Message passing for integrating and assessing renewable generation in a redundant power grid

Lenka Zdeborová (Los Alamos Natl. Lab.)

in collaboration with
Scott Backhaus (LANL)
Misha Chertkov (LANL)

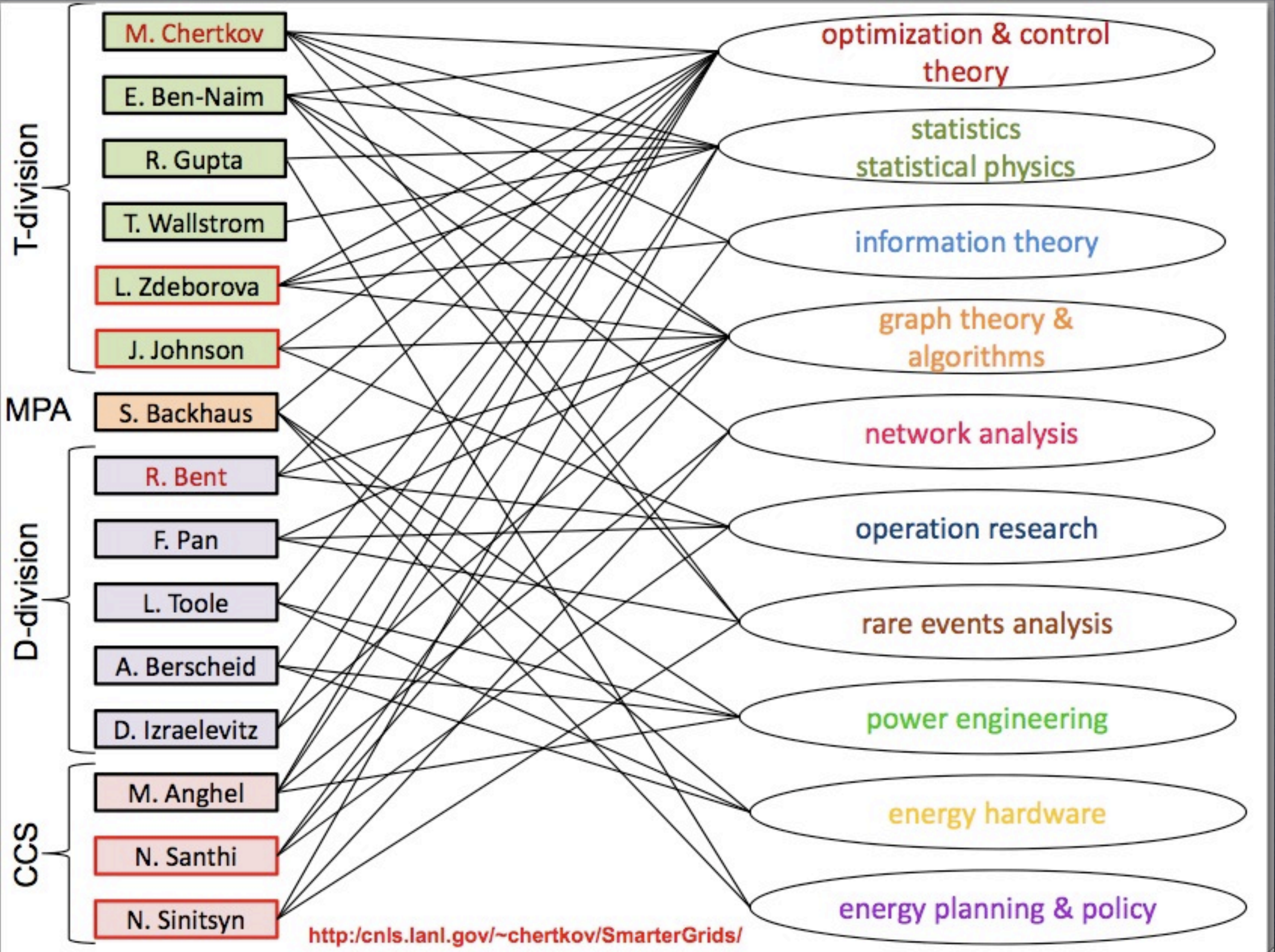
Los Alamos
NATIONAL LABORATORY
EST. 1943

LDRD project 2010 - 2012

Optimization & Control Theory for Smart Grids

http://cnls.lanl.gov/~chertkov/SmarterGrids/
(or google "Chertkov" and follow "smart grid" link)

Information science foundations
for the Smart Grid



T-division

- M. Chertkov
- E. Ben-Naim
- R. Gupta
- T. Wallstrom
- L. Zdeborova
- J. Johnson

