TLEN7000/ECEN7002: Analytical Foundations of Networks

Random Access Games and Medium Access Control Design

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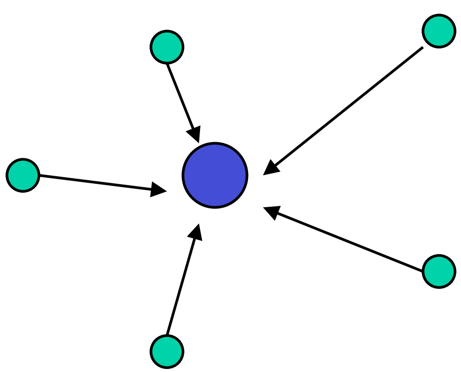
Agenda

- Contention-based medium access control (contention control)

- A game theoretic approach to contention control

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



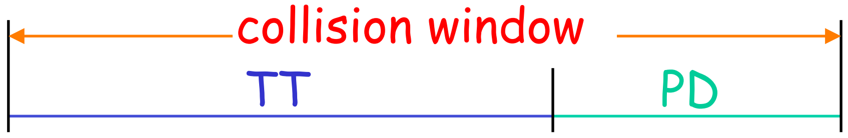
a multiple access network

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

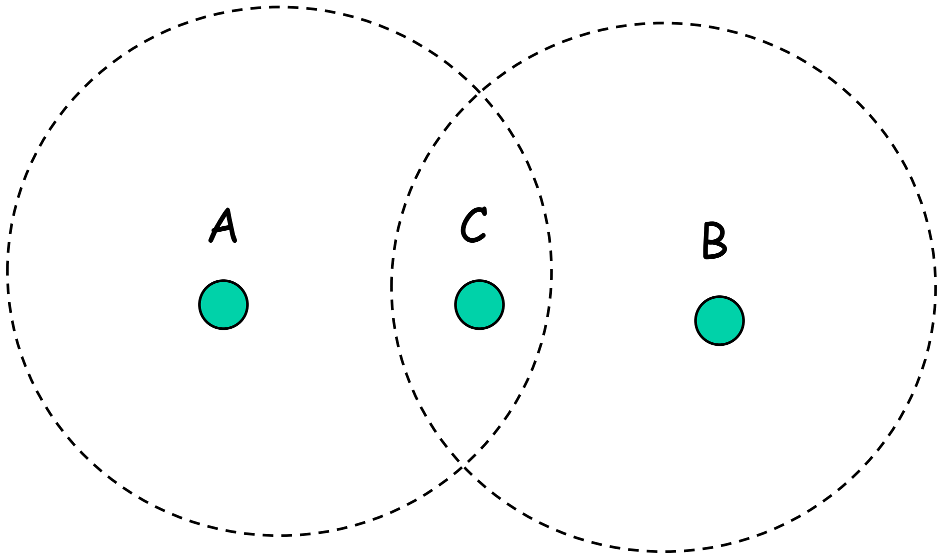
- What to do upon a collision
  - If the colliding nodes transmit immediately when the channel is idle after a collision, another collision is guaranteed
- Two collision resolution mechanisms
  - Persistence: transmit with a probability p
  - Backoff: wait for a random amount of time bounded by CW before 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

