PHY-MAC Cross-layer: multiuser systems

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7- Ad-hoc networks principles (Laneman)

4. Communication networks Introduction: Interaction between physical and higher network layers

In order to obtain practical solutions

-Multiuser systems (A.Goldsmith textbook)
-Opportunistic scheduling
- Multipacket reception model versus collision channel model
- Case 1: SDMA for uplink
- Case 2: CDMA multipacket reception MAC for ad-hoc networks

Multiuser systems

- -Multiple access
  - -FDMA
  - -TDMA
  - -CDMA
  - -SDMA
  - -Hybrid techniques
- -Random Access
  - -Pure Aloha
  - -Slotted Aloha
  - -CSMA
  - -Scheduling
- -Power control

Opportunistic scheduling

Or multiuser diversity, motivated by an information-theoretic result of Knopp and Humbell

Foreseen for IEEE802.20 or IS-856 (small rx-tx signalling is needed)

Optimal power control scheme that is tailored to the fading statistics of the channel can achieve an information capacity higher than that of "perfect" power control.

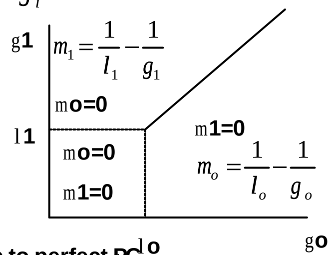
$$y = \sum_{i=0}^{K-1} a_i x_i + n \qquad m_i = \frac{g_{si}}{g_i}$$

$$\max_{m_i} \int \log\left(1 + \sum_{i=0}^{K-1} m_i(?) g_i\right) f(?)\, d?$$

Inst. SNIR

$$s.t. \quad \int m_i(?)\, f(?)\, d? = 1$$

$$m_i(?) \geq 0$$



More power if the channel is good!!: the opposite to perfect PC
Temporal waterfilling. The bigger K, the better results.

Fairness, delay ?

Opportunistic scheduling can be applied to different diversity schemes. If spatial Diversity is available: Transmit-diversity selection, phased array transmit diversity,...

If <u>multiuser transmitters or receivers are implemented</u>, multi-user opportunistic Scheduling is a choice

Heterogeneity: different channel coding, modulation, packet length

$$K_o = \max_K \left(\sum_{i \in K} q_i PER(g_i) \right)$$

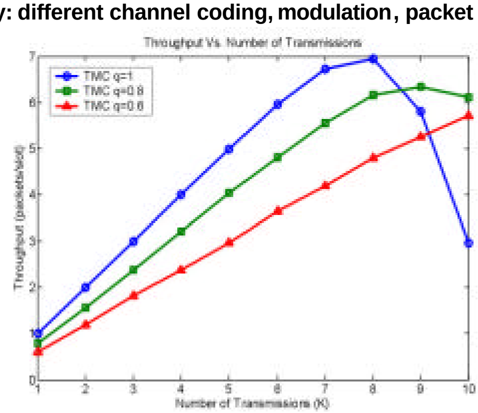
Traffic

Best terminals that must be simultaneously scheduled.

ZF receiver

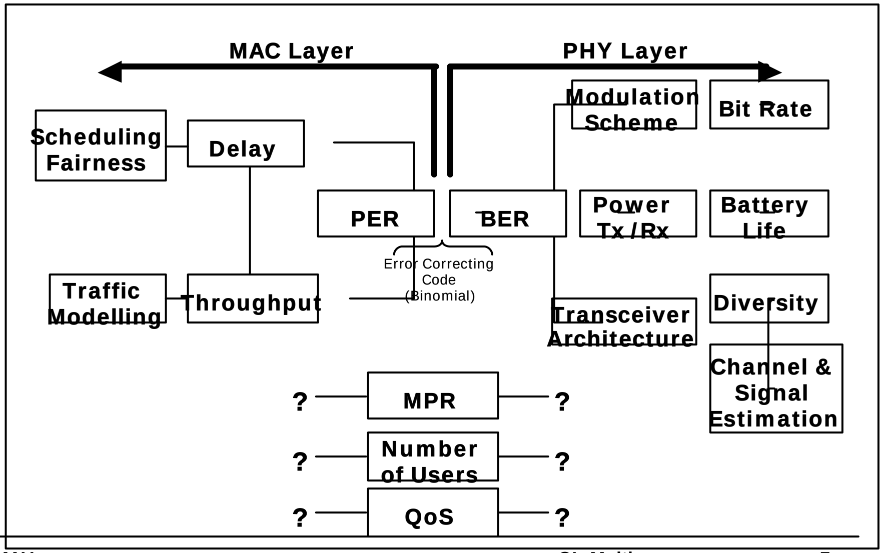
Traffic issues are extremely correlated to resource allocation

