Distributed Base Station Processing in the Uplink of Cellular Networks

Emre Aktas[†], Jamie Evans[‡] and Stephen Hanly[‡]

[†]Department of Electrical and Electronics Engineering

Hacettepe University, Ankara, Turkey

[‡] Department of Electrical and Electronic Engineering

University of Melbourne, Australia

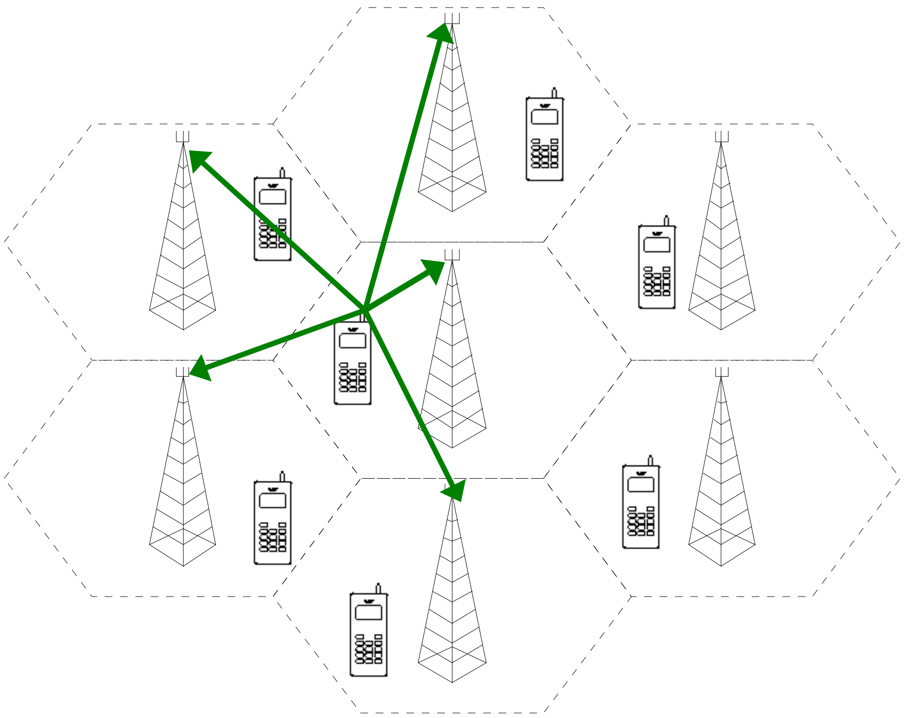
COST289 Meeting

March 23-24, 2006 - University of Novi Sad, Serbia and Montenegro

Outline

- Uplink channel of cellular network
- Global processing in the uplink
- Optimum global receiver for linear cellular array
- Belief propagation preliminaries
- Iterative global receivers for planar cellular array

Uplink Channel of Cellular Network



- Signal transmitted by a mobile in a cell received at the base station of that cell and base stations of neighbor cells

Global Receiver

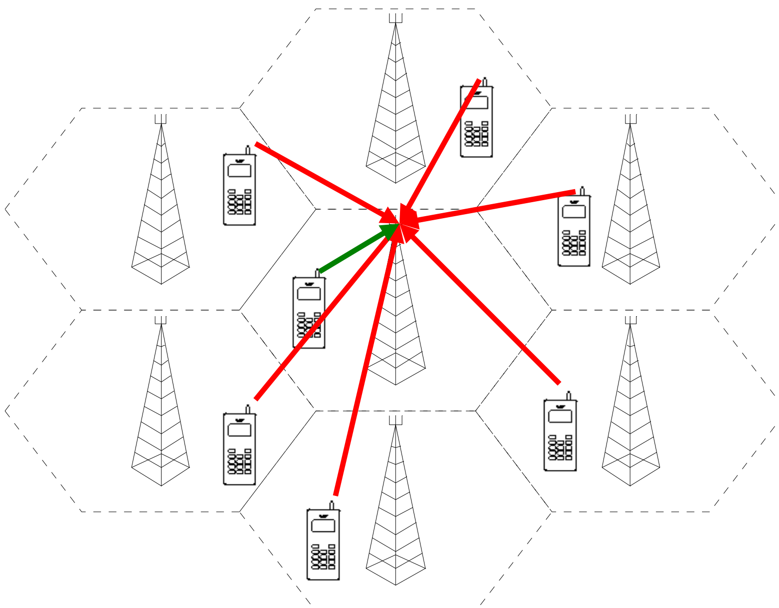
- Single-cell receiver
  - each base station processes individually
  - each base station's task is to decode users' signal at its cell
- Global receiver: a conceptual receiver where
  - the entire cellular network is a single multiaccess link
  - multiple transmitters, a single receiver with multiple antennas
  - each base station acts as an antenna of the receiver
  - optimum multiuser decoding is performed

