(J.Q. Bao, L. Tong)

A Performance Comparison between Ad Hoc and Centrally Controlled CDMA Wireless LANs

Ad Hoc Networking
- Prof. Hermanns -
SS 2004

Stephan Zimmer

Outline

Introduction

Goal:

Performance comparison between two types of code division multiple-access wireless LANs:

Centrally Controlled and **Ad Hoc**

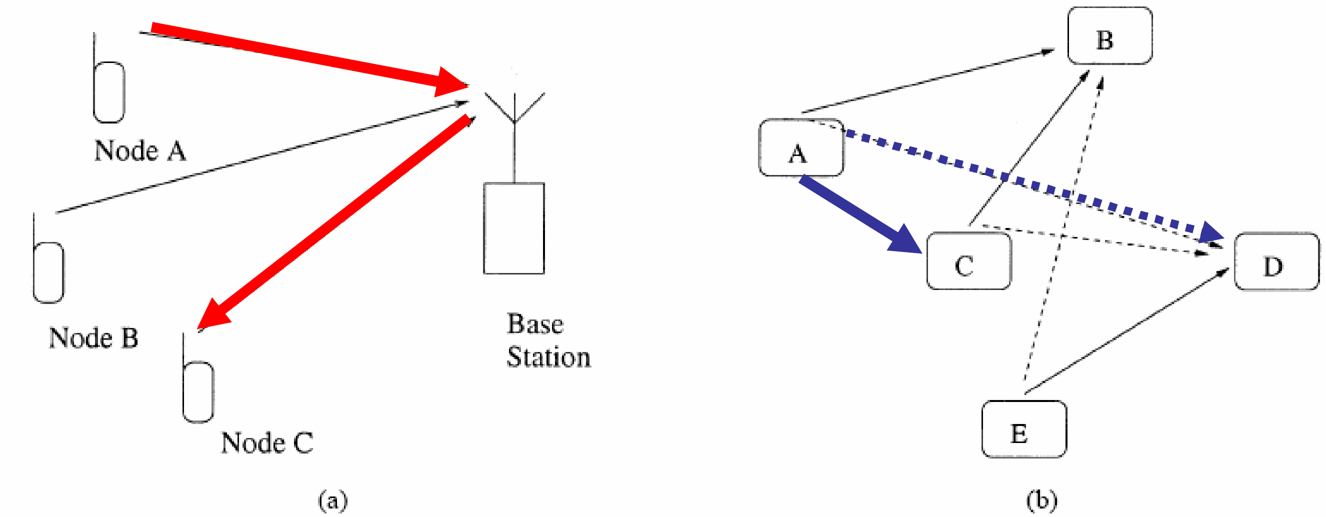


Fig. 1. (a) Centrally controlled system. (b) Ad hoc system.

Introduction

General restrictions:

- packet-switched code division multiple-access (CDMA) system
- employing *slotted ALOHA* random access protocols
- restriction to small coverage area allows to ignore near-far effect

System Models

Description Centrally Controlled Network:

Multiple nodes transmit packets to each other through the *Base Station (BS)*.

Time division duplex system (TDD) with equal sized uplink and downlink packets, each occupies one **time slot**.

Nodes: half-duplex and always in receiving mode during downlink and in transmitting mode during uplink.

Slotted ALOHA random access protocol is used by all nodes in the uplink.

Each node uses a unique spreading code in the uplink.

Receiver at the Base Station is a bank of *matched filters.*

Base Station uses orthogonal codes (for packets intended for different receivers)
-> receiving node is always successful
-> transmission only depends on uplink reception

System Models

Description Ad Hoc System:

Nodes tansmit **directly** to each other (through a common channel).

Each node can be transmitter or receiver.

Also slotted ALOHA is employed by all nodes.

Every node uses a unique code to transmit packets.
(Assume each node has knowledge of all possible spreading codes)

Different *reception capability* of nodes compared to CC system:
i.e. a transmitting node in the ad hoc network cannot receive packets from other nodes
-> collision between transmitter and receiver

System Models

Assumptions and notations:

Backlogged node : a node which needs to retransmit a packet
(otherwise the node is the *unbacklogged* state)

Finite-population model is used
(Number of nodes in both systems finite.)

Ignore channel noise and assume that errors in a packet are caused by multiple access interference (MAI) alone.