MPA

- S. Backhaus

D-division

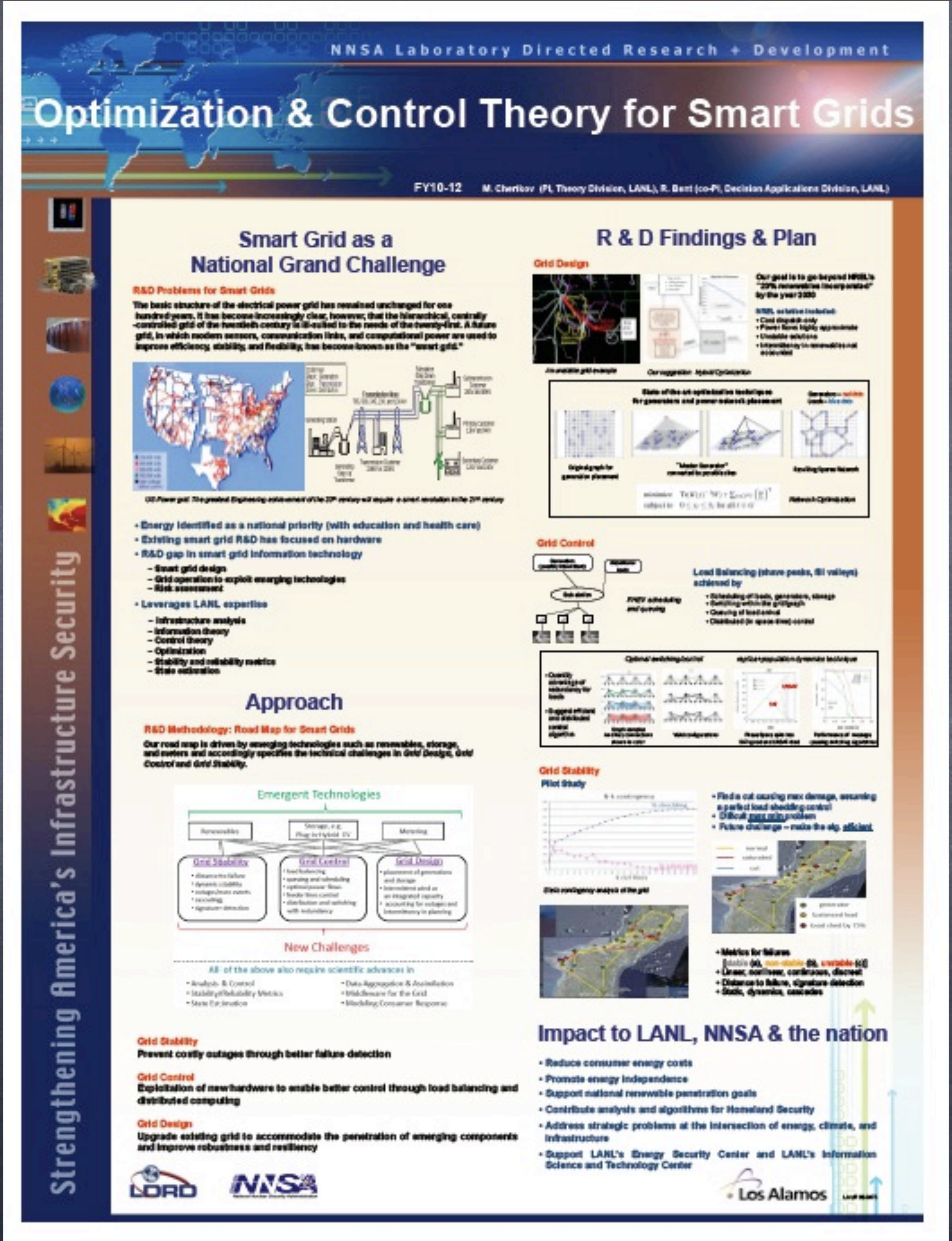
- R. Bent
- F. Pan
- L. Toole
- A. Berscheid
- D. Izraelevitz

CCS

- M. Anghel
- N. Santhi
- N. Sinitsyn

- optimization & control theory
- statistics statistical physics
- information theory
- graph theory & algorithms
- network analysis
- operation research
- rare events analysis
- power engineering
- energy hardware
- energy planning & policy

http:/cnls.lanl.gov/~chertkov/SmarterGrids/



NNSA Laboratory Directed Research + Development

Optimization & Control Theory for Smart Grids

FY10-12 M. Chertkov (PI, Theory Division, LANL), R. Bent (co-PI, Decision Applications Division, LANL)

Strengthening America's Infrastructure Security

Smart Grid as a National Grand Challenge

R&D Problems for Smart Grids

The basic structure of the electrical power grid has remained unchanged for one hundred years. It has become increasingly clear, however, that the hierarchical, centrally-controlled grid of the twentieth century is ill-suited to the needs of the twenty-first. A future grid, in which modern sensors, communication links, and computational power are used to improve efficiency, stability, and flexibility, has become known as the "smart grid."

- Energy identified as a national priority (with education and health care)
- Existing smart grid R&D has focused on hardware
- R&D gap in smart grid information technology
  - Smart grid design
  - Grid operation to exploit emerging technologies
  - Risk assessment
- Leverages LANL expertise
  - Infrastructure analysis
  - Information theory
  - Control theory
  - Optimization
  - Stability and reliability metrics
  - State estimation

Approach

R&D Methodology: Road Map for Smart Grids

Our road map is driven by emerging technologies such as renewables, storage, and meters and accordingly specifies the technical challenges in *Grid Design, Grid Control* and *Grid Stability.*

Emergent Technologies

New Challenges

All of the above also require scientific advances in

Grid Stability
Prevent costly outages through better failure detection

Grid Control
Exploitation of new hardware to enable better control through load balancing and distributed computing

Grid Design
Upgrade existing grid to accommodate the penetration of emerging components and improve robustness and resiliency

R & D Findings & Plan

Grid Design

Our goal is to go beyond NREL's "20% renewables incorporated" by the year 2030

Grid Control

Load Balancing (shave peaks, fill valleys) achieved by
- Scheduling of loads, generators, storage
- Switching within the grid/graph
- Queuing of load arrival
- Distributed (in space-time) control

Grid Stability

Pilot Study

- Find a cut causing max damage, assuming a perfect load shedding control
- Difficult max min problem
- Future challenge – make the alg. efficient

- Metrics for failures
- Linear, nonlinear, continuous, discreet
- Distance to failure, signature detection
- Static, dynamics, cascades