Information-Theoretic Results

- Frequency planning:
  - Different frequency bands (orthogonal signals) are assigned to nearby cells
  - Goal is to avoid inter-cell interference
- Frequency planning is based on single-cell processing
- If global receiver was available?

- Full-frequency use with global receiver is the best strategy
  [Wyner:1994] [Hanly and Whiting:1993], [Somekh and Shamai:2000]

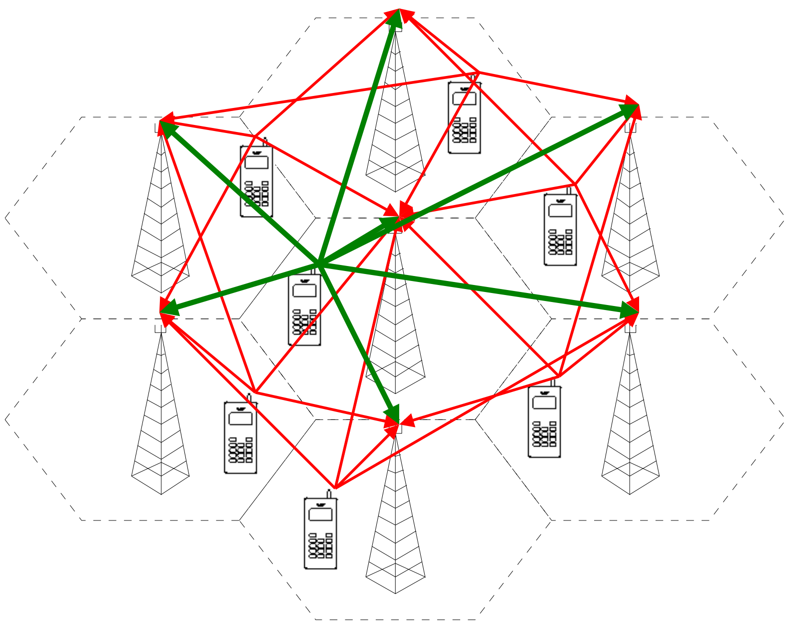
Single-cell vs. Global Processing



- Conventional cellular systems employ single-cell processing:
- Each mobile assigned a base station
- Intended communication is between a mobile and its base station

- Signals from mobiles in other cells undesired, regarded as inter-cell interference (ICI)
- ICI mitigation limited to observation at single base station

Single-cell vs. Global Processing



- Global processing:
  - Have access to all received signal due to desired user: receiver diversity
  - Have access to all received signal due to interfering users: better suppression of inter-cell interference

Global Receiver – Practical Issues

- Practical challenges of implementing a global receiver
  - Collecting received signals from all base stations at a single processor
  - Complexity of multi-user detection: e.g. $\mathcal{O}(N^3)$ for LMMSE receiver, $\mathcal{O}(M^N)$ for optimal receiver with M-ary signaling

Goal

- Goal in this work: Distributed global receiver
  - Message passing among base stations allowed only between adjacent cells
  - With increasing network size, the following should remain constant
    - Complexity for each base station
    - Decoding delay – number of consecutive message passings

Contribution

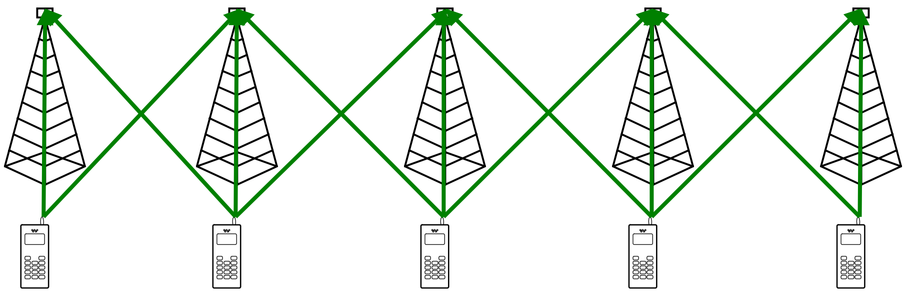
- Proposed distributed iterative processing methods for planar array model
  - Employed the belief propagation algorithm
  - Performance close to individually optimum maximum *a-posteriori* (MAP) receiver