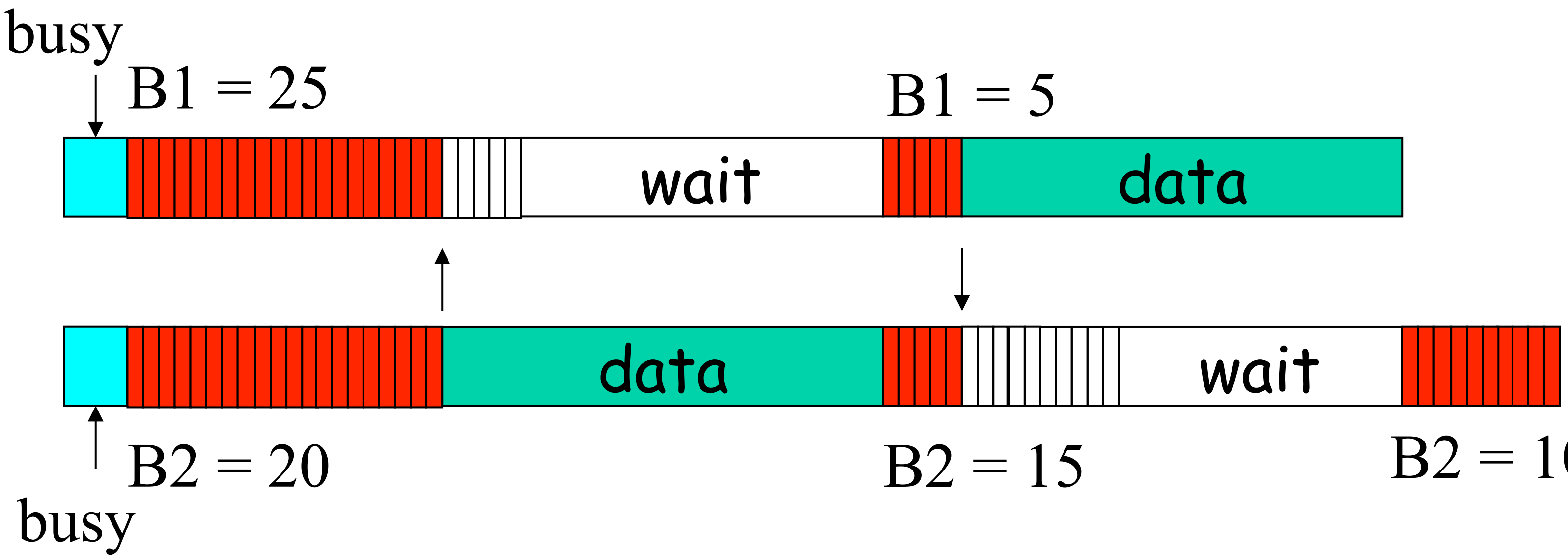
CSMA/CA

- 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



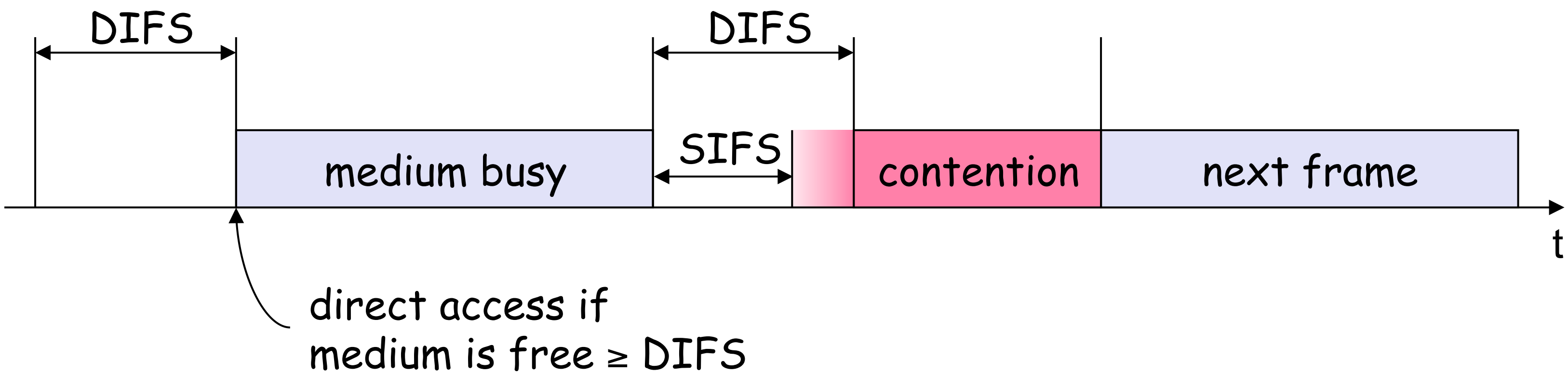
CW=32

Wireless 802.11 DCF (basic)

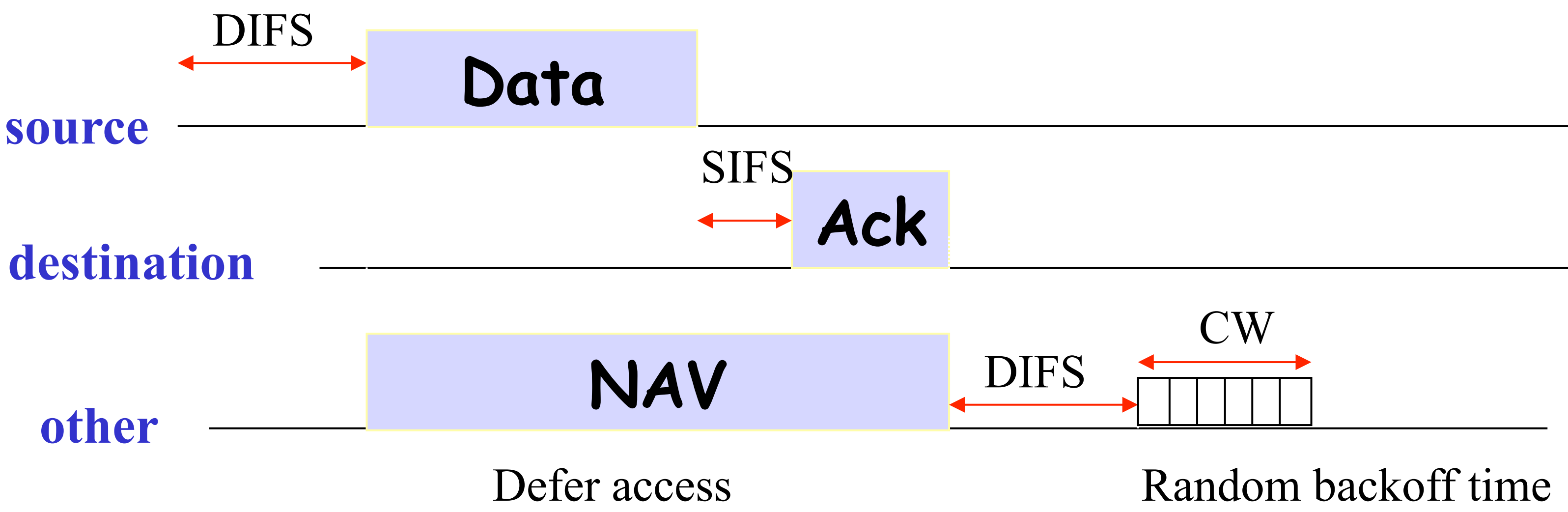
- DCF stands for distributed coordination function
- A CSMA/CA medium access protocol
  - CSMA: sense before transmission
  - CA: random backoff to reduce collision probability
    - when transmitting a packet, choose a backoff interval in the range [0, CW-1]
  - Count down the backoff interval when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



Agenda

- Contention-based medium access control (contention control)

- A game theoretic approach to contention control

Contention-based MAC (contention control)

- Medium access control (MAC): coordinate channel access
  - avoid collision
  - efficient utilization of wireless spectrum
  - Quality of Service control
- Contention resolution mechanisms
  - persistence: transmit with a probability p
  - backoff: wait a random amount of time bounded by contention window CW before transmission
- Contention resolution algorithm is the key
  - i.e., decide p or CW value in response to network contention