Important used parameters:

M : total number of nodes
n : number of backlogged nodes

N : spreading gain
t : number of correctable errors

System Models

Assumption 1: Nodes generate packets according to independent Poisson processes with equal arrival rate λ

Assumption 2: Immediate feedback about the status of transmission

Assumption 3: No buffer at any node
(i.e. each node can at most hold one packet at a time)

Assumption 4: With probability s_{ki} the receiver (in both systems) sucessfully detects i out of k colliding packets in a time slot

Assumption 5: Each node has equal probability to transmit to every other node

Markovian Analysis

For performance evaluation we need to set up a mathematical model for these two systems

Markov chain approach for finite-population model
with n = number of backlogged nodes as network state

-> for M-node network:
(M+1) x (M+1) ***transition matrix*** $P = [p_{nk}]$

p_{nk} = probability that network state goes from n to k in one step

Markovian Analysis

- Centrally Controlled Network -

The goal:

transition matrix $P^c = [p^c_{nk}]$ for centrally controlled network

p^c_{nk} = probability that network state goes from n to k
in ***two*** *time slots*

To obtain P^c we need:

- *reception matrix* $S = [s_{jk}]$

$$S = \begin{pmatrix} s_{10} & s_{11} & 0 & \dots & 0 \\ s_{20} & s_{21} & s_{22} & \dots & 0 \\ \dots & & & & \dots \\ \dots & & & s_{(M-1)(M-1)} & 0 \\ s_{M1} & s_{M2} & s_{M3} & \dots & s_{MM} \end{pmatrix}$$

with s_{jk} : pr. that the BS demodulates k out of j packets

Markovian Analysis

- Centrally Controlled Network -

Elements of S are a function of the pr. of a node to *successfully detect a packet in a collision*

For CDMA packet systems it is *difficult* to determine the exact probability $p_c(k)$ of successfully detecting a packet by a receiver

Additional simplification:
Output of matched filter corresponding to multiple access interference (MAI) assumed to be a white Gaussian random process

Leads to packet success probability (see [6]):

$$p_c(k) = \sum_{i=0}^{t} \binom{L}{i} x^i (1-x)^{L_p - i}$$

With parameters:

t : number of bit errors that can be corrected by coding
L : length of packet (bits)
x : bit error rate (BER)

$$x = Q\left(\sqrt{\frac{3N}{k-1}}\right)$$

Markovian Analysis

- Centrally Controlled Network -

Each matched filter at BS´s receiver works independently:

Therefore s_{nk} = pr. that n out of k independent Bernoulli trials are successful with a single trial success probability $p_c(k)$

$$s_{nk} = \binom{k}{n} p_c(k)^n (1 - p_c(k))^{k-n}$$

-> elements of the reception matrix S

Remind: We (still) want the **transition matrix P^c**

What else is needed do determine P^c?

How is change of network state defined?

Markovian Analysis

- Centrally Controlled Network -

Change of network state is determined by
difference between *unsuccessful* transmissions from *unbacklogged nodes* and the *successful* transmission from *backlogged nodes*

In addition to the reception matrix S we need:

pr. that k *unbacklogged* nodes transmit

$$Q_a^c(k,n) = \binom{M-n}{k}(1-p_a^c)^{M-n-k}(p_a^c)^k$$

pr. that k *backlogged* nodes transmit

$$Q_r^c(k,n) = \binom{n}{k}(1-p_r)^{n-k}\,p_r^{\,k}$$

p_a^c : pr. at least one packet arrives at an unbacklogged node during two slots for Poisson arrival with rate λ

p_r : retransmission pr. for a backlogged node during uplink

Markovian Analysis

- Centrally Controlled Network -

(Finally) **transition probability p^c_{nk}** is given by:

$$p^c_{nk} = \begin{cases} \sum_{y=n-k}^{n} \sum_{x=0}^{M-n} s_{(x+y)[x+(n-k)]} Q_r^c(y,n) Q_a^c(x,n) & 0 \le k < n \\ \sum_{x=k-n}^{M-n} \sum_{y=0}^{n} s_{(x+y)[x-(k-n)]} Q_a^c(x,n) Q_r^c(y,n) & n \le k \le M \end{cases}$$

reception matrix S

probability that x unbacklogged nodes transmit

probability that y backlogged nodes transmit

Defined Markov chain is *irreducible* and *aperiodic*, so we can obtain the ***stationary distribution*** $\{q^c_n\}_{n=0}^{M}$ of the network state

by solving the balance equation: $\vec{q}^{\,c} = \vec{q}^{\,c} * P_c$

Markovian Analysis

- Ad Hoc Network -

Network state can change during **one** time slot because of direct transmission.