Assumptions

- High bandwidth, error-free land-line communication between base stations of adjacent cells
- Intra-cell and inter-cell synchronized mobile users
- Full frequency reuse
- TDMA within a cell
- Flat fading channel, coefficients available at base station
- Uncoded system
- ICI from users in adjacent cells only

Decoding for the Linear Array Model

- Cells located on a line, most has two adjacent cells



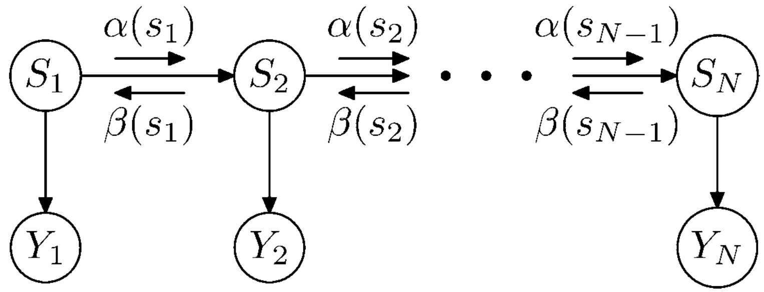
$$Y_k = \sum_{i=-1}^{1} B_{k+i} H_k(i) + N_k$$

- Equivalent to ISI channel with memory 2
- Optimal distributed MAP decoding:
  [Grant, Hanly, Evans, Müller:2004]
- For each cell form a state by clustering the transmitted symbols from adjacent cells

$$S_k = (B_{k-1}, B_k, B_{k+1})$$

Decoding for the Linear Array Model

- The states $S_1, S_2, \ldots, S_N$ form a hidden Markov chain



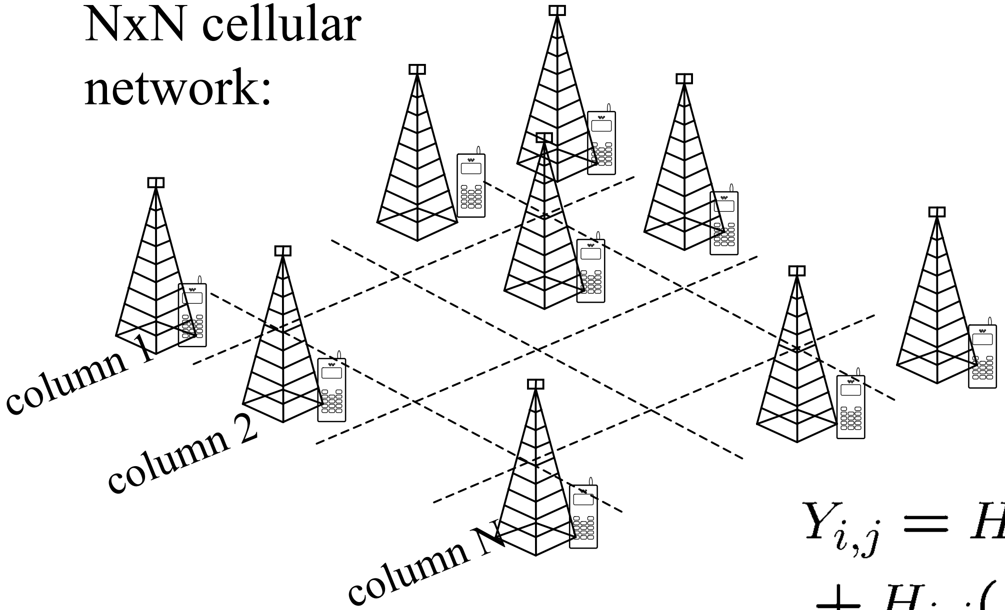
Each observation depends on 1 state only

$\Rightarrow$ use the BCJR [Bahl, Cocke, Jelinek, Raviv : 1974] algorithm to calculate $p(s_k|y_1, \ldots, y_N)$

- Can be implemented at the each station with local processing and message passing between adjacent cells
- With increasing N:
  - complexity for each base station remains constant
  - decoding delay increases