Impact to LANL, NNSA & the nation

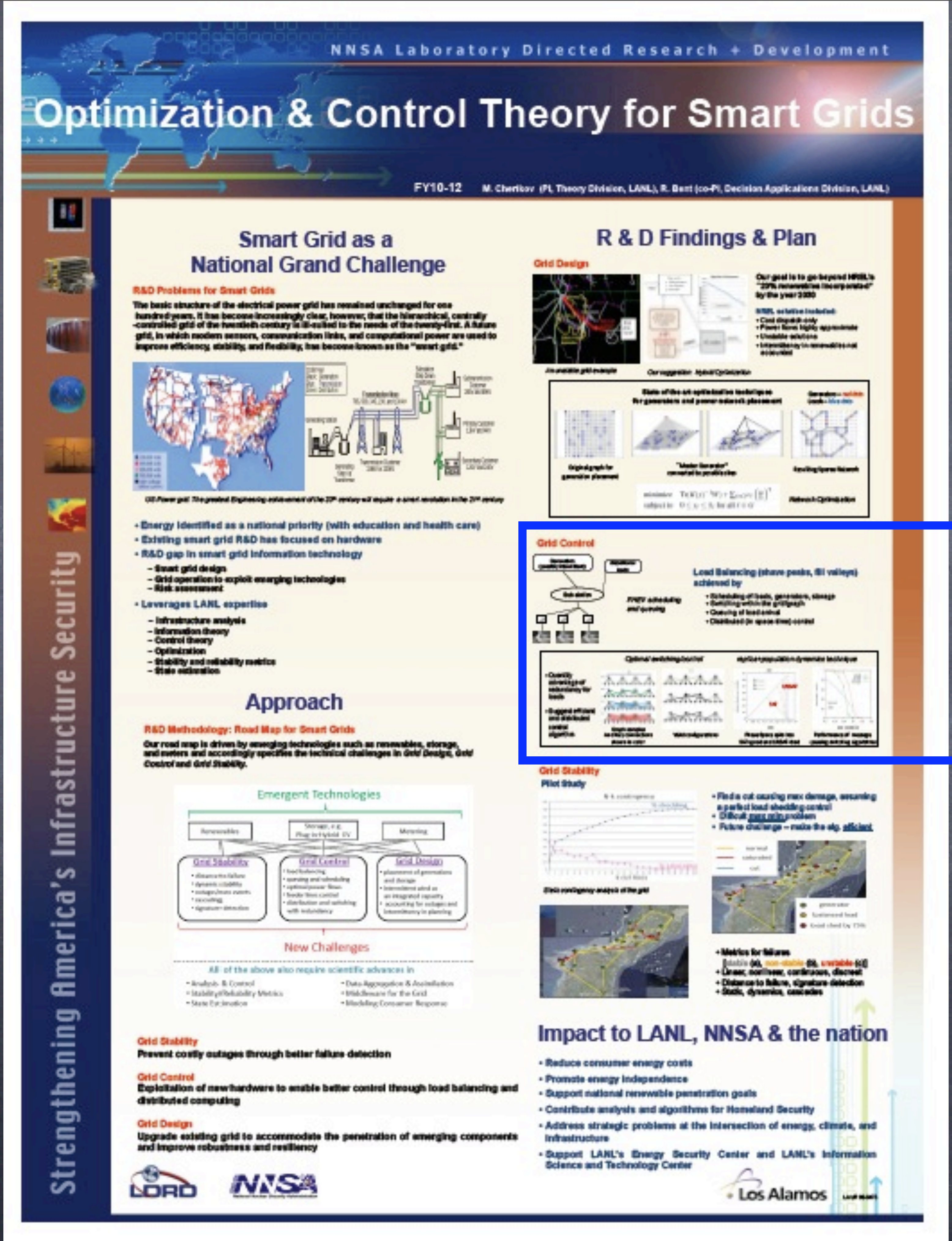
- Reduce consumer energy costs
- Promote energy independence
- Support national renewable penetration goals
- Contribute analysis and algorithms for Homeland Security
- Address strategic problems at the intersection of energy, climate, and infrastructure
- Support LANL's Energy Security Center and LANL's Information Science and Technology Center

LDRD NNSA Los Alamos

design

control

stability



NNSA Laboratory Directed Research + Development

Optimization & Control Theory for Smart Grids

FY10-12 M. Chertkov (PI, Theory Division, LANL), R. Bent (co-PI, Decision Applications Division, LANL)

Smart Grid as a National Grand Challenge

R&D Problems for Smart Grids

The basic structure of the electrical power grid has remained unchanged for one hundred years. It has become increasingly clear, however, that the hierarchical, centrally-controlled grid of the twentieth century is ill-suited to the needs of the twenty-first. A future grid, in which modern sensors, communication links, and computational power are used to improve efficiency, stability, and flexibility, has become known as the "smart grid."

- Energy identified as a national priority (with education and health care)
- Existing smart grid R&D has focused on hardware
- R&D gap in smart grid information technology
  - Smart grid design
  - Grid operation to exploit emerging technologies
  - Risk assessment
- Leverages LANL expertise
  - Infrastructure analysis
  - Information theory
  - Control theory
  - Optimization
  - Stability and reliability metrics
  - State estimation

Approach

R&D Methodology: Road Map for Smart Grids

Our road map is driven by emerging technologies such as renewables, storage, and meters and accordingly specifies the technical challenges in *Grid Design*, *Grid Control* and *Grid Stability*.

Grid Stability
Prevent costly outages through better failure detection

Grid Control
Exploitation of new hardware to enable better control through load balancing and distributed computing

Grid Design
Upgrade existing grid to accommodate the penetration of emerging components and improve robustness and resiliency

R & D Findings & Plan

Grid Design

Our goal is to go beyond NREL's "20% renewables incorporated" by the year 2030

Grid Control

Load Balancing (shave peaks, fill valleys) achieved by
- Scheduling of loads, generators, storage
- Switching within the grid/graph
- Queuing of load arrival
- Distributed (in space-time) control

Grid Stability
Pilot Study
- Find a cut causing max damage, assuming a perfect load shedding control
- Difficult max min problem
- Future challenge – make the alg. efficient

- Metrics for failures
- Linear, nonlinear, continuous, discrete
- Distance to failure, signature detection
- Static, dynamics, cascades

Impact to LANL, NNSA & the nation

- Reduce consumer energy costs
- Promote energy independence
- Support national renewable penetration goals
- Contribute analysis and algorithms for Homeland Security
- Address strategic problems at the intersection of energy, climate, and infrastructure
- Support LANL's Energy Security Center and LANL's Information Science and Technology Center

LDRD NNSA Los Alamos

design

control

stability

Assessing renewable generation

- Intermittent renewable-sources-based generation destabilizes the grid.
  How to improve grid control schemes?
- If renewable sources produce power x, how much can be saved on the level of the firm generation?