The reception matrix S for the Centrally Controlled system does not completely characterize the multiple packet reception capability for the Ad Hoc system:

For example:

Node B cannot receive node A‘s packet because of half-duplex operation of transceiver.

Furthermore if node C successfully detects one packet, there is only half chance that the packet from B is detected.

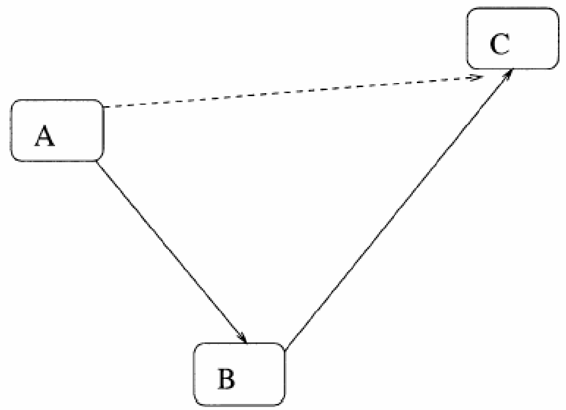


Fig. 2. Two issues in DS/SS slotted Aloha ad hoc networks.

Markovian Analysis

- Ad Hoc Network -

We define the ***reception matrix R*** for the Ad hoc network:

$$R = \begin{pmatrix} r_{10} & r_{11} & 0 & \dots & 0 \\ r_{20} & r_{21} & r_{22} & \dots & 0 \\ \dots & & & & \dots \\ \dots & & & r_{(M-1)(M-1)} & 0 \\ r_{M1} & r_{M2} & r_{M3} & \dots & r_{MM} \end{pmatrix}$$

In general, R is a function of S and the network traffic pattern.
The conversion of S to R is given by a Theorem (see Paper Appendix A)

Making use of the theorem we get the matrix R and can now just substitute s_{ij} by r_{ij} in the formula for the transition probability of CC system

Transmission pr. of unbacklogged and backlogged nodes in Ad hoc system:

$$Q_a^{\ a}(k,n) = \binom{M-n}{k}(1-p_a^{\ a})^{M-n-k}(p_a^{\ a})^k \qquad Q_r^{\ a}(k,n) = \binom{n}{k}(1-p_r)^{n-k}p_r^{\ k}$$

Markovian Analysis

- Ad Hoc Network -

So we retrieve **transition probability p^a_{nk}** for the Ad hoc system:

$$p^a_{nk} = \begin{cases} \sum_{y=n-k}^{n} \sum_{x=0}^{M-n} r_{(x+y)[x+(n-k)]} Q_r^{\ a}(y,n) Q_a^{\ a}(x,n) & 0 \le k < n \\ \sum_{x=k-n}^{M-n} \sum_{y=0}^{n} r_{(x+y)[x-(k-n)]} Q_a^{\ a}(x,n) Q_r^{\ a}(y,n) & n \le k \le M \end{cases}$$

reception matrix R
for Ad hoc

probability that x unbacklogged nodes transmit

probability that y backlogged nodes transmit

Markov chain is irreducible and aperiodic.

Similar to CC system we can obtain the stationary distribution by solving the Markov chain balance equation:

$$\vec{q}^{\,a} = \vec{q}^{\,a} * P_a$$

Performance Comparison

Investigated criteria:

- Network throughput
- Average packet delay

Comparisons of these criteria are evaluated to determine the *effect of the Ad Hoc architecture* on the network performance

also:

Effects of **spreading gain N** and **error control coding t**

which lead to the understanding of *efficiency of bandwidth utilization*

Throughput Comparison

Network throughput defined as the average number of successfully received packets by their intended receiver in a time slot.