Throughput vs. Nº users



Interaction between physical and higher network layers

Introduction



Random access methods

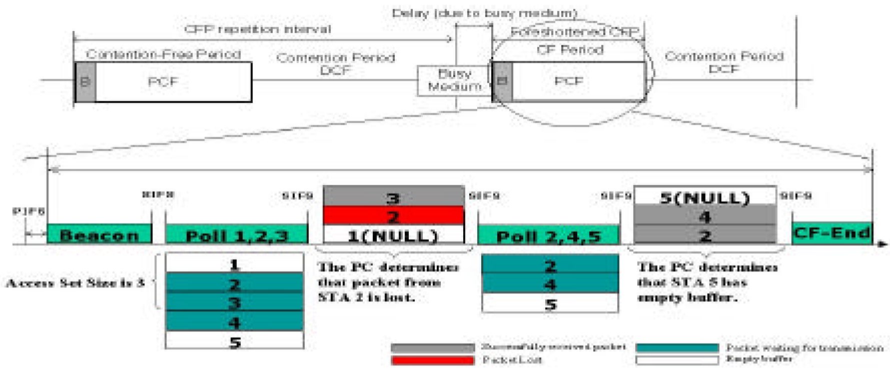
Users transmit information in packets over a common channel. There is no multiuser reception Capability. The packets are generated according to some statistical model and access is basically Random . Users access the channel when they have one or more packets to transmit. When more than one user attempts to transmit packets simultaneously, the packets overlap in time, i.e., they collide, and, hence, a conflict results , which must be resolved by devising some channel Protocol for retransmission of the packets .

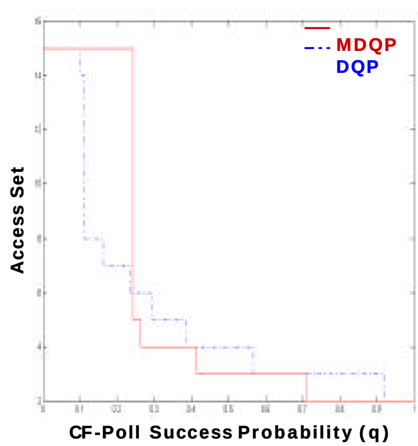
MultiPacket Reception (MPR) Capability

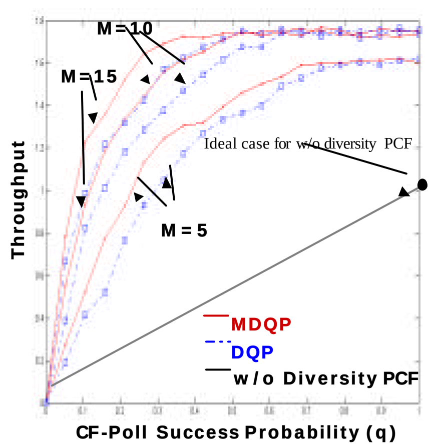
The receiver MPR capability determines the number of simultaneous transmissions that maximize throughput. When there is a probability q of a user to transmit a packet, the number of scheduled users that maximize throughput increases as long as q decreases.

An example:

Advantages of the Modified Dynamic Queue Protocol Vs. Dynamic Queue Protocol under the context of the 802.11 PCF polling scheme employing diversity. Figures show that the <u>knowledge of the *active users*</u> in MDQP, changes the access set size, i.e., number of users to be polled, and increases throughput.