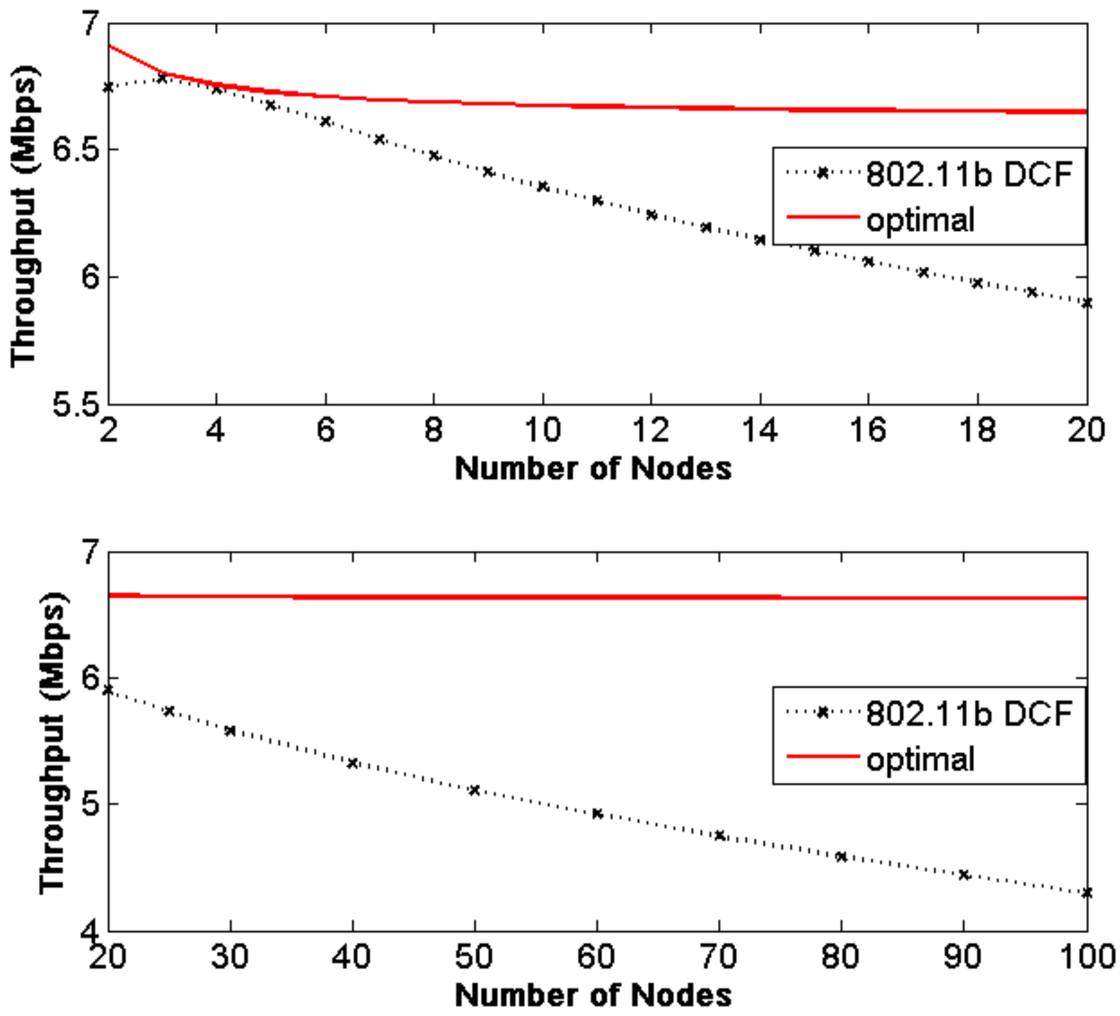
Wireless 802.11 distributed coordination function (DCF)

- Contention resolution algorithm: Binary exponential backoff

$$CW \leftarrow 2CW, \qquad\qquad if\,(\text{collision})$$
$$CW \leftarrow CW_0, \quad if\,(\text{successful transmission})$$

  - respond to a binary feedback signal - packet collision
- Performance problems
  - excessive collision and low throughput
  - poor short-term fairness
  - cannot distinguish packet collision from corrupted frame