Throughput of Centrally Controlled network:

Given network state n, number of packets successfully received by their intended receivers in *two time slots*

$$N = \sum_{k=1}^{M} p_k{}^c \sum_{l=0}^{k} l s_{kl}$$

where

$$p_k{}^c = \sum_{x=0}^{k} Q_a^c(x,n) Q_r^c(k-x,n)$$

is the pr. that total k packets are transmitted in the uplink time slot

Throughput Comparison

Because throughput $\beta_c(n)$ and average throughput $\beta_c(n)$ are defined **per time slot** we get for the *centrally controlled* network:

$$\beta_c(n) = \frac{N}{2}$$

$$\overline{\beta}_c = E(\beta(n)) = \sum_{n=0}^{M} \beta_c(n) q_n{}^c$$

Throughput of the Ad Hoc network:

$$\beta_a(n) = \sum_{k=1}^{M} p_k{}^a \sum_{l=0}^{k} l r_{kl}$$

$$\overline{\beta_a}(n) = E(\beta_a(n)) = \sum_{n=0}^{M} \beta_a(n) q_n{}^a$$

where p_k^a is the pr. that total k packets are transmitted in one time slot

Throughput Comparison

Throughput bound for Ad Hoc network:

Intuition:
If the receiver is *perfect*, i.e. all collided packages can be received successfully, throughput should reach the maximum.

Holds for the CC network but not for the Ad Hoc network.
Reason: half-duplex mode of transceivers impose limits on the throughput.

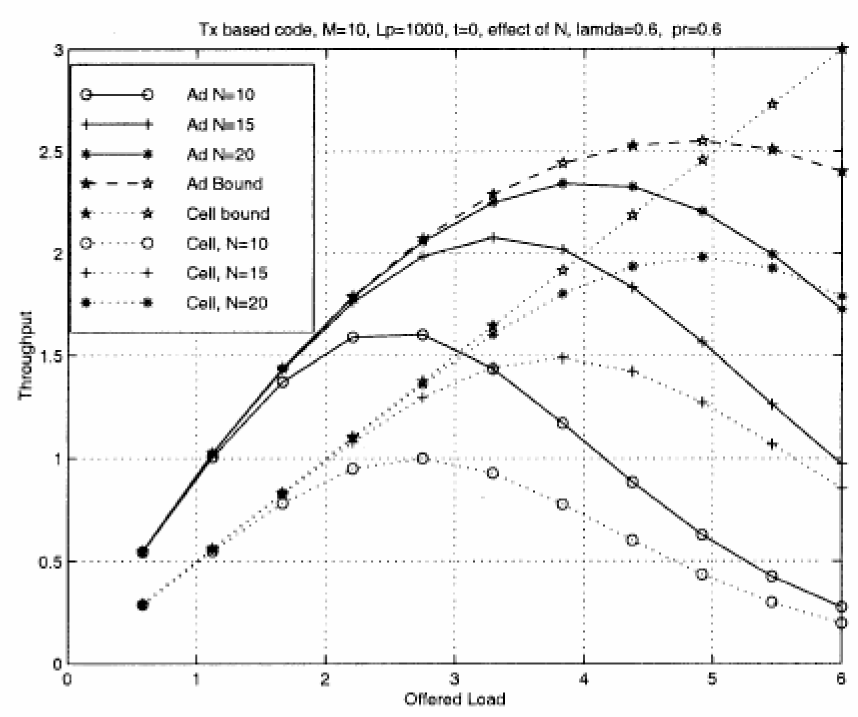
$$\beta_a(n) \le \sum_{k=1}^{M} p_k \sum_{l=0}^{k} l q_l = \sum_{k=1}^{M} p_k \sum_{l=0}^{k} l \binom{k}{l} \left(\frac{M-L}{M-1}\right)^{l} \left(\frac{L-1}{M-1}\right)^{k-l}$$