Improvement trough redundancy

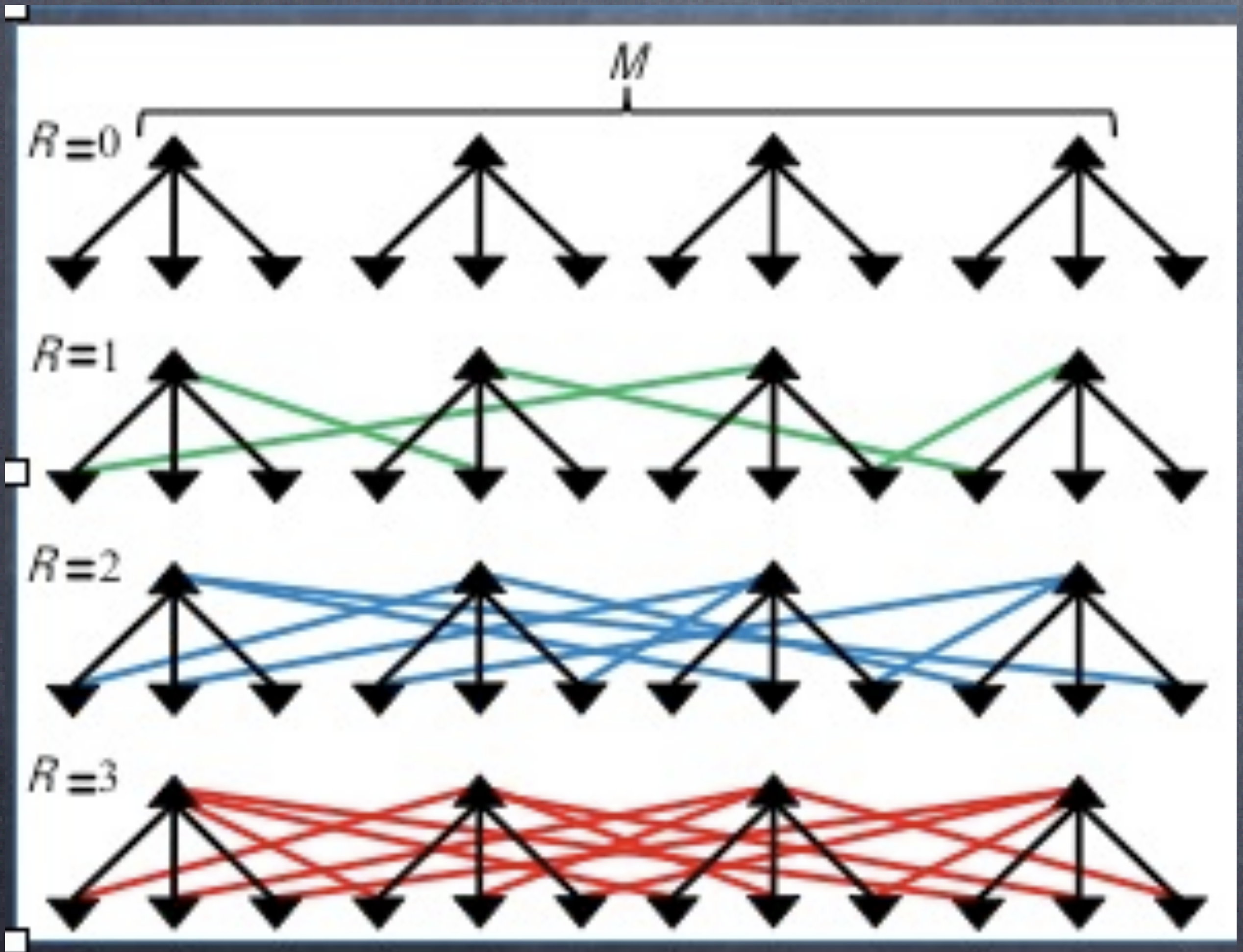
- Build additional power lines and introduce switches (on / off = power line connected to / disconnected from the network)
- Redundancy must help to optimize both stability and efficiency - larger space to optimize over. But how much does redundancy help?

Methodology:

- Approach A: Take a realistic power grid model and several computers and run simulations. Do again when details change ...
- Approach B (probabilistic + physicist way): Study behavior of simple abstract models that facilitate the analysis, and look for universal properties, dependencies and behavior.
  Model choice criteria (in physics): The simpler and richer the better.

Our power grid model

- M producers, N=DM consumers
- Out of every D consumers R have auxiliary lines



Consumer “i” consumes x_i

produces z_i

Producer “a” capability y_a

M=4, N=12, D=3

Setting

Switch variables for power lines:

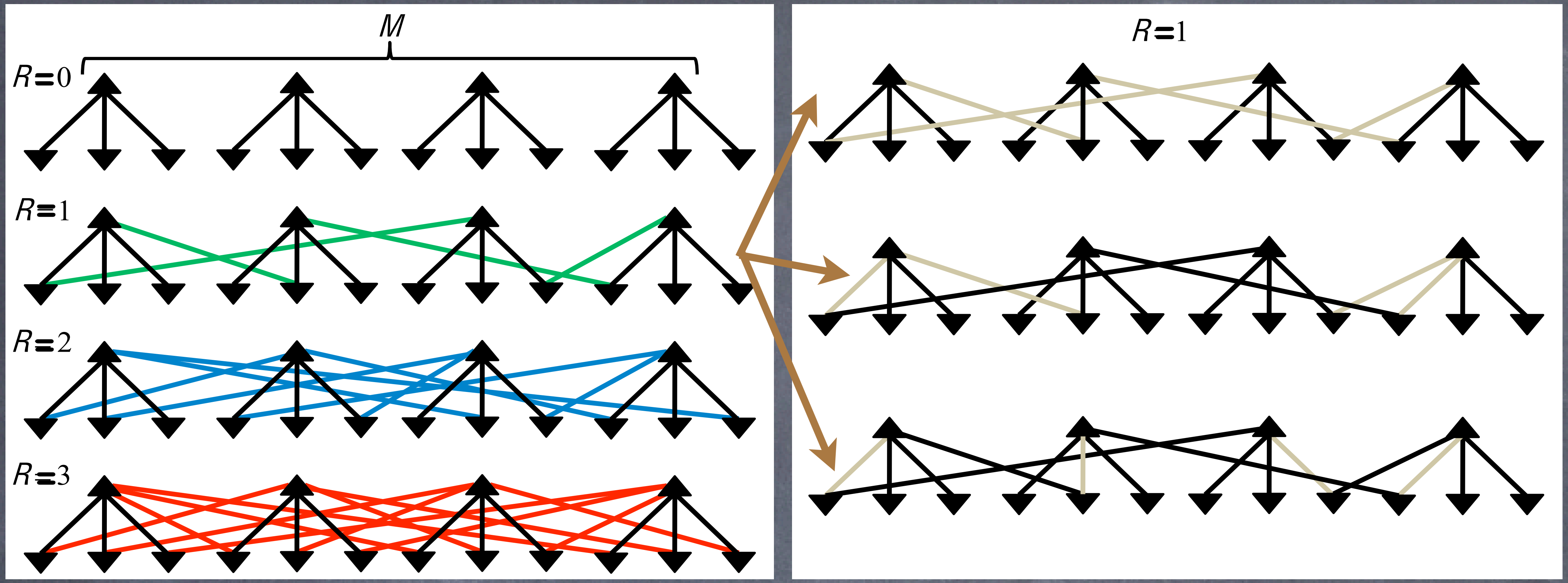
$$\sigma_{ia} = 0 / \sigma_{ia} = 1$$

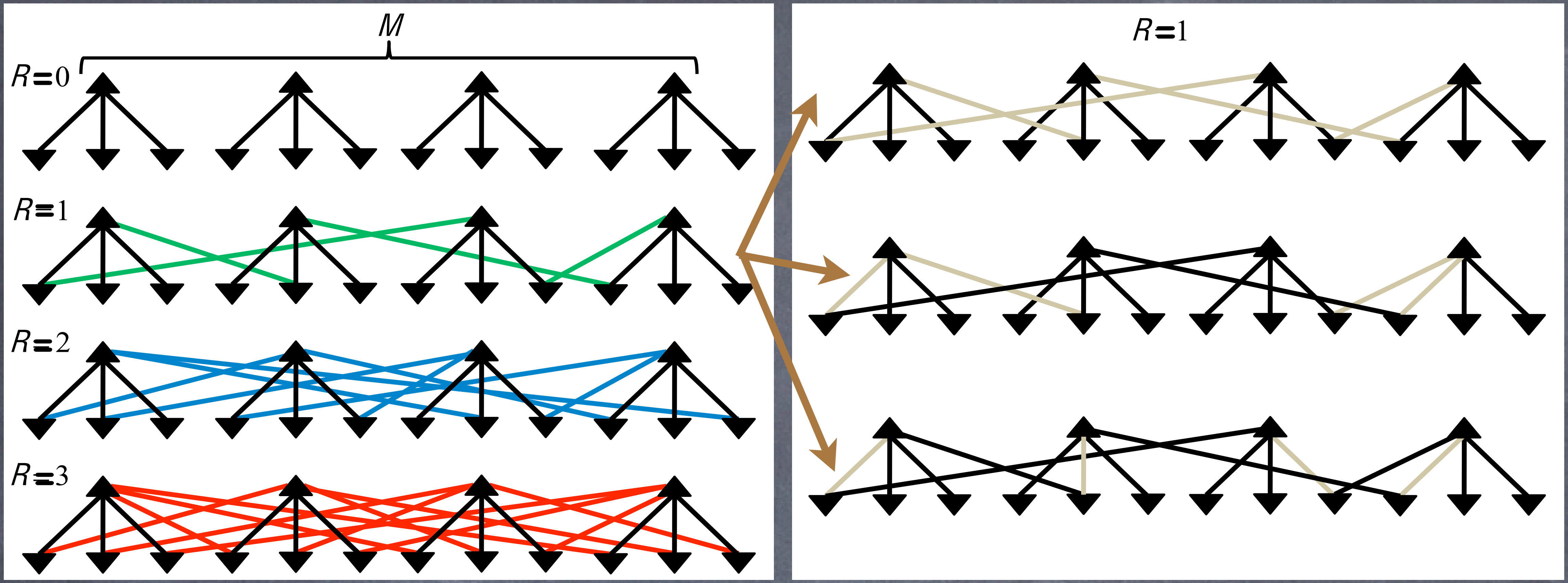
Each consumer has exactly one line on.

Constraints

$$\sum_{a \in \partial i} \sigma_{ia} = 1$$ Every consumer one connection

$$\sum_{i \in \partial a} \sigma_{ia}(x_i - z_i) \le y_a$$ Producers not overloaded


M
$R=0$
$R=1$
$R=2$
$R=3$
$R=1$



Note that the final topology is a tree, hence the Kirchhoff's laws satisfied.

However, general power flow optimum cannot be worse than the tree case!

Questions

Given $\{x_i\}, \{z_i\}, \{y_a\}$ can all the constraints be simultaneously satisfied? (Nobody overloaded.)

If yes, then how many satisfying configurations of the switches are there? Is it easy to find one?

Answer: via Belief Propagation

How does BP work?