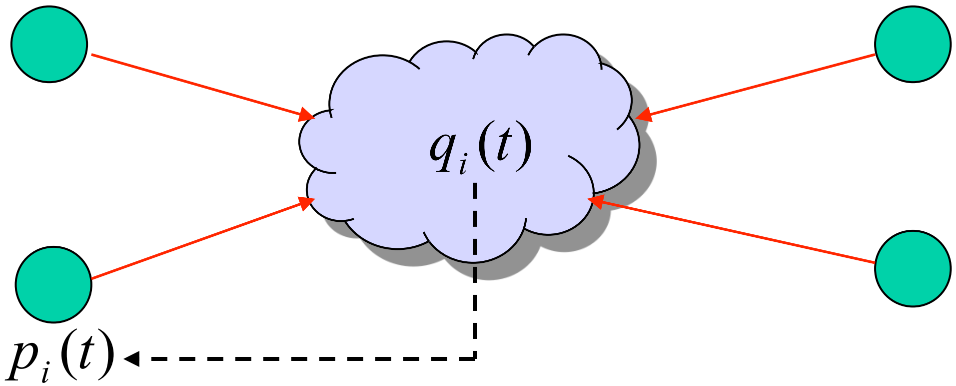
DCF throughput



Better design

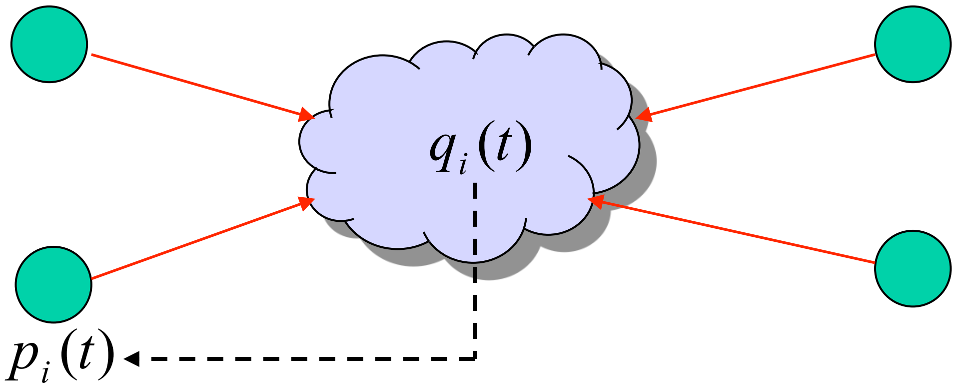
- Many works exist
  - mostly based on intuition and heuristics and evaluated by simulation
  - optimal design, but with sophisticated methods to estimate the number of contending nodes
- Our "theory-based" approach
  - reverse engineering: see what mathematical problem contention control implicitly solves
  - forward engineering: understand and engineer the underlying problem to derive the design in a formal and structured way

Contention control: dynamical model



- Two components
  - contention resolution algorithm: adjusts channel access probability in response to contention
    - e.g., DCF uses binary exponential backoff
  - feedback mechanism: updates a contention measure and sends it back to wireless nodes
    - e.g., DCF uses a binary contention measure - packet collision

Contention control: dynamical model



- Dynamical model

$$p_i(t+1) = \mathcal{F}_i(p_i(t), q_i(t))$$

$$q_i(t+1) = \mathcal{G}_i(p(t))$$

  - the exact form of $\mathcal{F}_i$ and $\mathcal{G}_i$ are determined by or can be designed for the specific MAC protocol
- Present a game-theoretic model to understand the above dynamical system and use it to design new protocols

Random access game

$$p_i(t+1) = \mathcal{F}_i(p_i(t), q_i(t))$$

$$q_i(t+1) = \mathcal{G}_i(p(t))$$

$\downarrow$ fixed point

$$\boxed{p_i = \mathcal{F}_i(p_i, q_i)}$$

$$\Downarrow$$

$$\boxed{q_i = F_i(p_i)}$$

$$\Downarrow$$

$$\boxed{U_i(p_i) = \int F_i(p_i)dp_i}$$

- determined by the contention resolution algorithm
- usually continuous, increasing, and concave

Random access game

Definition (Chen el al '06; '10): A random access game is defined as a quadruple

$$\mathbf{G} := \{N, (S_i)_{i\in N}, (u_i)_{i\in N}, (q_i)_{i\in N}\}$$

- N is a set of players (wireless nodes)
- strategy $S_i := \{p_i \mid p_i \in [v_i, w_i]\}$ with $0 \le v_i \le w_i < 1$
- payoff function $u_i(p) := U_i(p_i) - p_i q_i(p)$ with certain contention measure $q_i = \mathcal{G}_i(p)$

Random access game

Contention control can be seen as a distributed strategy update algorithm solving the random access game

- the steady state properties can be understood and designed through the specification of U_i and q_i
  - conditional collision probability $q_i(p) = 1 - \prod_{j \neq I_i} (1 - p_j)$ as contention measure
- the adaptation of channel access probability can be specified through $(\mathcal{F}_i, \mathcal{G}_j)$, corresponding to different strategies to approach the equilibrium

- Conditional collision probability as contention measure

$$q_i(p) = 1 - \prod_{j \neq I_i} (1 - p_j)$$

- Assumptions (single cell wireless LANs):
  - A0: $U_i(\cdot)$ is continuously differentiable, strictly concave, and with bounded curvature away from zero, i.e.,

$$1/\mu \geq -1/U_i''(p_i) \geq 1/\lambda > 0$$

  - A1: let $\gamma(p) = \prod_i (1 - p_i)$ and denote the smallest eigenvalue of $\nabla^2 \gamma(p)$ by $\nu_{\min}$. Then, $\mu + \nu_{\min} > 0$.
  - A2: functions $\Gamma_i(p_i) = (1 - p_i)(1 - U_i'(p_i))$ are all strictly increasing or all strictly decreasing

Equilibrium

Theorem: The random access game has a unique Nash equilibrium (NE).

- a channel access probability p^* is a Nash equilibrium of random access game, if

$$u_i(p_i^*, p_{-i}^*) \geq u_i(p_i, p_{-1}^*),\ \forall p_i \in S_i,\ \forall i \in N.$$

- Proof: Equilibrium condition

$$(U_i'(p_i^*) - q_i(p^*))(p_i - p_i^*) \leq 0, \forall p_i \in S_i$$

is optimality condition for a strictly convex optimization

Symmetric equilibrium

Definition: A NE p^* is said to be symmetric if $p_i^* = p_j^*$ for wireless nodes i, j in the same class, and an asymmetric equilibrium otherwise.

Theorem (CLD ’06; CLD ’10): The random access game has a unique and symmetric NE.

