

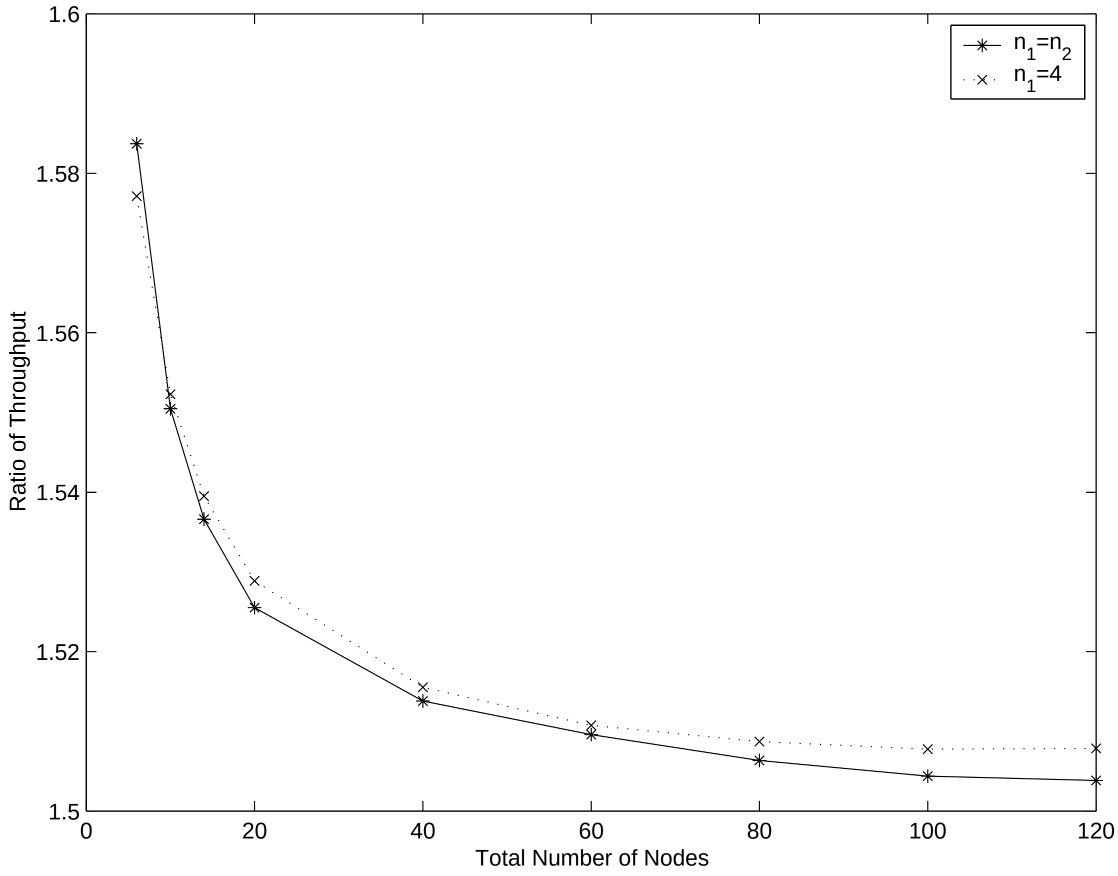




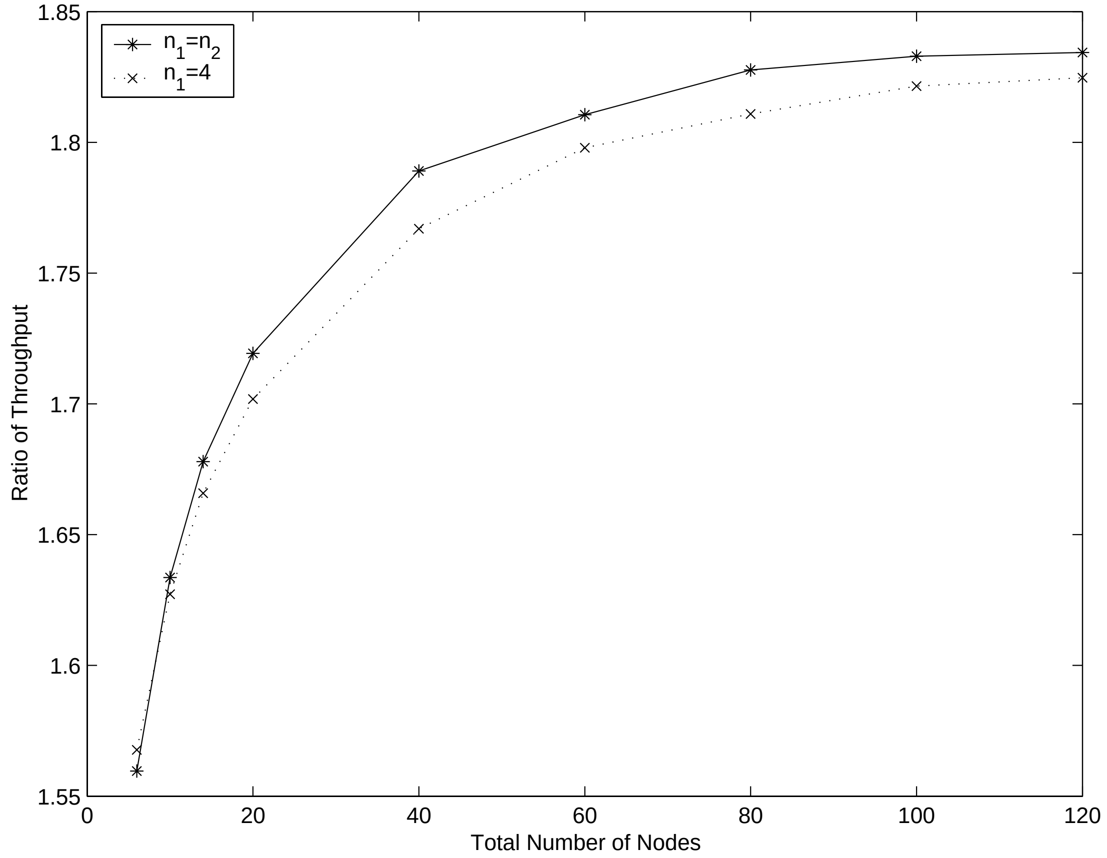
Fairness comparison



Service differentiations



n_1: number of class 1 nodes (w_1 = 0.06 and a_1 = 15)
n_2: number of class 2 nodes (w_2 = 0.04 and a_2 = 15)



n_1: number of class 1 nodes (w_1 = 0.04 and a_1 = 10)
n_2: number of class 2 nodes (w_2 = 0.04 and a_2 = 20)

Utility and reverse-engineering

- Utility functions $\Leftrightarrow$ Equilibria of random access games and the stable operating points of MAC protocols
- Reverse-engineering
  - The stable operating point defines an implicit relation $p_i = \mathcal{F}_i(p_i, q_i)$
  - Exists a unique continuously differentiable function F_i such that $q_i = F_i(p_i)$
  - Define the utility functions as $U_i(p_i) = \int F_i(p_i)dp_i$, with which we can define a random access game. MAC can be interpreted as a distributed strategy update algorithm to achieve Nash equilibrium of the random access game.

Conclusions

- Presented game theoretic framework for contention control
  - Define a general game theoretic model to capture interaction/contention among wireless nodes
  - Capable of modeling a large class of system-wide QoS models via the specification of per-node utility functions.
  - Design MAC according to distributed strategy update algorithm achieving Nash equilibrium.
  - Study a concrete random access game and medium access control design and show it achieves superior performance than the standard protocol
  - Provides an analytical framework to understand the equilibrium and dynamics properties of different MAC protocols and their interactions