Prob. that line “ia” is in state σ_{ia} conditioned

$\psi^{a\to i}_{\sigma_{ia}}$ constraint on “i” is missing

$\chi^{i\to a}_{\sigma_{ia}}$ constraint on “a” is missing

$$\Rightarrow$$

Iterative “message passing” scheme

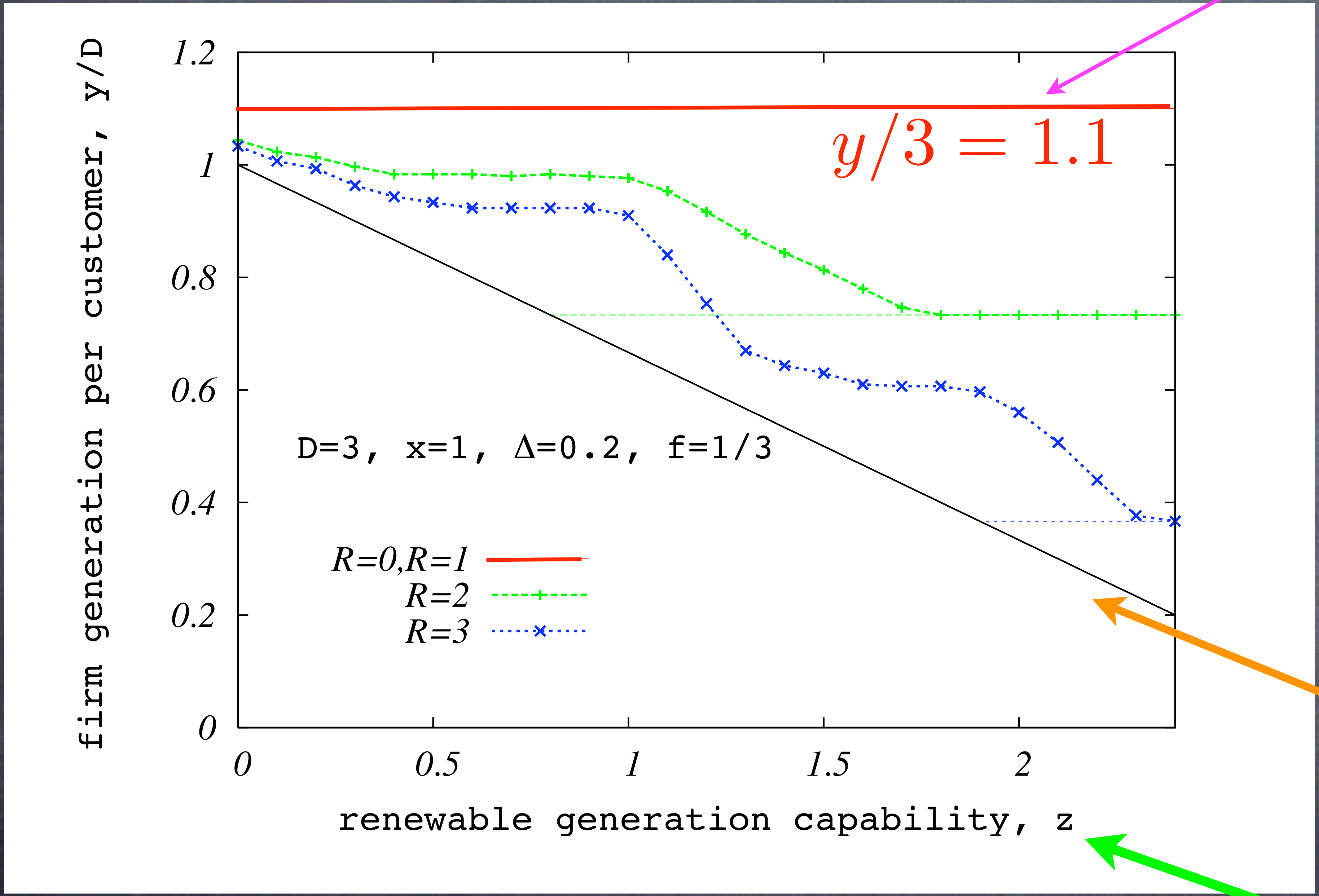
Belief Propagation

- Distributed approximative way of:
- (a) computing the probability that a given switch is on or off.
- (b) estimating number of valid (not overloading) configurations.

- For large number of customers and producers (thermodynamic limit) - average analysis solvable.