Implications:

- guarantees fair sharing of wireless channel among the same class of wireless nodes
- provides service differentiation among different classes of wireless nodes

Dynamics (learning algorithms)

- Studies how interacting players (wireless node) could converge to a NE
- In setting of random access
  - players (wireless nodes) can observe outcome of others' actions (i.e., to sense the carrier)
  - players do not have direct knowledge of other players' actions or payoffs
- Consider repeated play of the random access game, and look for distributed strategy update mechanism to achieve NE

Gradient play

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

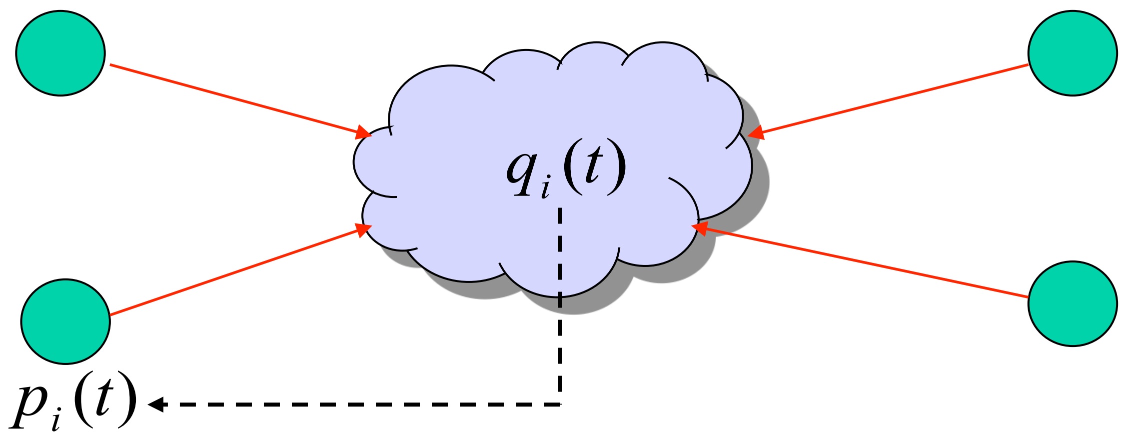
<u>Theorem</u> (CLD ’06; CLD ’10): The gradient play converges to the unique NE if stepsize $\varepsilon_i < \frac{2}{\lambda + |N| - 1}$. for any $i \in N$.

- proof by Lyapunov method.
- also studied its robust verification to estimation error (CLD ’10)
- extensions to multi-cell networks (CLD ’10)

MAC design

- Design MAC according to distributed strategy update algorithm to achieve the equilibrium of random access game
  - by appropriately choosing utility function and contention measure, we can achieve different performance objectives
  - can choose to implement different converging algorithms to the same equilibrium
    - same equilibrium property but different dynamical properties

Medium access method via gradient play



each wireless node estimates its conditional collision probability and updates its channel access probability according to the gradient play

- by appropriately choosing utility functions, we can achieve different performance objectives
- conditional collision probability can be estimated by sensing idle periods

Medium access method via gradient play

After each transmission

{

/* Wireless node observes n idle slots before a transmission*/

$isum \leftarrow isum + n$

$ntrans \leftarrow ntrans + 1$

if ($ntrans \geq maxtrans$){

/*compute the estimator*/

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

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

/*update access probability*/

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

/*update contention window*/

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

/*reset variables*/

$isum \leftarrow 0$

$ntrans \leftarrow 0$

}

}

- Adapt to continuous feedback signal
- Equation-based control

A concrete MAC design

- Consider a single-cell network with L classes of users
- Each class l associated with a weight ϕ_l
- Want to achieve maximal throughput under the weighted fairness constraint

$$\frac{T_l}{T_m} = \frac{\phi_l}{\phi_m}, 1 \le l, m \le L.$$

Utility design

- Let $\xi = \sum_i p_i$, under the assumption of Poisson arrival, the throughput achieves maximum at ξ^* that satisfies

$$(1-\xi^*)e^{\xi^*} = 1 - \sigma / \mathrm{T}_c$$

  - σ the duration of idle slot, T_c the duration of a collision
- Under the decoupling approximation, to achieve weighted fairness requires

$$\frac{p_l}{p_m} = \frac{\phi_l}{\phi_m}, 1 \le l, m \le L.$$

- Utility function

$$U_l(p_l) = (1 + \frac{e^{-\xi^*}}{\phi_l}) p_l + e^{-\xi^*}(1 + \frac{1}{\phi_l}) \ln(1 - p_l)$$