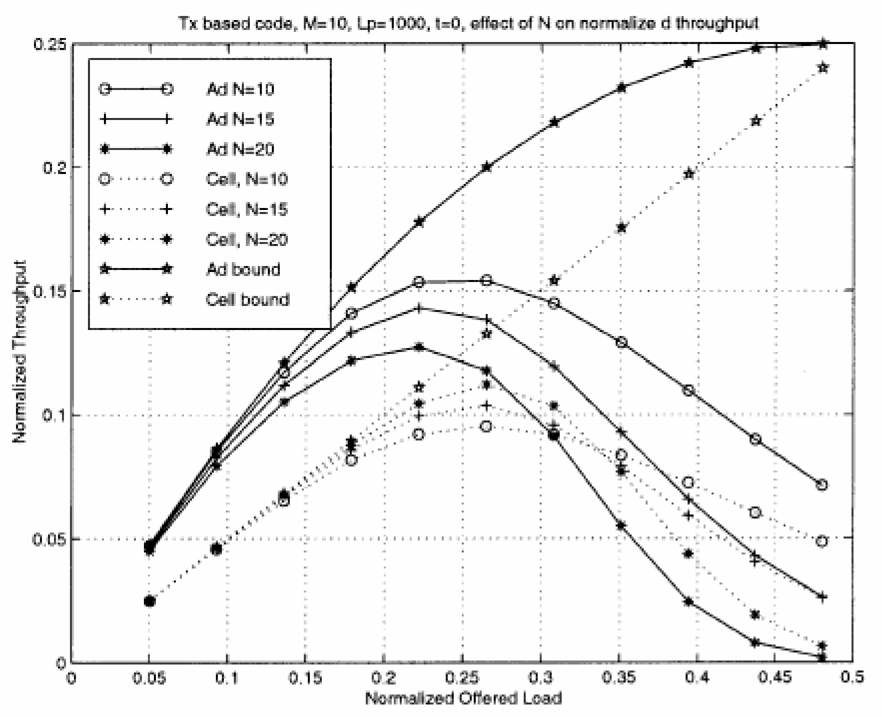
Normalization of Throughput:

β_u : average number of information bits successfully received by their intended receivers per second per hertz

Throughput Comparison

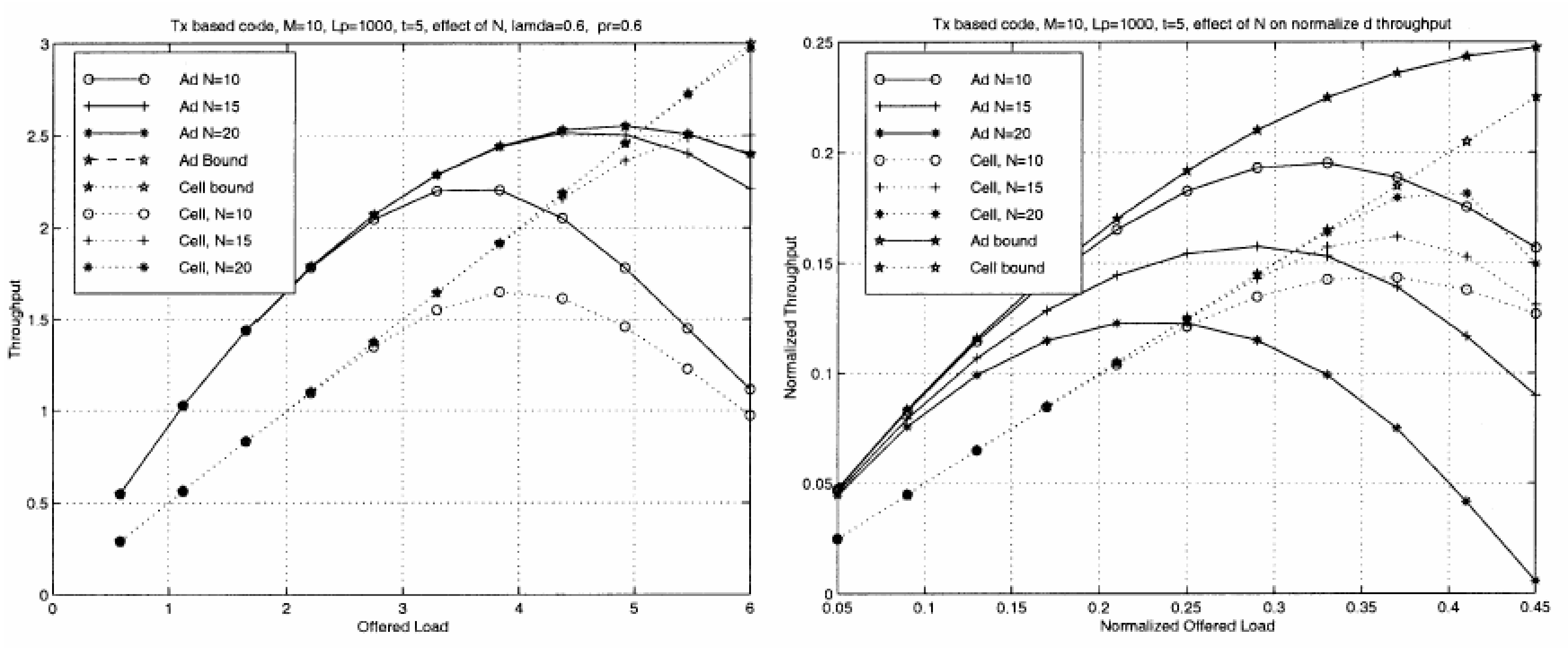
Throughput versus offered load; t=0, λ=0.6, p_r=0.6