Decoding for the Planar Array Model

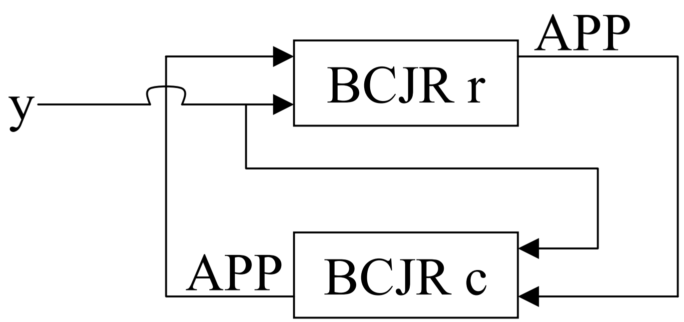
NxN cellular network:



$$Y_{i,j} = H_{i,j}(0,0)B_{i,j} + H_{i,j}(-1,0)B_{i-1,j} + H_{i,j}(1,0)B_{i+1,j} + H_{i,j}(0,-1)B_{i,j-1} + H_{i,j}(0,1)B_{i,j+1} + N_{i,j}.$$

- Consider rectangular array model (extension to hexagonal case straightforward)
- Most cells have 4 adjacent cells
- No natural ordering to form a Markov chain as in linear array model

Iterative Decoder



Turbo-decoder-like iterative decoding

- *A-posteriori* probability of one decoder used as prior of the next decoder

A Bayesian Network Approach

- Alternatively, construct a graphical representation - Bayesian belief network
- Apply the belief propagation algorithm on this graph

Belief Propagation Algorithm

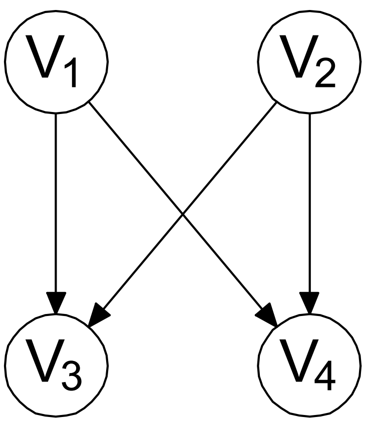
- Belief propagation algorithm
  - Given some variables, calculates posterior distributions of other variables
  - Algorithm is defined by messages among the nodes on the graph
- In order to define a BP algorithm
  - construct a graph
  - choose message scheduling on this graph

Belief Propagation Algorithm

- BP is a good candidate for our purposes because
  - BP is distributed
  - BP is numerically efficient
- We envision a system which achieves global processing, where
  - The calculations for each node is done by the base station of a cell
  - The message passings among the nodes: Base stations communicate with adjacent base stations

Bayesian Network Preliminaries

- Directed graph: Edges from parent nodes to child nodes
- Each child node and its parent represent a conditional distribution in the factorization of the joint pdf