$$p_l \in [0, w]$$

Equilibrium and dynamics

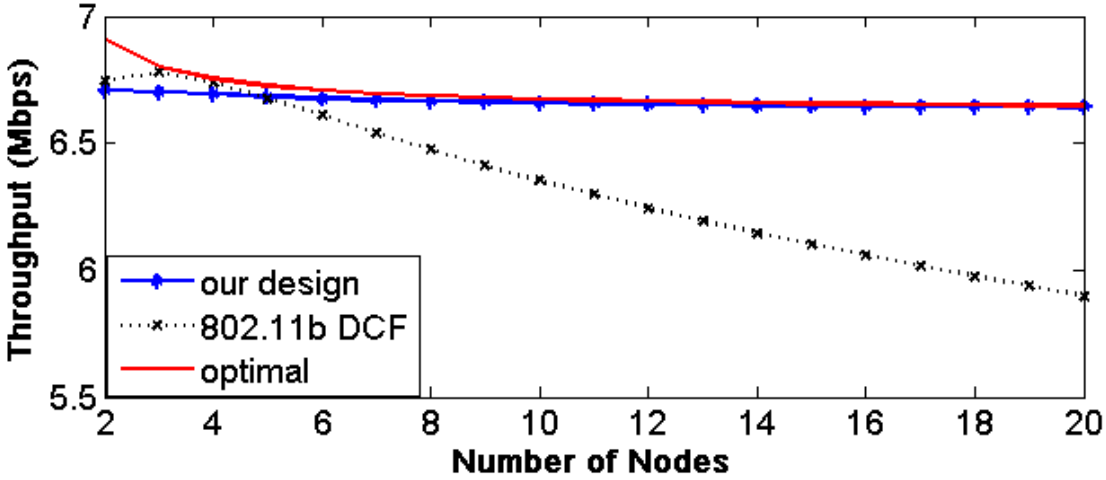
Theorem (Chen el al ’10): Suppose

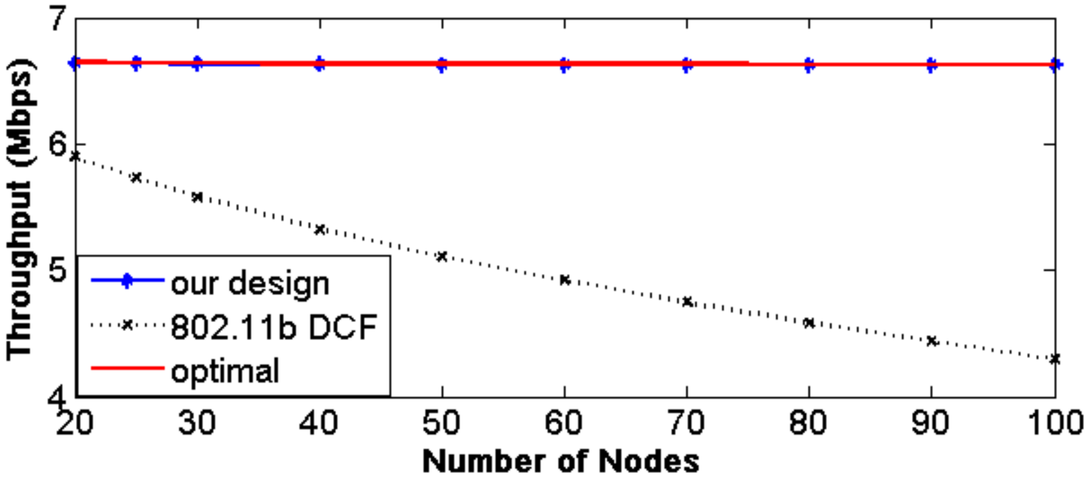
$$\frac{1-e^{-\xi}}{1+e^{-\xi}/\phi_{\max}} \le w < 1-\frac{e^{\xi}}{1+1/\phi_{\max}}.$$

The random access game has a unique and symmetric NE, and the gradient play converges.