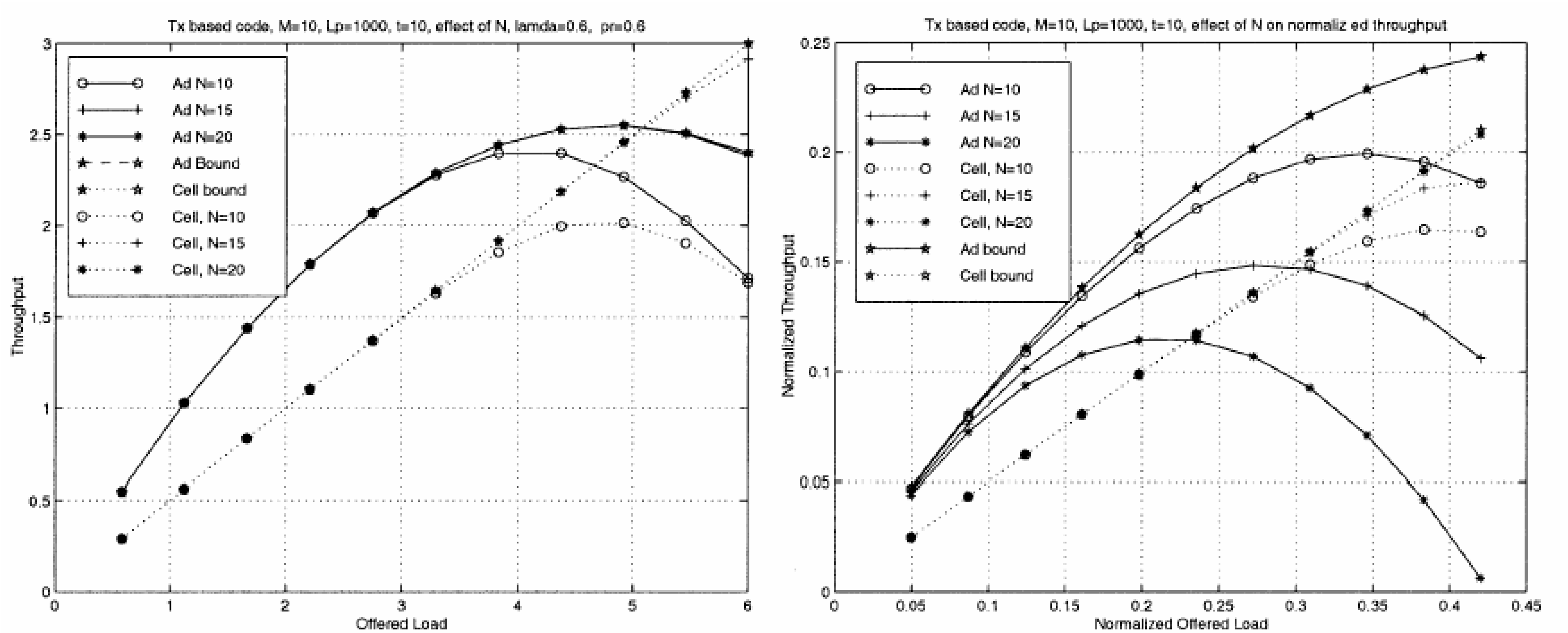
Throughput Comparison

Throughput versus offered load; t=5, λ=0.6, p_r=0.6



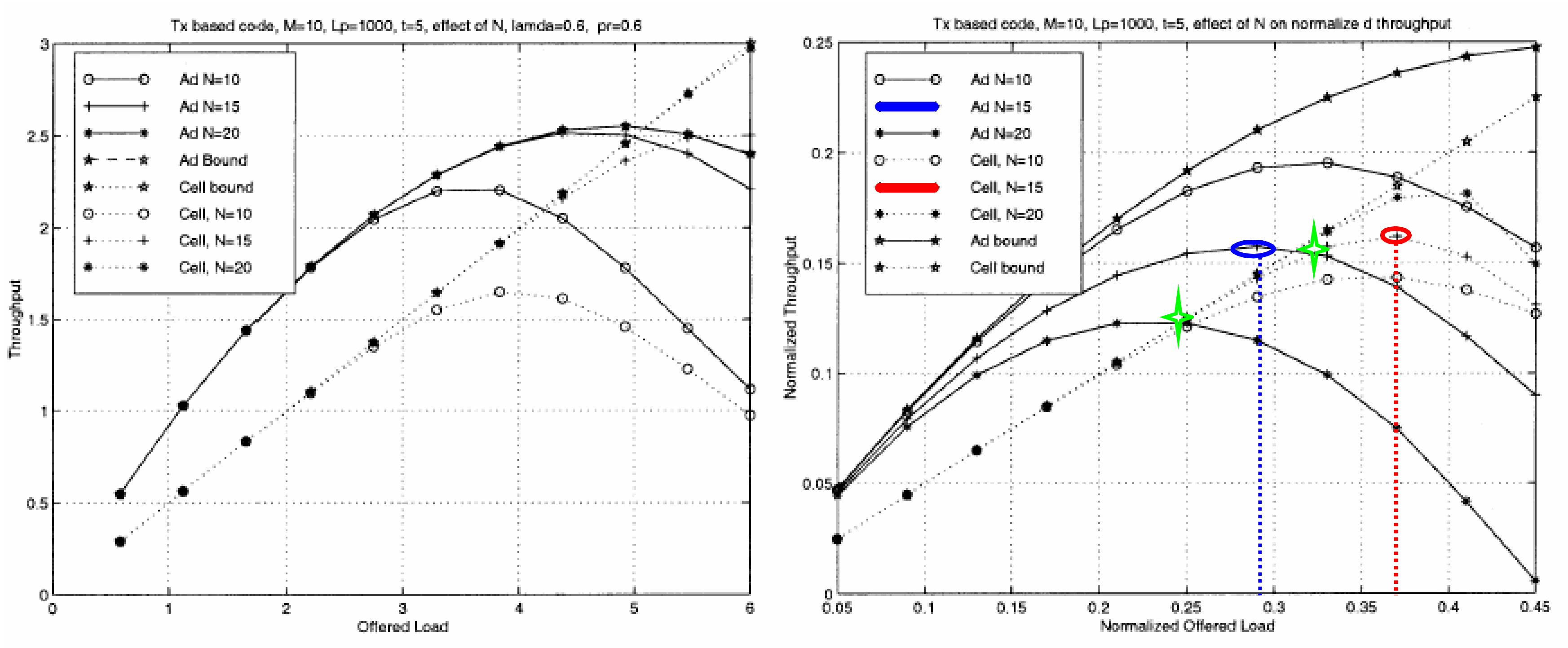
Throughput Comparison

Throughput versus offered load; t=10, λ=0.6, p_r=0.6



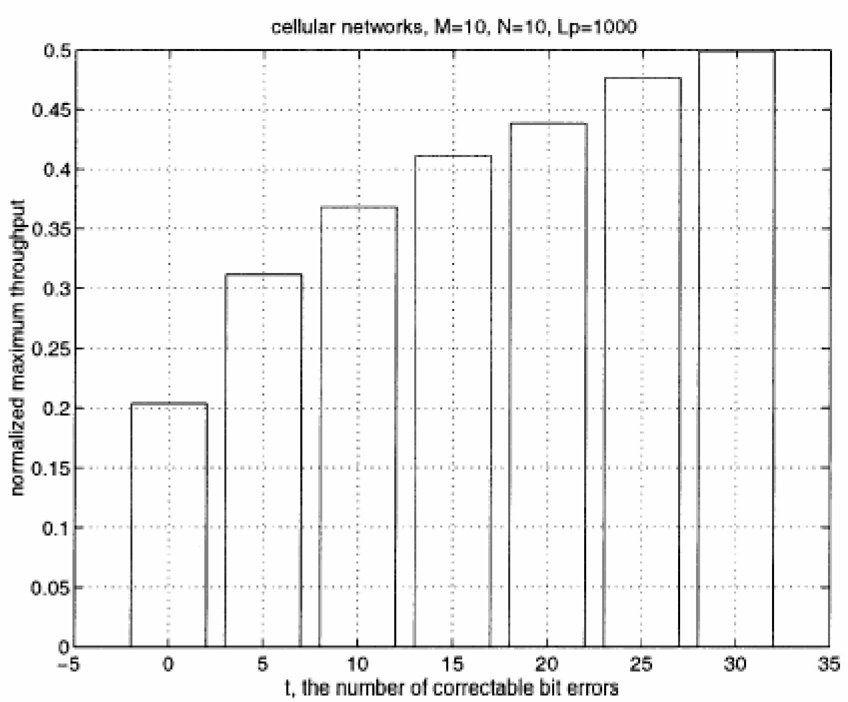
Throughput Comparison

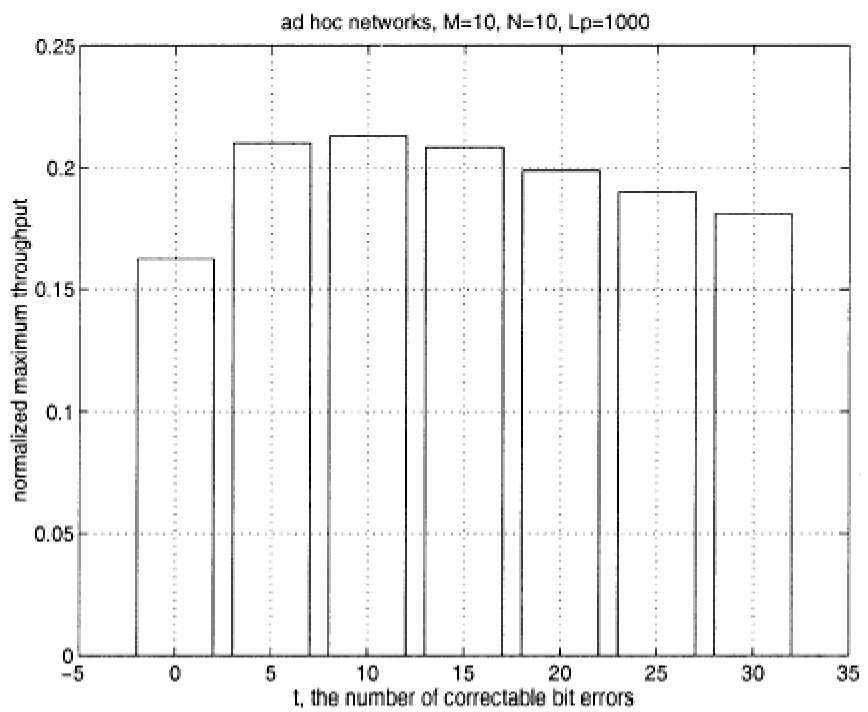
Throughput versus offered load; t=5, λ=0.6, p_r=0.6



Throughput Comparison

Number of correctable bit errors versus maximum normalized throughput





Conclusion

- Performance of **Ad Hoc** network is negatively affected by two factors:
  1) Availibility of node to receive packets
  2) Possibility that a node detected packets intended for other nodes

- Penalty caused by this issues is more significant when the network traffic is heavier

- These issues do not occur for the **Centrally Controlled** network *but* the process of relaying packets by the BS penalizes the network performance (especially at light traffic condition)

With constant spreading gain and error control coding:

Light traffic: Ad Hoc system had higher troughput and smaller packet delay

Heavy traffic: Centrally Controlled system outperforms the Ad Hoc system

Conclusion

Centrally Controlled network:

- With moderate powerful receivers, higher spreading gain can increase normalized throughput
- With poor receivers, higher spreading gain actually decreases normalized troughput under heavy traffic conditions
- Because of smaller bandwidth expansion introduced by the error control than the spreading gain, it is more efficient to use error control to improve centrally controlled networks

Conclusion

Ad Hoc network:

- Improvement of network throughput obtained from increased spreading gain cannot offset bandwidth expansion

-> increasing spreading gain monotonically decreases normalized throughput

- For given N, relationship between normalized throughput and correctable bit errors is not monotonic

-> optimum value for correctable bit errors can be selected to maximize the normalized throughput

THE END

and thanks for listening...