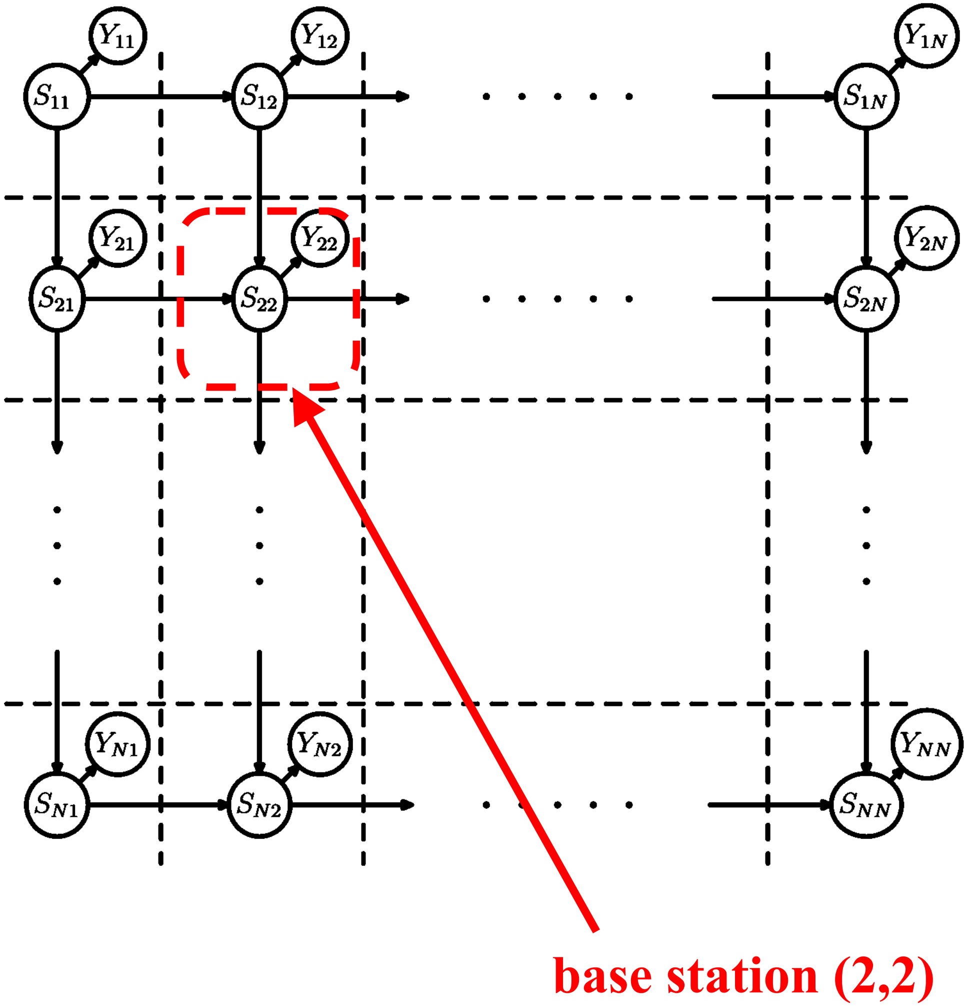


Message $V_2 - V_4$: function of $\mathcal{V}_2$

Message $V_4 - V_2$: function of $\mathcal{V}_2$

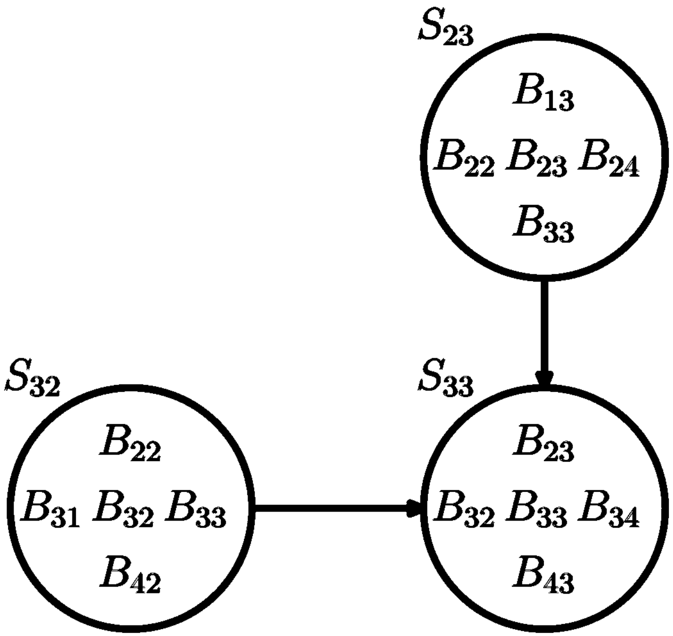
$$p(v_1, v_2, v_3, v_4) = p(v_3|v_1, v_2)p(v_4|v_1, v_2)p(v_1)p(v_2)$$