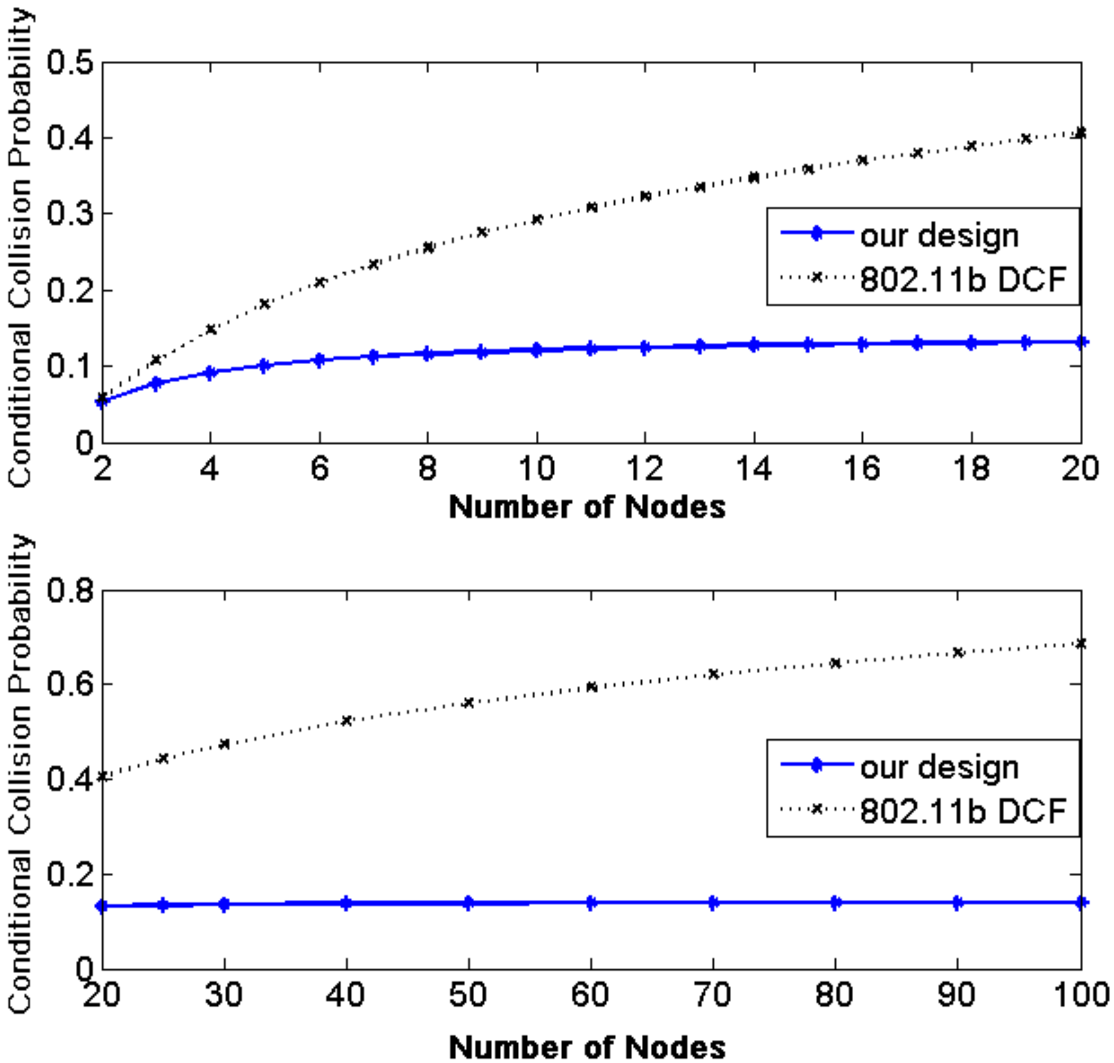
- allows a very large design space

Performance: throughput

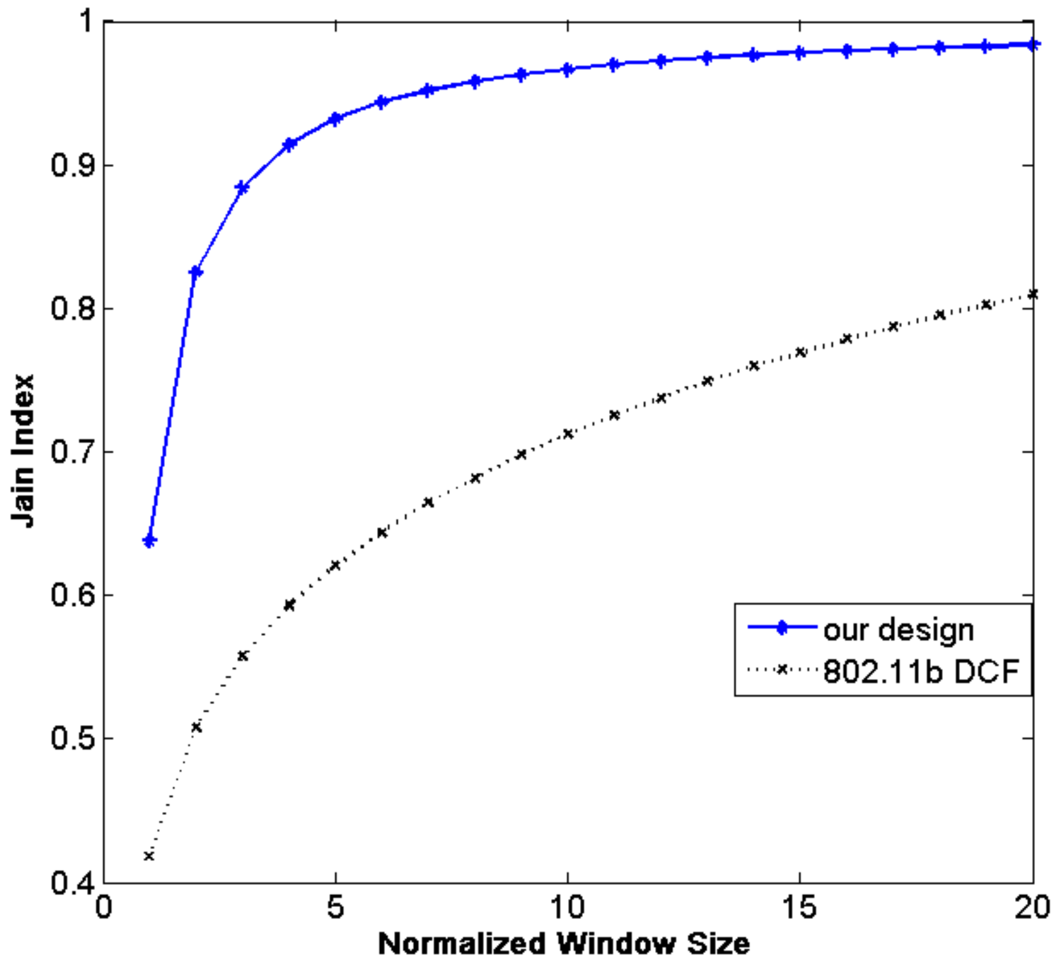




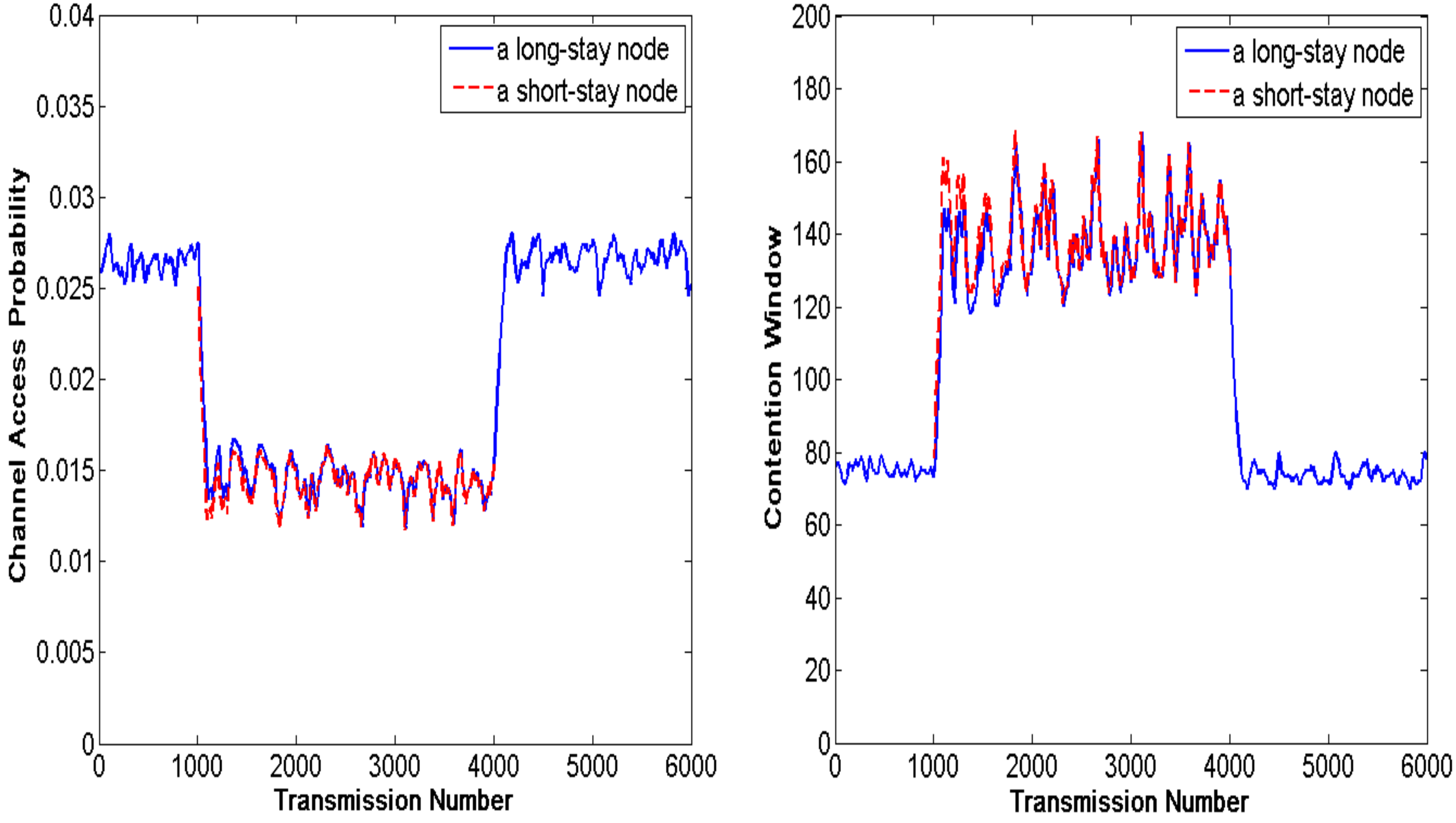