$$C_{n,k} = P[k \text{ packets are correctly received} \mid n \text{ packets are transmitted}]$$

$$1 \le n \le M (\text{num. of users})\,;\, 0 \le k \le n$$

$$C_{n,k} = B(k,n,Ps(n))$$

$$B(k,n,Ps(n)) = \binom{n}{k} Ps(n)^k (1-Ps(n))^{n-k}$$

$$C = \begin{pmatrix} C_{1,0} & C_{1,1} & 0 & \cdots & \cdots & 0 \\ C_{2,0} & C_{2,1} & C_{2,2} & 0 & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & 0 \\ C_{M,0} & \cdots & \cdots & \cdots & \cdots & C_{M,M} \end{pmatrix}$$

$$C_n = \sum_{k=1}^{n} k C_{n,k}$$

$$\eta = \max_{n=1,\dots,M} (C_n)$$

$$\eta_0 = \arg(\max_{n=1,\dots,M} (C_n))$$

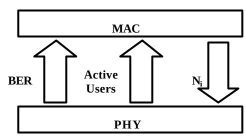
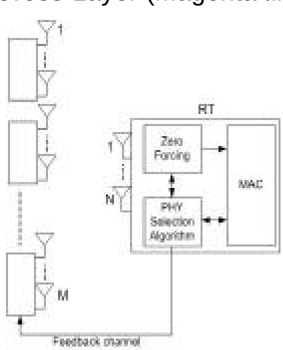
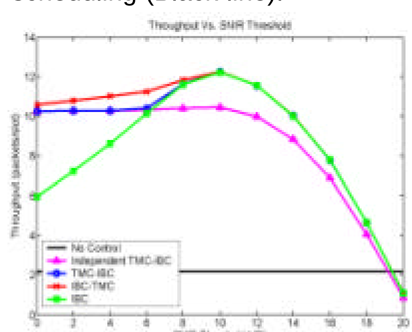


Figure 1. PHY-MAC dialogue

Case 1: SDMA for uplink

Based on the receiver MPR capability an optimal minimum SNIR threshold is obtained for multipacket opportunistic scheduling (green line). If the minimum SNIR threshold is fixed, the optimal number of simultaneous packets that maximize throughput can be obtained following different cross-layer approaches (Red and Blue lines). No Cross-Layer (Magenta line) and no scheduling (Black line).





Throughput analsysis

$$\mathbf{y}=\mathbf{H}\mathbf{s}+\mathbf{w} \qquad a_i = \frac{1}{\left(\left(\mathbf{H}^H\mathbf{H}\right)^{-1}\right)_{ii}}$$

The instantaneous Packet Success Rate for the ith transmission

$$PSR_i(a_i) = \sum_{k=0}^{r} \binom{P_l}{k} BER(a_i)^k (1-BER(a_i))^{P_l-k}$$

Impact of the rx structure

The multipacket reception performance of a receiver: average number of successfully rx Packets when k transmissions take place

$$C_k = \int_0^{\infty}\cdots\int_0^{\infty} \sum_{i=1}^{k} i\,PSR(a_i)\; p(a_1,\ldots,a_k)\; da_i$$

Throughput

$$h_K = \sum_{k=0}^{K} p_{Kk} C_k$$

p_{kK}: probability of having k active tx. when K are considered

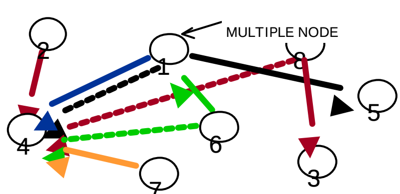
p_{kK} depends on the traffic and the <u>cross-layer protocol</u>.
Ex.: if q is the probability that a user transmit a packet

$$p_{Kk} = \binom{K_l}{k} q^k (1-q)^{K-k}$$

Case 2: Multi-packet reception MAC for ad-hoc nets

LAMAN Vs. Aloha-CDMA. The LAMAN protocol adapts to changes in the traffic load by properly adjusting contention and conflict-free components. The concept of *network* MPR capability is used. Furthermore, a multiple node might transmit more than one packet simultaneously.

