Low Complexity Cross-Layer Design for Dense Interference Networks

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Outlines

• Physical layer/ Network layer/ Cross layer approaches
• Motivations and Objectives
• Resource Allocation
• Dense Network
• Game Analysis
• Numerical Results
• Remarks and Conclusions
Transmission Rate at Physical Layer

- Assumption: saturated queues
- Allocation of rate and power is based on the state of the physical channel.

capacity/achievable rate region:

- data sharing by transmitters → Multiple Input Broadcast Channel.
- data sharing by receivers → MAC.
- No data sharing, only state information exchange → Interference channel.
Arrival Rates at Network Layer

- Assumptions on the rates provided by the physical layer
- Allocation of the rates based on the state of queues

Stability Region!
(Our) Cross-layer Approach

- Finite length buffer
- Fading channel

- When to transmit?
- How to transmit (power and rate)?
- Accept/Reject?
Motivations and Objectives

We are searching for a control mechanism that:

- Supports the self-forming and self-haling properties of ad hoc networks → decentralized algorithm.

- Guarantees network stability → finite length buffer and admission control mechanism.

- Has good performance in slow-fading channels having only statistical knowledge of states of other communication pairs → minimization of outage probability.

- Relates achievable rate at physical layer to the network layer arrival rate → cross-layer control mechanism, joint power and rate allocation.
System Model (1)

- Arrival process follows an i.i.d. distribution with average rate $\lambda_i$.
- Link between a source and a destination is an N-dimensional vector channel with equal average power attenuation over all $N$ paths.
- The average power attenuation of each link is an ergodic Markov chain.
- Time is uniformly slotted.
- Packets have constant length.
- Possible choice of rate $\mu_i^R$ with $\mu_i \in \{0, ..., M_i\}$ and $R$ constant.
- State and action sets have finite cardinalities.
System Model(2)

• We consider different receivers depending on the assumption we make about:
  – The level of the information about interference available to the receiver.
  – Use of suboptimal receiver based on preliminary pre-decoding processing (e.g. detection) followed by decoding.
  – Type of decoder (single user/joint decoder)
Problem Statement(1)

User \( i \) decides \( a_i = (\mu_i, p_i, c_i) \):

- \( \mu_i \in \{0, \ldots, M_i\} \): rate of transmission including zero.
- \( p_i \in \{0, \ldots, P_i\} \): power of transmission including zero.
- \( c_i \in \{0, 1\} \): Accept/Reject
Problem Statement(2)

How does the user decide?

Information:

- transmitter state $x_i = (\sigma_i^i, q_i)$; state of channel and state of queue.
- type of decoder

Objective:

- maximizing the individuals’ expected throughput

subject to:

- constraint on average transmitted power.
- constraint on average queue length.
- constraint on probability of outage.

SINR expression
Large System Approximation

• For dense networks, we determine the strategy assuming $K, N \to \infty$ with $\frac{K}{N} \to \beta > 0$.

• Relevant Properties
  – In dense interference networks the effect of interference tends to deterministic limits.
  – Given a receiver $i$, the group $m$ of transmitters $n$ having received power $p^i_n = p_n \sigma^i_n$ and transmitting at rate $\mu_i R$ is
    \[ g^{(i)}_m : \left\{ n \in \{1, \ldots, K\} \mid (p^i_n, \mu_n) = (p^i_m, \mu_m) \right\} \]
  – For those groups, the ratio $\frac{\left| g^{(i)}_m \right|}{N} \overset{a.s.}{\to} \beta^i_m$, converges to a constant
    These properties will enable to decrease the complexity!
Large System Analysis of the receivers

<table>
<thead>
<tr>
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<th>MMSE+SUD</th>
<th>Joint Decoder</th>
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<tbody>
<tr>
<td>KIS</td>
<td>----</td>
<td>SGD/MGD</td>
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<tr>
<td>UIS</td>
<td>SGD</td>
<td>SGD</td>
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KIS: Known Interference Structure
UIS: Unknown Interference Structure
SGD: Single Group Decoding
MGD: Multi Group Decoding

Condition to be satisfied:

\[ \mu_1 R \leq \frac{C^X(SNR, \beta_1^{(1)})}{\beta_1^{(1)}} \]
Large System Analysis of the receivers
No Preprocessing / Known Interference Structure / Multi Group Joint Decoding

1. In each block interval, find the maximal decodable set (MDS) among the transmitter groups, at receiver 1 [Khandani, 07].

\[ S \]

2. If group 1 belongs to the MDS, the interference cause by the other groups in the set can be canceled prior to decoding group 1.

\[ X_{g^{(1)}} \rightarrow X_{g^{(1)} \setminus S} \]

[Khandani, 07] To decode the interference or to consider it as noise, Nov. 2007.
Maximum Decodable Set

• For each receiver there exist a unique *maximal decodable set* of transmitters [Khandani,07].