Performance: collision



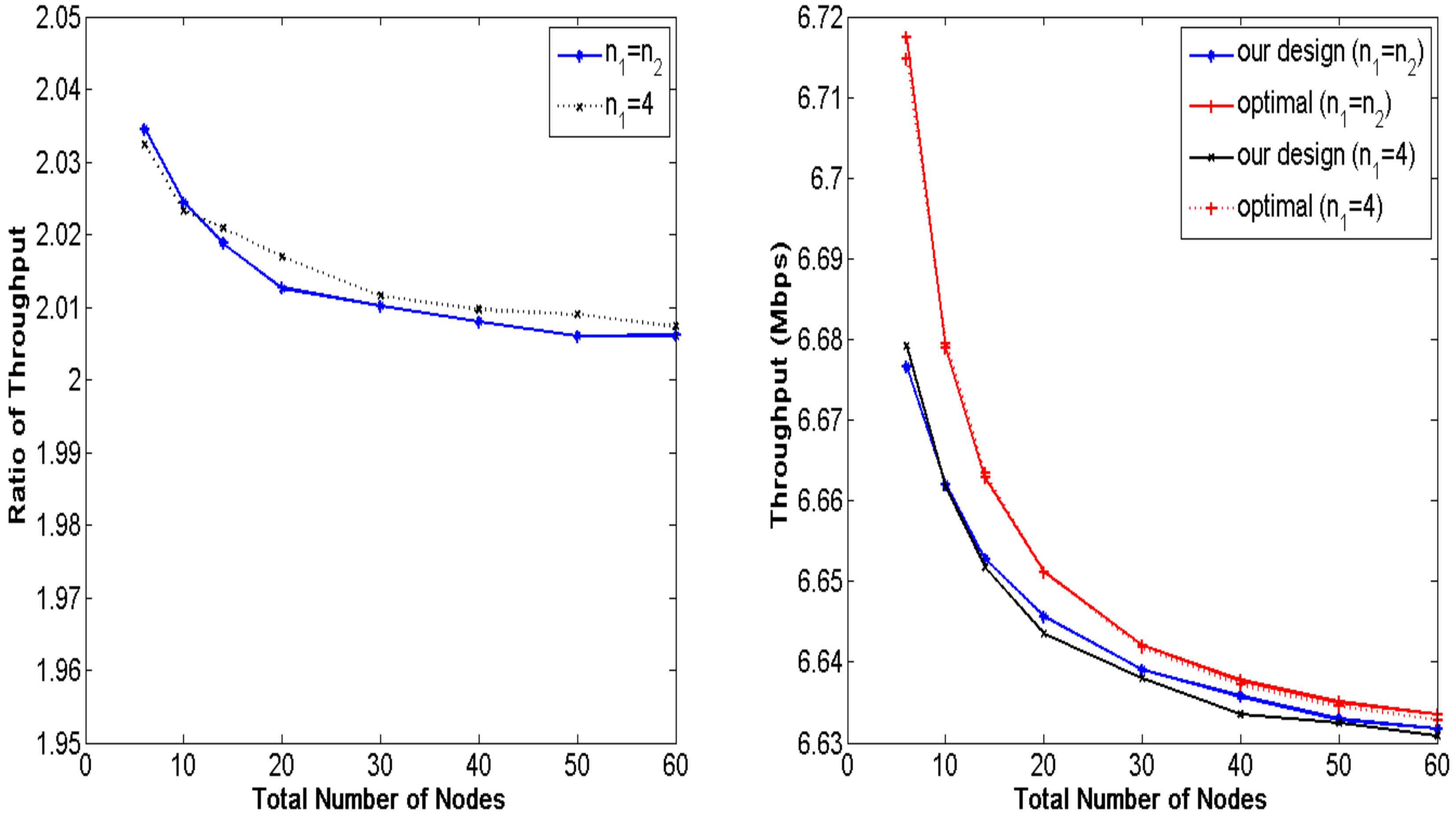
Performance: short-term fairness



Performance: dynamic scenario



Performance: service differentiation



Game theory based decomposition