M= nodes in the network= 8
N= codes in the network= 5
Nc= multiple node codes= 2
Nr= remaining codes for simple nodes= 3
Codes:

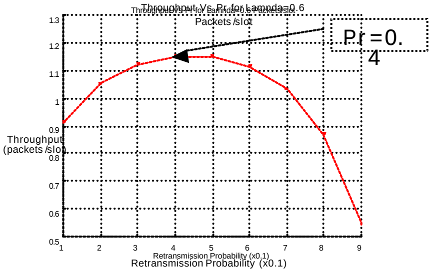


- Tranceivers are not full-duplex
- A node can successfully decode a packet not intended for him

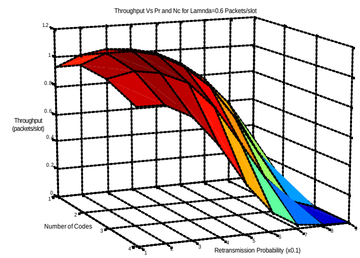
} Packets are lost

SIMULATIONS

CDMA based MAC

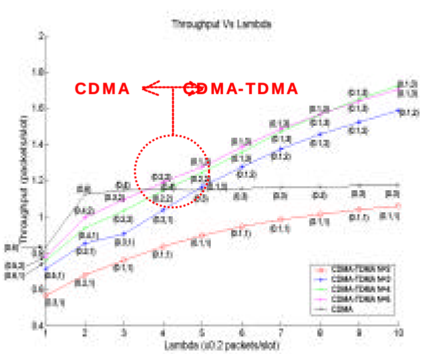


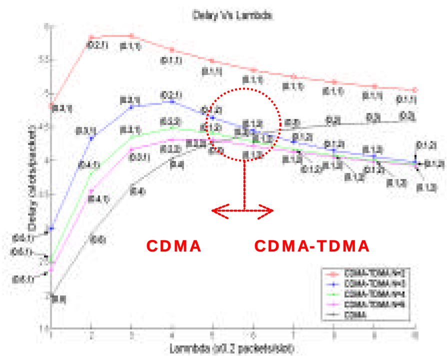
Adaptive CDMA-TDMA based MAC



Number of Nodes=5
Number of Codes=5
Bank of Matched Filters
Data Modulation: BPSK
Spreading Gain (Sp)=11
Packet Length (P_l)=1000
SNR((1/ s^2))=10

Example for 5 Node Network





Reconfigurability for spectral efficiency

Future work

- Further work on multipacket reception capability, cross-layer modeling and estability issues (queuing theory): convergence PHY (IT) – Network theory
- Cross-layer signaling
- Resource Multiplexing: Multi-dimensional spectrum
- Convergence between PHY-MAC QoS and Network QoS
- Open or flexible spectrum
- Decentralized systems: ad-hoc networks

Call for special issue on

Advances in Signal Processing-assisted cross-layer designs (www.cttc.es/spjournal)

EURASIP Signal Processing Journal (http://www.eurasip.org/signal_processing.htm)

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5. Generalized model for scheduling in MIMO multiple access systems

From Special Issue on Cross-layer of the Signal Processing Journal (to appear, December 2005), Marc Realp and Ana Perez

From ICC2005 (Korea, May 2005), Marc Realp and Ana Perez

- Introduction
- Signal model
- Generalized MPR Channel model
- Scheduling policies
- An example: the sensor network

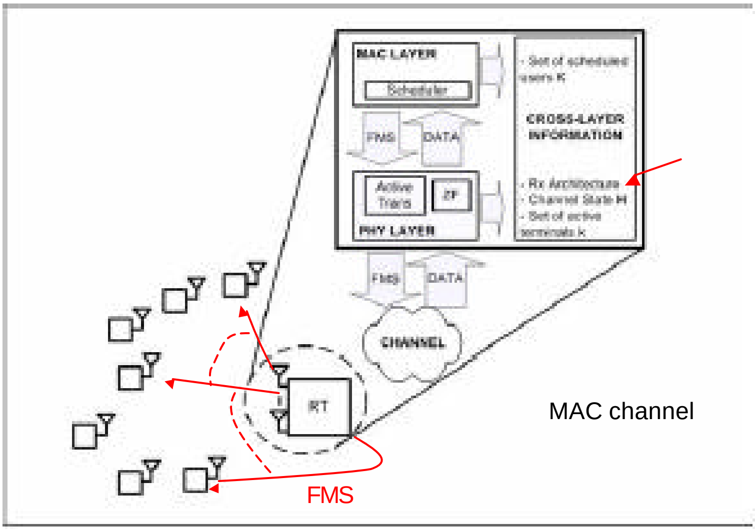
Introduction

- Research on MIMO MAC is traditionally carried out from the information theoretic point of view
- They assume homogeneous users: same modulation, channel coding, data transmission rate, packet length and no traffic consideration. Users only differ in their channel
- In this systems, max capacity is the same as max throughput
- WHAT ABOUT HETEROGENEOUS SYSTEMS?