Example n. 1

somebody must serve D-R+1 fully demanding consumers



$y/3 = 1.1$

producers

$$M \to \infty$$

consumers

$$N = 3M$$

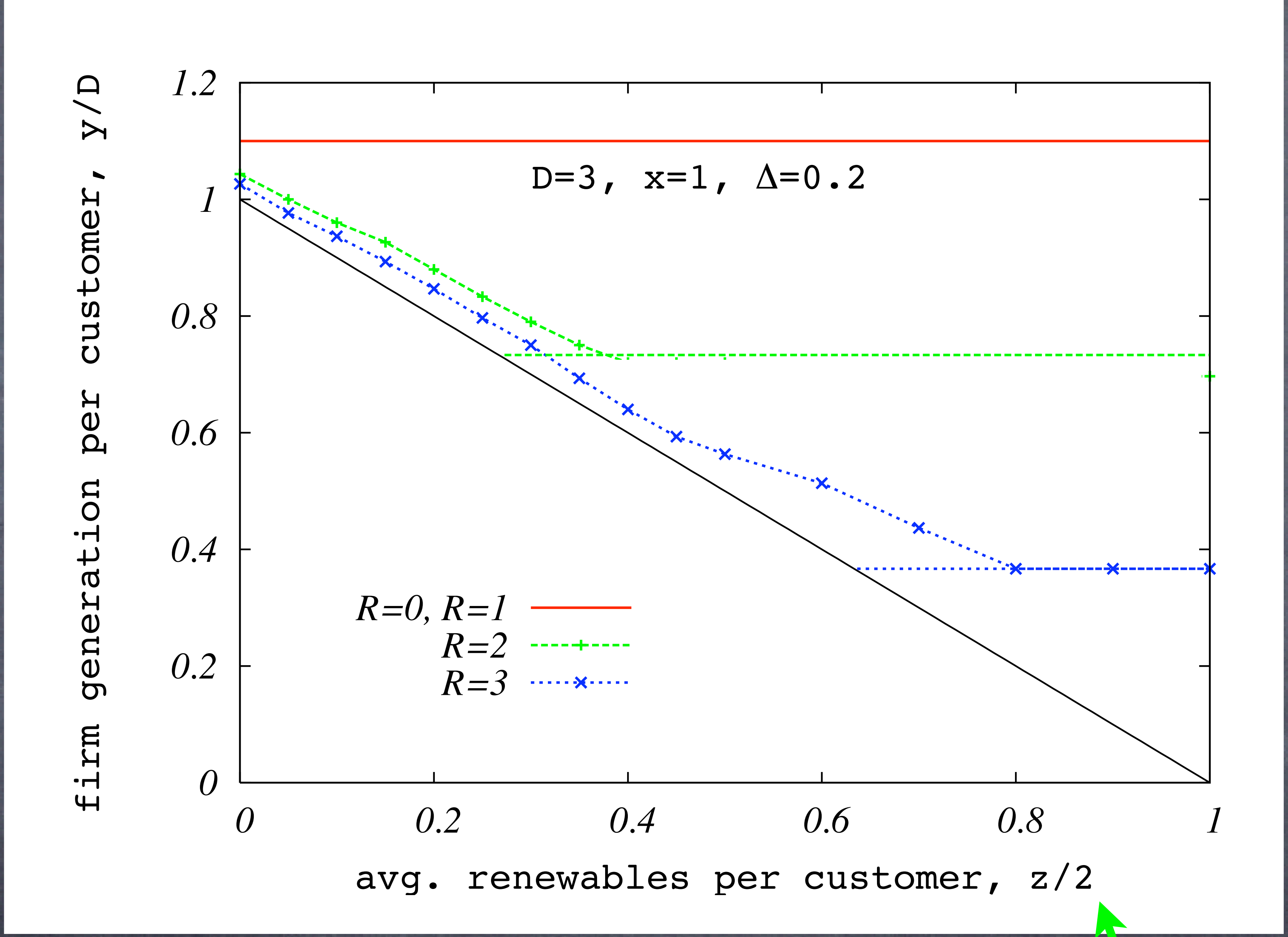
generation > consumption

$$y/3 = 1 - z/3$$

Fraction 1/3 of consumers produce amount z

Every consumer consumes random number in (0.9,1.1)

Example n. 2

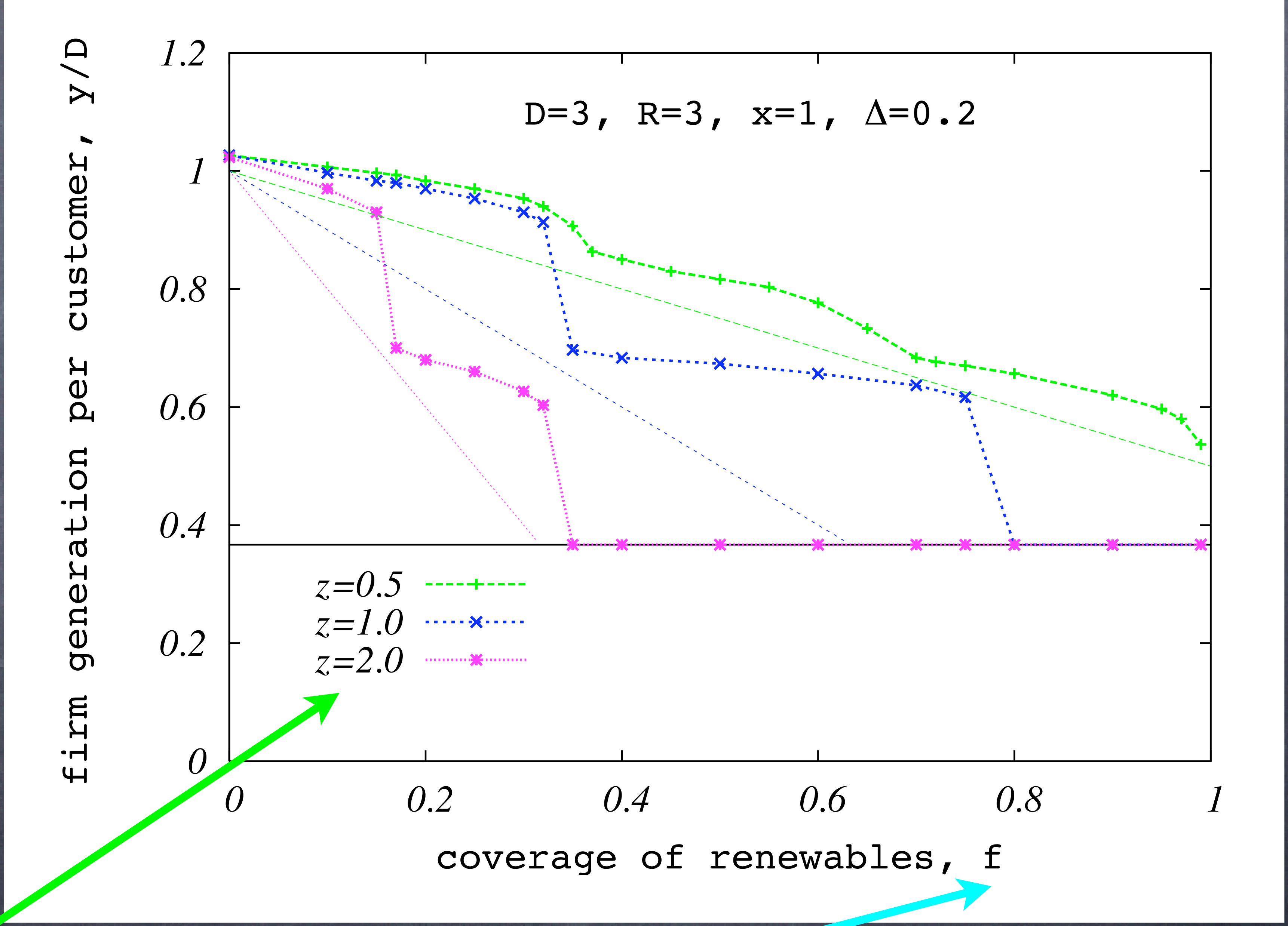


Every consumer produced a random number between (0,z)

Example n. 3

produced > consumed

$$y/3 > 1 - fz$$



amount z is produced by fraction f of consumers

Conclusions and Perspectives

- Existence of SAT/UNSAT phase transition and regimes where higher penetration useful or futile.
- Redundancy + switches help renewable integrations. Belief propagation a tool of analysis but also distributed control algorithm.
- In physics: Study of toy models (and phase transitions) leads to qualitative understanding. Is that true also for the Smart Grid?
- Combine belief propagation with DC or AC power flow rules on a non-tree topology.