Bayesian Network – Clustered Graph

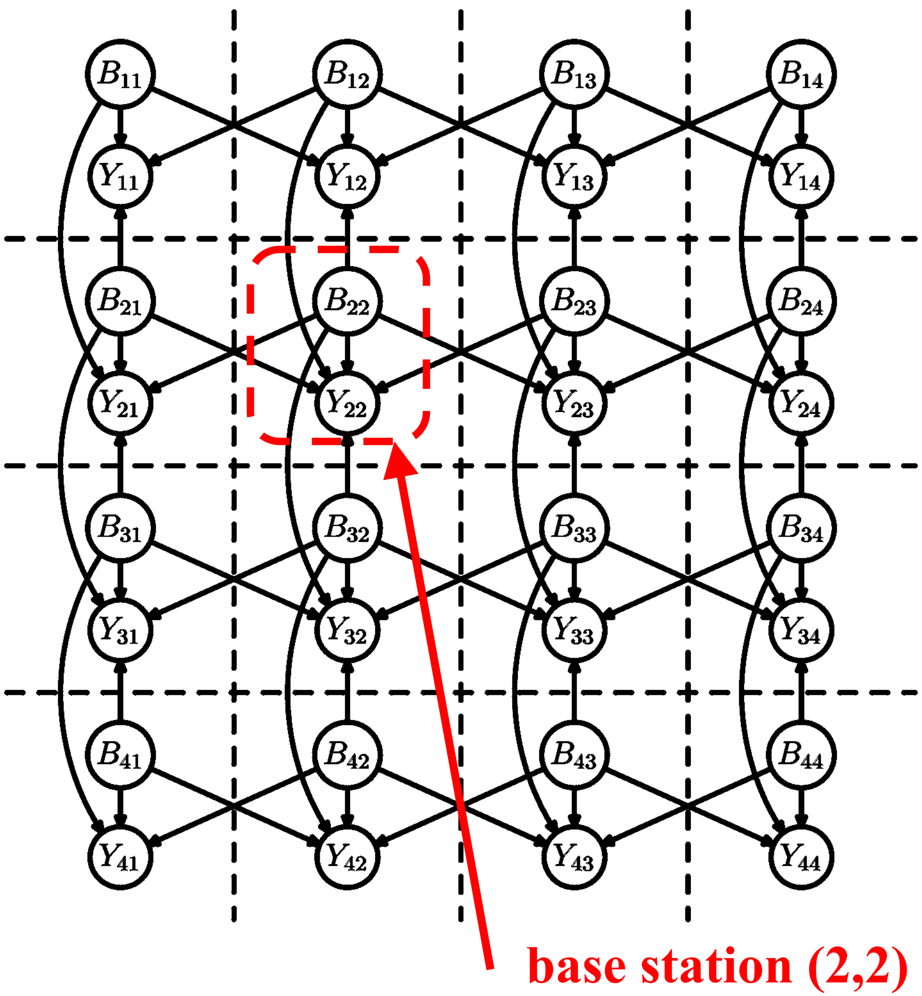


- A graph where each observation has a single parent node
- Each state node is a clustered node that contains the symbols that contribute to that observation
- Inspired by the Markov chain model of the BCJR algorithm