↓

Generalized MPR matrix model to account for heterogeneity

System model



$$\mathbf{y}_k = \mathbf{H}_k \mathbf{s}_k + \mathbf{w}_k$$

$$H \rightarrow H_k$$

FMS sequence: Feedback Multicast Sequence is sent from BS to terminals in Order to tell them whether they can transmit or not.

Different Scheduling policies determine different FMS:

The scheduling policy indicates which users are to be scheduled Simultaneously K

Out of K, there will be k simultaneous transmissions

Generalized MPR channel model

$$\gamma_i = \frac{\overline{\gamma}}{2}\alpha_i(\mathbf{H}_k) \qquad \overline{\gamma} = \frac{P}{\sigma_w^2}$$

Noise enhacement factor that accounts for channel fading and MAI through Receiver implementation

$$BER_{\alpha(\mathbf{H}_k)}(i) \simeq C_1 \exp(-C_2 \frac{\overline{\gamma}}{2}\alpha_i(\mathbf{H}_k))$$

$$PSR_{\alpha(\mathbf{H}_k)}(i) = \sum_{m=0}^{r} \binom{P_l}{m} \left(BER_{\alpha(\mathbf{H}_k)}(i)\right)^m \left(1-BER_{\alpha(\mathbf{H}_k)}(i)\right)^{P_l-m}$$

Depends on channel and on K

or

$$PSR_{\alpha(\mathbf{H}_k)}(i) = \left(1-BER_{\alpha(\mathbf{H}_k)}(i)\right)^{P_l}$$

Average number of successfully received packets. It gives a measure of the trade-off between the number of simultaneous transmission k and the MAI or quality

$$C_{\alpha_{\mathbf{H}}}(k) = \sum_{i \in k} R(i) PSR_{\alpha(\mathbf{H}_k)}(i) \quad [packets/slot]$$

The average for the K scheduled users is

$$\eta_{\alpha_{\mathbf{H}}}(\mathcal{K}) = \sum_{k \subseteq \mathcal{K}} p_{\mathcal{K}k} \sum_{i \in k} R(i) PSR_{\alpha(\mathbf{H}_k)}(i) = \sum_{k \subseteq \mathcal{K}} p_{\mathcal{K}k}\, C_{\alpha_{\mathbf{H}}}(k) \quad [packets/slot]$$

Probability that all terminals in k transmit when access to the channel is given to the terminals in K. Might be either constant or a function of the traffic characteristics of The terminals, input rates and departure rates. Ex: evolution of the buffer size.

One comment: from throughput to goodput

$$R(i) = \frac{Pl_i}{Tx_{a(H_k)}(i)}$$

i: each user may present a different transmission mode
Pl: packet payload
Tx: transmission time

From ICC2005 (Korea, May 2005), Marc Realp and Ana Perez

Finally, to get the average throughput of the network

Define the scheduling policy

$$\mathcal{S}_{\mathcal{H}} = \left\{ s_{\mathbf{H}} \in [0,1]^{2^N} : \sum_{\mathcal{K} \subseteq \mathcal{P}\{1,\ldots,N\}} s_{\mathbf{H}}(\mathcal{K}) = 1,\ \mathbf{H} \in \mathcal{H} \right\}$$

Note that SH is a vector with entries defining the proportional amount of time a Set K of terminals is scheduled for a given channel realization H, or equivalently, the probability that a set K of terminals is scheduled for a given channel Realization H

Since $\mathcal{K} \subseteq \mathcal{P}\{1,\ldots,N\}$ There are 2^N possible sets

$$\eta(\mathcal{S}_{\mathcal{H}}) = \sum_{\mathcal{H}} \pi_{\mathcal{H}} \sum_{\mathcal{K} \subseteq \mathcal{P}\{1,\ldots,N\}} s_{\mathbf{H}}(\mathcal{K})\, \eta_{\alpha_{\mathbf{H}}}(\mathcal{K})\ [packets/slot]$$

Some examples on how the general MPR model can be particularized to model multiple access channel in any kind of communications system