References

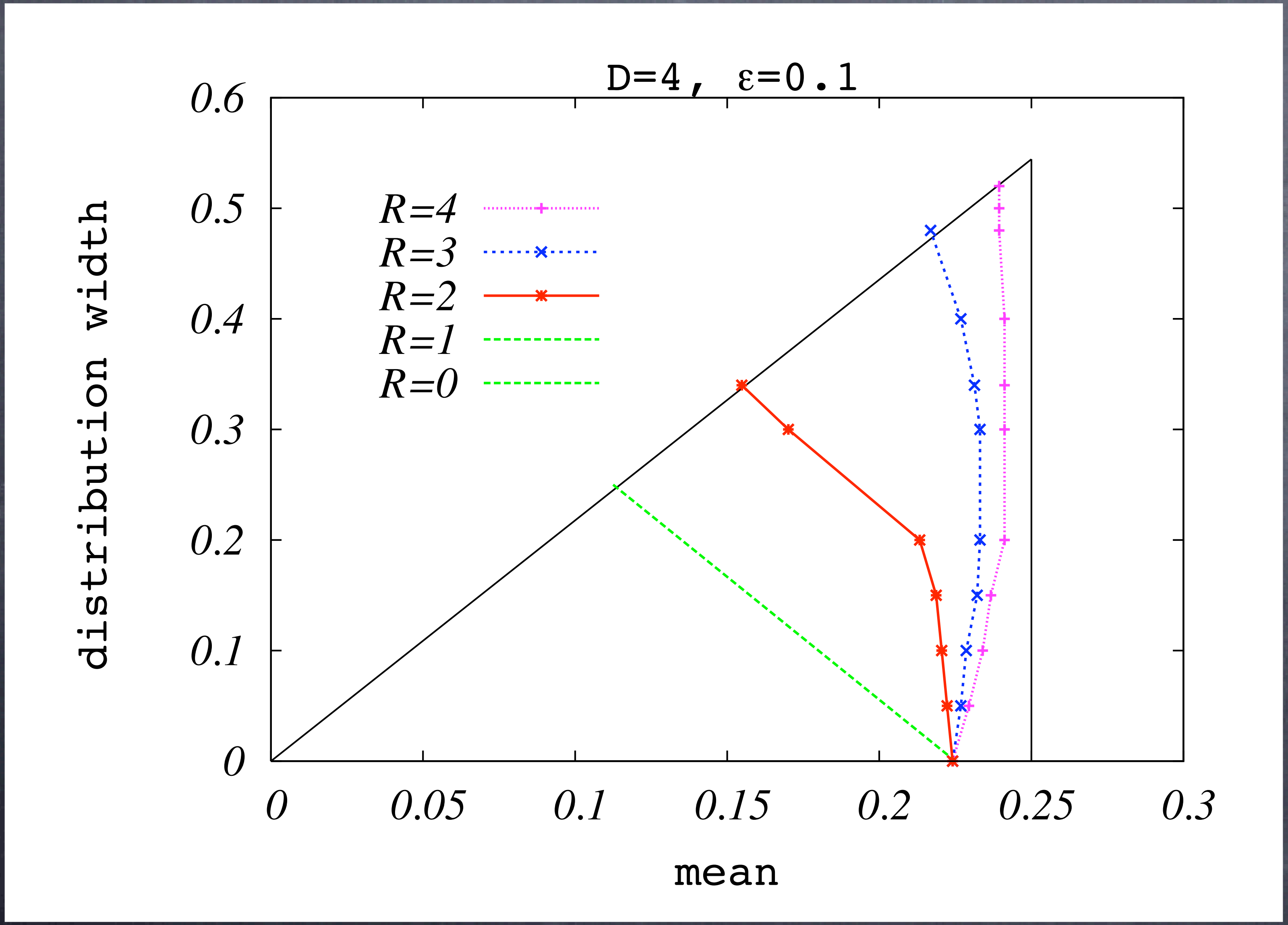
- L. Zdeborová, A. Decelle, M. Chertkov; Phys. Rev. E 90, 046112 (2009).
- L. Zdeborová, S. Backhaus, M. Chertkov; in HICSS 43.

Belief Propagation Equations

$$\begin{aligned}
\chi_1^{i\to a} &= \frac{1}{Z^{i\to a}} \prod_{b\in\partial i\setminus a} \psi_0^{b\to i} \\
\chi_0^{i\to a} &= \frac{1}{Z^{i\to a}} \sum_{b\in\partial i\setminus a} \psi_1^{b\to i} \prod_{c\in\partial i\setminus a,b} \psi_0^{c\to i} \\
\psi_1^{a\to i} &= \frac{1}{Z^{a\to i}} \sum_{\sigma_{\partial a\setminus ia}} \theta(y_a - w_i - \sum_{j\in\partial a\setminus i} \sigma_{ja} w_j) \prod_{j\in\partial a\setminus i} \chi_{\sigma_{ja}}^{j\to a} \\
\psi_0^{a\to i} &= \frac{1}{Z^{a\to i}} \sum_{\sigma_{\partial a\setminus ia}} \theta(y_a - \sum_{j\in\partial a\setminus i} \sigma_{ja} w_j) \prod_{j\in\partial a\setminus i} \chi_{\sigma_{ja}}^{j\to a}
\end{aligned}$$

Example n. 0

Everybody consuming random number between (mean-width/2) and (mean+width/2), epsilon - fraction of consumers with no demand.



$$y_a = 1 \qquad \forall a$$

$$z_i = 0 \qquad \forall i$$

Asymptotic, but also algorithmic solution