Bayesian Network – Clustered Graph

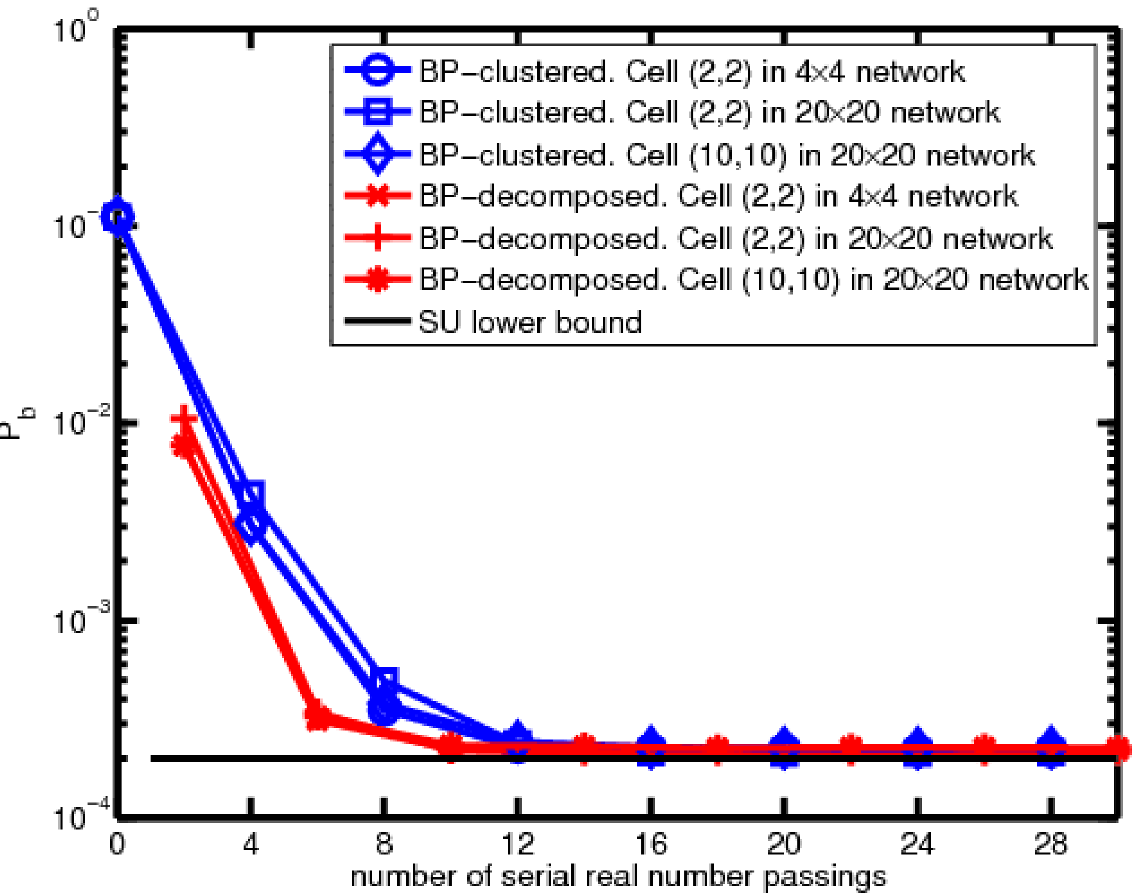


Bayesian Network – Decomposed Graph



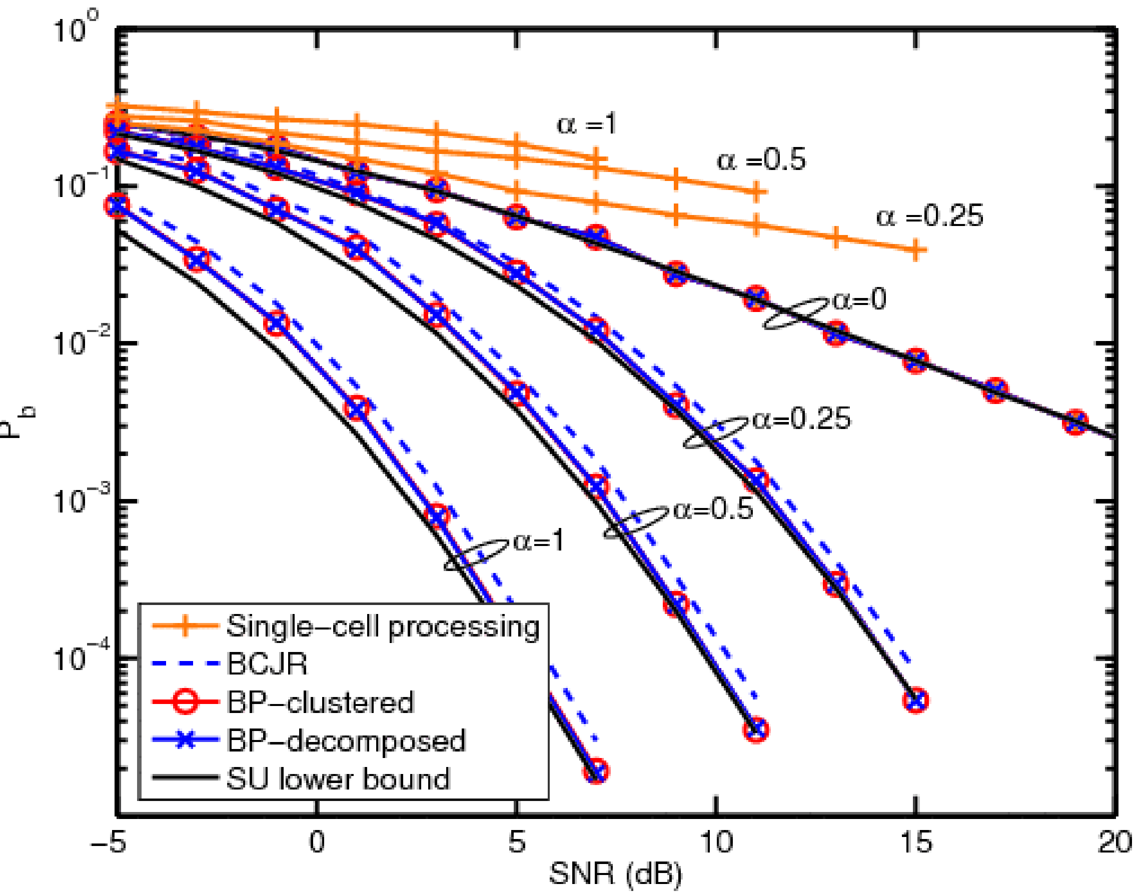
- Graph where each variable is represented by a separate node
- The clustered nodes are decomposed
- Reveals the structure explicitly