The collision channel

$$\alpha_i(\mathbf{H}_k) = \begin{cases} \alpha_i(\mathbf{h}_k) & \text{for } k \in \{1, ..., N\} \\ 0 & \text{for } |k| > 1 \end{cases}$$

$$C_{\alpha_{\mathbf{H}}}(k) = \begin{cases} R\, PSR_{\alpha(\mathbf{h}_k)} & \text{for } k \in \{1, ..., N\} \\ 0 & \text{for } |k| > 1 \end{cases} \quad [packets/slot]$$

The orthogonal channel

It is the opposite to the collision channel: users do not interfere and all of them can transmit

$$\alpha_i(\mathbf{H}_k) = \alpha_i(\mathbf{h}_i)$$

$$C_{\alpha_{\mathbf{H}}}(k) = \sum_{i \in k} R(i) PSR_{\alpha(\mathbf{h}_i)}(i) \quad [packets/slot]$$

The Homogeneous MPR channel

It assumes that the MAI does not depend on the channel $\alpha_i(\mathbf{H}_k) = \alpha_{|k|}$

$$PSR_{\alpha(\mathbf{H}_k)}(i) = PSR_{\alpha_{|k|}}(i)$$

$$C_{\alpha_{\mathbf{H}}}(k) = C_{\alpha_{|k|}}(|k|) = |k| \;\; R \, PSR_{\alpha_{|k|}} \;\; [packets/slot]$$

The ZF MPR channel

$$\alpha_i(\mathbf{H}_{\mathcal{K}}) = \begin{cases} \frac{2}{[(\mathbf{H}_{\mathcal{K}}^H \mathbf{H}_{\mathcal{K}})^{-1}]_{ii}} & \text{for } |\mathcal{K}| \le M \\ 0 & \text{for } |\mathcal{K}| > M \end{cases}$$

$$C_{\alpha_{\mathbf{H}}}(k) = C_{\alpha_{\mathbf{H}}}(\mathcal{K}, k) = \sum_{i \in k} R(i) PSR_{\alpha(\mathbf{H}_{\mathcal{K}})}(i) \;\; [packets/slot]$$

IF through cross-layer design, the PHY knows the set of k active users

$$\alpha_i(\mathbf{H}_k) = \begin{cases} \frac{2}{[(\mathbf{H}_k^H \mathbf{H}_k)^{-1}]_{ii}} & \text{for } |k| \le N \\ 0 & \text{for } |k| > N \end{cases}$$

Improvement thanks
To crosslayer

$$C_{\alpha_{\mathbf{H}}}(k) = \sum_{i \in k} R(i) PSR_{\alpha(\mathbf{H}_k)}(i) \;\; [packets/slot]$$

Scheduling policies

The process that decides the set K of terminals to be scheduled is governed by the scheduling policy SH. Such scheduling determines the proportional amount Of time that every set of terminals has to be served or equivalently, the Probability of every set of terminals to be scheduled.

The optimal scheduling policy

$$\mathcal{S}_{\mathcal{H}}^{op} = \arg\max_{\mathcal{S}_{\mathcal{H}}} \left(\eta\left(\mathcal{S}_{\mathcal{H}}\right)\right)$$

It is throughput or Goodput optimization and no Shannon capacity: crosslayer

$$\mathcal{S}_{\mathcal{H}}^{op} = \left\{ \mathbf{s}_{\mathbf{H}}^{op} \in [0,1]^{2^M} : \begin{array}{l} s_{\mathbf{H}}^{op}(\mathcal{K}) = 1 \text{ if } \mathcal{K} = \mathcal{K}^{op},\ \mathbf{H} \in \mathcal{H} \\ s_{\mathbf{H}}^{op}(\mathcal{K}) = 0 \text{ if } \mathcal{K} \neq \mathcal{K}^{op},\ \mathbf{H} \in \mathcal{H} \end{array} \right\}$$

Be carefull with fairness

$$\mathcal{K}^{op} = \arg\max_{\mathcal{K} \subseteq \mathcal{P}\{1,\ldots,N\}} \left(\eta_{\alpha_{\mathbf{H}}}(\mathcal{K})\right)$$