**THEOREM 1:** A subset \( \hat{g}^{(1)} \subseteq g^{(1)} \) is the unique maximal decodable subset at receiver 1 iff the transmitters’ rates satisfy the following inequalities

\[
\begin{align*}
\sum_{i \in g'} & \mu_i R \leq \hat{I}(X_{g'}^{(1)}; Y^{(1)} | X_{\hat{g}^{(1)}} \backslash g'^{(1)}) \quad \forall g'^{(1)} \subseteq \hat{g}^{(1)} \\
\sum_{i \in g''} & \mu_i R > \hat{I}(X_{g''}^{(1)}; Y^{(1)} | X_{\hat{g}^{(1)}}) \quad \forall g''^{(1)} \subseteq g^{(1)} \backslash \hat{g}^{(1)}
\end{align*}
\]
The Game
payoff matrix/vector

(state, action) space of the other users: \((x_{-i}, a_{-i})\)

\[
C^{(i)}_{n_1n_2...n_K} = \begin{cases} 
0 & \mu_i R \geq r^{(i)}(t) \\
\mu_i R & \text{otherwise}
\end{cases}
\]

\[
r^{(i)}(t) = r^{(i)}(x^{(i)}(t), p(t))
\]

\(t: \text{Block Interval; } p(t) = (p_i(t), p_{-i}(t))\)

Assymptotic interference does not depend on block interval
Game Formulation

- $z_i(x_i, a_i)$: joint probability that transmitter $i$ performs action $a_i$ while being in state $X_i$ (i.e. probability of $<x_i, a_i>_n$). The utility function is

$$\rho_i = \sum_{<x,d>_n \in K} c(x, d, P(p)) z_n$$

- Transmitter $i$ needs to solve the optimization problem below knowing that the other users follow the same approach (rational users).

$$\begin{cases} \max \rho_i = \max f^i z_i \\ \text{s.t. power and queue constraints} \end{cases}$$
Game Solutions
Nash equilibrium

• The existence of NE for general class of constraint stochastic games, where players have independent state processes is proven in [EA,06].

• Uniqueness

   Does not exists where an interference cancelation mechanism is used!

[EA,06] Constrained cost-coupled stochastic games with independent state process.
Game Solution
Best Response

• Best response to the optimal policies of the others reduces to LP

• Algorithm for node $i$:
  1. Assign an arbitrary policy to $K-1$ nodes
  2. Find the optimal policy from the constraint optimization problem above
  3. Assign the obtained policy to all nodes
  4. Pick an arbitrary node and go to step 2
Policies

Settings:
• Arrival process: Poisson distribution with average rate $\lambda_i = 1$.
• CS varies according to a Markov chain with equal probability of keeping the state or changing one unit.
• The possible rates are multiple of $R = 0.5$
  \[ \beta = 2, \]
  \[ \text{buffer states } \in \{0,...,5\} \]
  \[ \text{channel states } \in \{0,...,2\} \]
  \[ \text{power states } \in \{0,...,3\} \]
  \[ \text{possible rates } \in \{0,...,5\} \]

Comments:
1. Decision on rate is not affected by the CSs and it’s an increasing function of the QS.
2. The power level is independent of queue level and only a function of CS

This decoupling property is specific of dense network!
Different Receivers

Settings:
• Arrival process: Poisson distribution with average rate $\lambda_i = 1$.
• CS varies according to a Markov chain with equal probability of keeping the state or changing one unit.
• The possible rates are multiple of $R = 0.5$
  - $\beta = 2$
  - buffer states $\in \{0,...,5\}$
  - channel states $\in \{0,...,2\}$
  - power states $\in \{0,...,3\}$
  - possible rates $\in \{0,...,5\}$

Comments:
1. For ACL-(NP/KIS/MGD) the maximal rate is limited by the discrete rate set.
2. For two other receivers, the maximal rate has interference limited behavior.
Asymptotic Approximation: Performance Loss

**Settings:**
- Arrival process: Poisson distribution with average rate $\lambda = 1$.
- CS varies according to a Markov chain with equal probability of keeping the state or changing one unit.
- The possible rates are multiple of $R = 0.5$
  - $\beta = 2$
  - buffer states $\in \{0,...,5\}$
  - channel states $\in \{0,...,2\}$
  - power states $\in \{0,...,3\}$
  - possible rates $\in \{0,...,5\}$

**Comments:**

Even when the number of transmitters is very low, the finite network performs almost as well as the large interference network.
Cross-layer vs. Conventional

Settings:
• Arrival process: Poisson distribution with average rate $\lambda_i = 1$.
• CS varies according to a Markov chain with equal probability of keeping the state or changing one unit.
• The possible rates are multiple of $R = 0.5$
  \[ \beta = 2, \]
  buffer states \( \in \{0,...,5\} \)
  channel states \( \in \{0,...,2\} \)
  power states \( \in \{0,...,3\} \)
  possible rates \( \in \{0,...,5\} \)

Comments:
1. In the conventional approach more power is consumed for sending a given packet.
2. There is cases that power is adjusted to satisfy a rate while there is not enough data in the queue.
Remarks and Conclusions

• We investigated distributed algorithms for joint admission control, rate, and power allocation aiming at maximizing the individual throughput.
• We considered different receivers based on assumptions on: (I) the level of knowledge about interference, (II) Use of pre-decoding processing (e.g. detection), (III) single user/joint decoder.
• The asymptotic approach enables a sizable complexity reduction: the complexity does not scale with the number of users but with the number of transmitter groups.
• The policies obtained for a dense network presents interesting decoupling properties.
• The performance loss due to the application of policies obtained from asymptotic case on a finite network is very low.
• The neglect of the state of queue causes a relevant performance loss since the power is not efficiently allocated.
• In a two communication flows network, the performance of optimal policies obtained for dense network is almost as well as the one adapted to the network.
State of art

- [EA, 07]: MAC channel, fix transmission rates for all users, decentralized control mechanism, power allocation, admission control.

  Heuristic utility function and very high complexity!

- [SA, 09]: satisfies the items in “motivations and objectives” but too complex! Complexity grows exponentially with the users and the cardinality of state and action sets!