Numerical Results



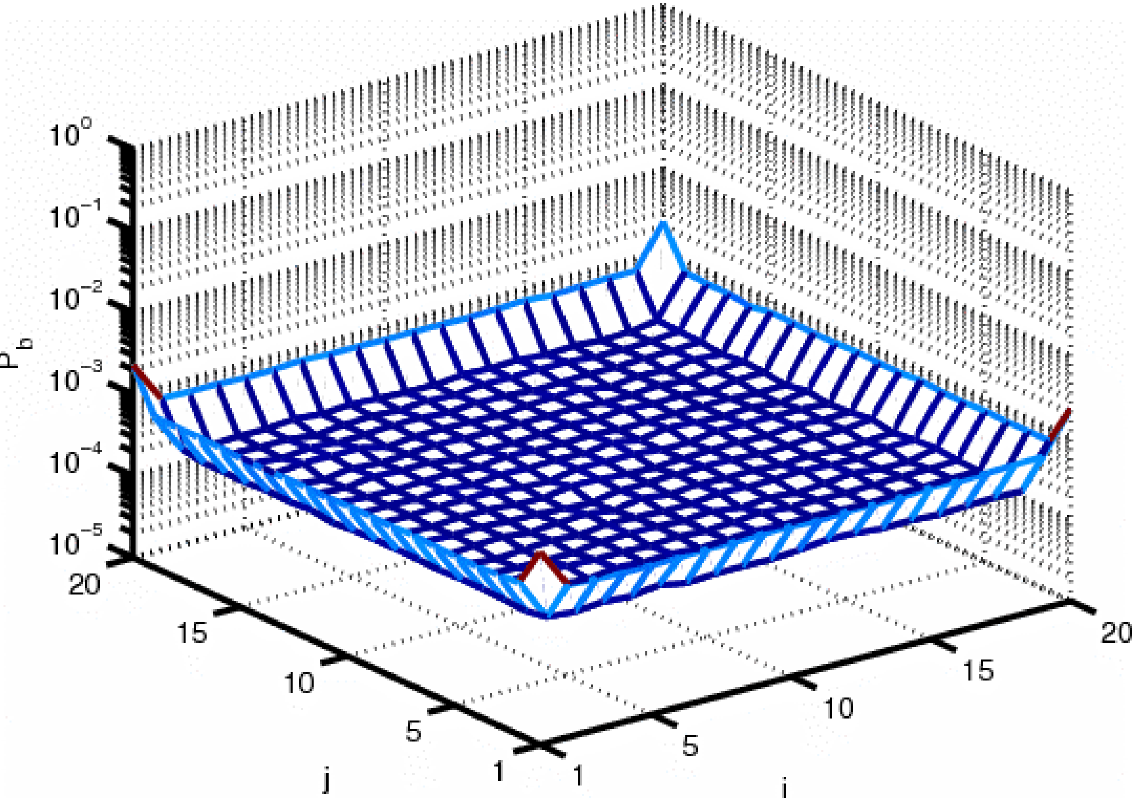
- Rayleigh fading
- MS-to-own-BS channel: unit variance
- MS-to-other-BS channel: variance α^2
- $\alpha = 0.5$, SNR = 9 dB
- Both algorithms quickly achieve near single-user performance
- BP on decomposed graph slightly faster
- Convergence rate does not vary with network size, location of cell

Numerical Results



- 4x4 planar array
- Optimal single-cell processor also given
- ICI parameter α = 0: No ICI, optimal APP for single-user channel
- As ICI power increases algorithms can
  - Handle the ICI
  - Exploit diversity and energy provided by ICI
- Very large gain due to message passing

Numerical Results



- Performance with respect to the location of the cell
- $\alpha = 0.5$, SNR = 9 dB
- Performance does not vary as long as the cell is not at the edge of the network
- Loss is due to absence of diversity and energy

Conclusions

- Distributed decoding of planar cellular array
- Algorithms with local processing and message passing
- Numerically observed near optimal performance
- Methods examples of BP algorithm working in graphs with loops
- Future work:
  - Integrating the iterative method with synchronization, channel estimation, coded signals