The average scheduling policy

In order to simplify the complexity of the policies shown before

$$\mathcal{S}^{av} = \left\{ \mathbf{s}^{av} \in [0,1]^{2^M} : \begin{array}{l} s(\mathcal{K}) = \frac{1}{\binom{N}{|\mathcal{K}|}} \text{ if } |\mathcal{K}| = \mathcal{K}^{av} \\ s(\mathcal{K}) = 0 \text{ if } |\mathcal{K}| = \mathcal{K}^{av} \end{array} \right\}$$

$$K^{av} = \min \left\{ \arg\max_{|\mathcal{K}|} \left(\frac{1}{\binom{N}{|\mathcal{K}|}} \sum_{\substack{\mathcal{I} \subseteq \mathcal{P}\{1,\ldots,N\} \\ s.t.\ |\mathcal{I}| = |\mathcal{K}|}} \sum_{\mathcal{H}} \pi_{\mathcal{H}} \eta_{\alpha_{\mathbf{H}}}(\mathcal{I}) \right) \right\}$$

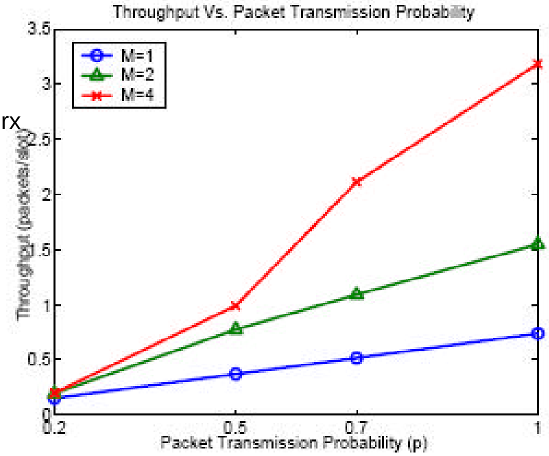
$$\sum_{\substack{\mathcal{I} \subseteq \mathcal{P}\{1,\ldots,N\} \\ s.t.\ |\mathcal{I}| = \mathcal{K}^{av}}} s(\mathcal{I}) = 1$$

Simulations

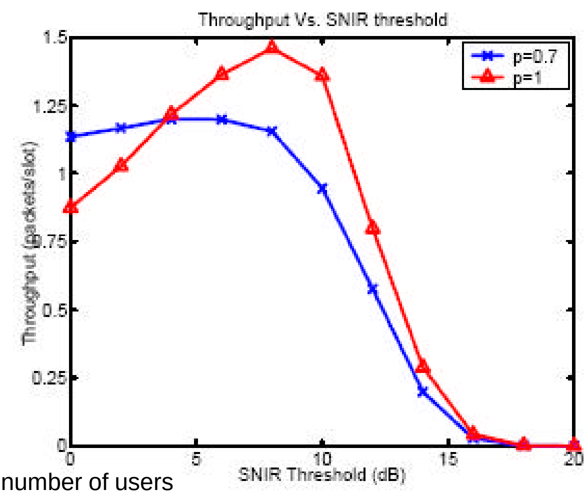
Sensor network with
10 sensors

Improved ZF

M antenna at rx

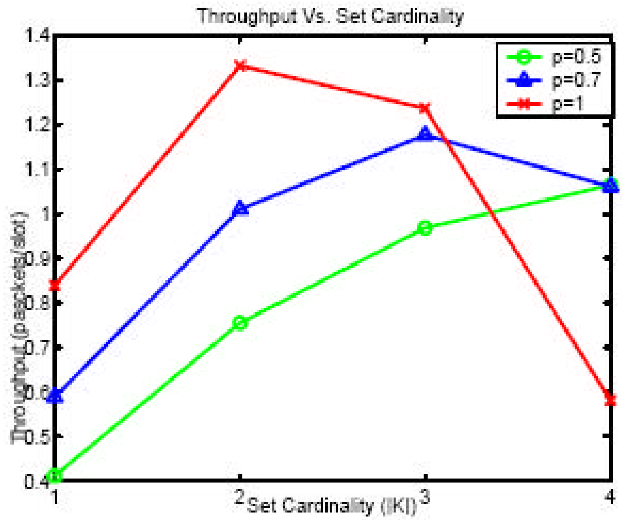


Optimal scheduling policy



The optimal number of users
depends on p

QoS scheduling policy



Average scheduling policy

An Example: The sensor network

The network

Assume the problem of information retrieval of a large network of sensors.
By means of FMS sequence, sensors are synchronized and scheduled (or polled) Periodically. We further assume our sensors to be environmental sensors that are In charge on providing with real-time information upon request.

The traffic model

$$p_{|\mathcal{K}||k|}(n) = p_{|\mathcal{K}||k|}$$

The channel model

An improved ZF receiver is considered, therefore

$\alpha_i(\mathbf{H}_k)$ is a weightened Chi-Square distributed variable

$$f_{|k|}(\alpha) = \frac{\alpha^{\frac{n}{2}-1}\exp(-\frac{\alpha}{2})}{2^{n/2}\Gamma(\frac{n}{2})}$$

$n = 2(M - |k| + 1)$ and $\Gamma(\frac{n}{2})$ stands for Gamma function.

Scheduling policies

1. The optimal scheduling policy: exhaustive search to maximize

$$\eta(\mathcal{S}_{\mathcal{H}}^{op}) = \sum_{\mathcal{K}\subseteq\mathcal{P}\{1,\dots,N\}} \sum_{k\subseteq\mathcal{K}} p_{\mathcal{K}k} \sum_{i\in k} R(i) \int_0^\infty s_{\alpha_{\mathbf{H}}}^{op}(\mathcal{K}) PSR_{\alpha(\mathbf{H}_k)}(i)\, f_{|k|}(\alpha)\, d\alpha \;\; [packets/slot]$$

2. QoS scheduling policy

Random selection algorithm

1) Set $FMS = \{1, ..., 1\}$ and $\mathcal{K} = \{i \in \{1, ..., N\} : FMS_i = 1\}$

2) Obtain $\mathbf{H} = [..., \mathbf{h}_i, ...]$

3) According to $\mathbf{H}$, compute $\alpha_i(\mathbf{H}_{\mathcal{K}})$ for $i \in \mathcal{K}$.

4) If minimum $\alpha_i(\mathbf{H}_{\mathcal{K}})$ is over α_{th}. Go to step 6

5) Else, set $FMS_i = 0$ being i the index corresponding to a terminal randomly chosen from those in $\mathcal{K}$. Set $\mathcal{K} = \{i \in \{1, ..., N\} : FMS_i = 1\}$ and go to step 3.

6) Send FMS.

Then

$$\eta\left(\mathcal{S}_{\mathcal{H}}^{QoS}\right) = \sum_{|\mathcal{K}|=1}^{N} \sum_{|k|=1}^{|\mathcal{K}|} p_{|\mathcal{K}||k|} R_{|K||k|} \quad [packets/slot]$$

$$R_{|K||k|} = \sum_{\substack{j\subseteq\mathcal{J}\subseteq\mathcal{P}\{1,\ldots,N\} \\ s.t.\ |\mathcal{J}|=|\mathcal{K}| \\ s.t.\ |j|=|k|}} \sum_{i\in k} R(i) \left[\left(\prod_{|\mathcal{J}|=N}^{|\mathcal{K}|-1} \int_0^{\alpha_{th}} f_{|\mathcal{J}|}(\alpha) d\alpha \right) \right.$$

$$\left. \frac{\int_{\alpha_{th}}^{\infty} f_{|\mathcal{K}|}(\alpha) d\alpha}{\binom{N}{|\mathcal{K}|}} \right] \frac{\int_{\alpha_{th}}^{\infty} PSR_{\boldsymbol{\alpha}(\mathbf{H}_k)}(i) f_{|k|}(\alpha) d\alpha}{\binom{|\mathcal{K}|}{|k|} \int_{\alpha_{th}}^{\infty} f_{|k|}(\alpha) d\alpha}$$

2. The average scheduing policy

$$\eta\left(\mathcal{S}_{\mathcal{H}}\right) = \sum_{|k|=1}^{K^{av}} p_{K^{av}|k|} R_{K^{av}|k|} \; [packets/slot]$$

where

$$K^{av} = \min\left\{ \arg\max_{|\mathcal{K}|} \left(\sum_{|k|=1}^{|\mathcal{K}|} p_{|\mathcal{K}||k|} R_{|\mathcal{K}||k|} \right) \right\}$$