Network Coding: An Overview

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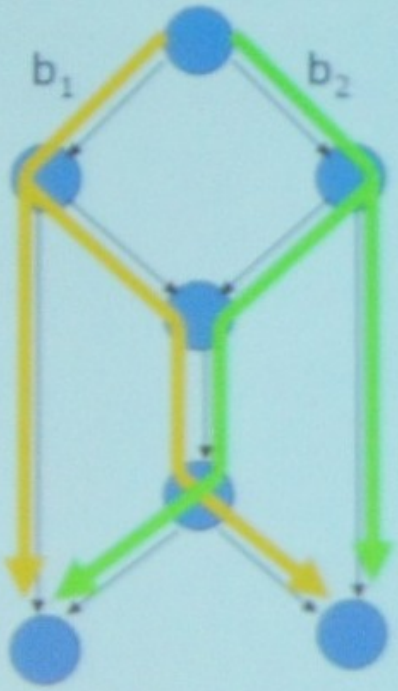
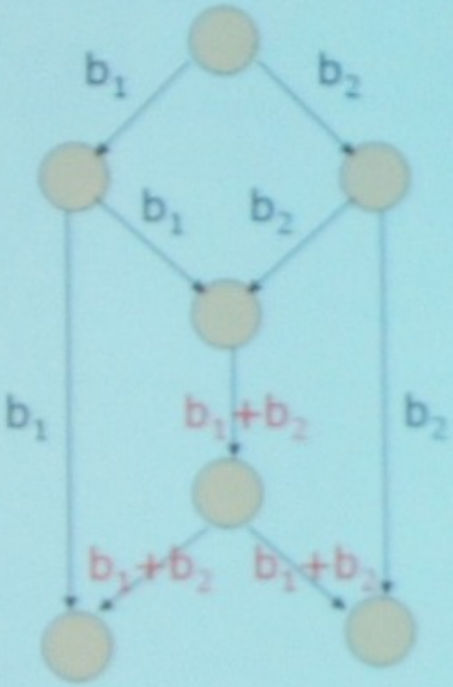
Outline

- Introduction and Examples
- Single-Source Network Coding
- Recent Developments
- Concluding Remarks

A Network Coding Example

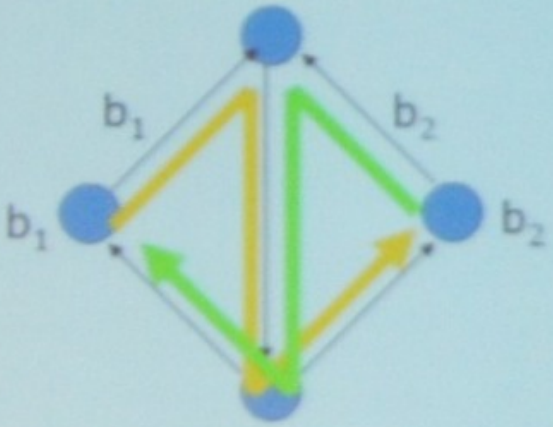
The Butterfly Network

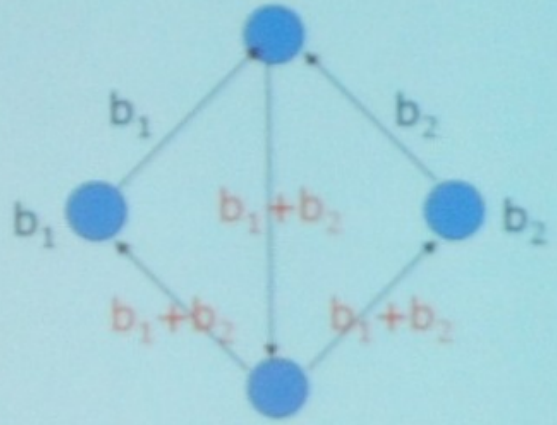

b_1
b_2


b_1
b_2
b_1
b_2
b_1
b_1+b_2
b_2
b_1+b_2
b_1+b_2

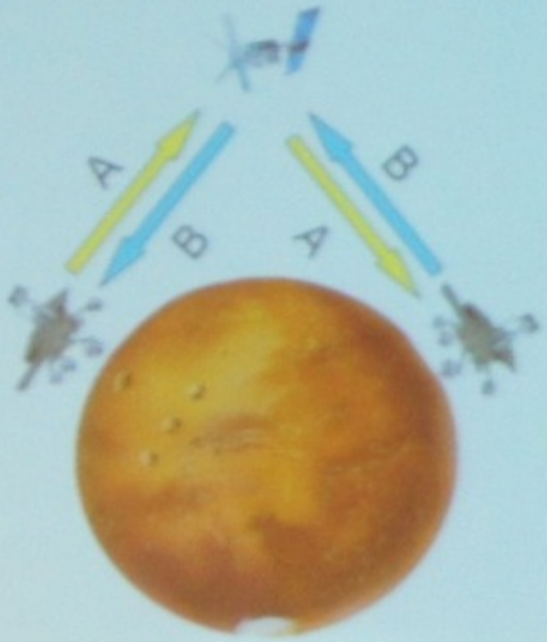
A Network Coding Example

with Two Sources


b1
b2
b1
b2


b1
b2
b1
b1+b2
b2
b1+b2
b1+b2

Satellite/Wireless Application



Satellite/Wireless Application

- NASA project proposal (2008)

Two Themes of Network Coding

- When there is 1 source to be multicast in a network, store-and-forward may fail to optimize bandwidth
- When there are 2 or more independent sources to be transmitted in a network (even for unicast), store-and-forward may fail to optimize bandwidth

Single Source vs. Multiple Sources

- Single-source network coding
  - Explicit characterization by Max-flow Min-Cut Theorem for information flow (graph-theoretic)
  - Numerous applications are emerging
- Multi-source network coding
  - Implicit characterization in terms of achievable entropy functions (Yan, Yeung, Zhang, 2007)
  - Still at the stage of theoretical research

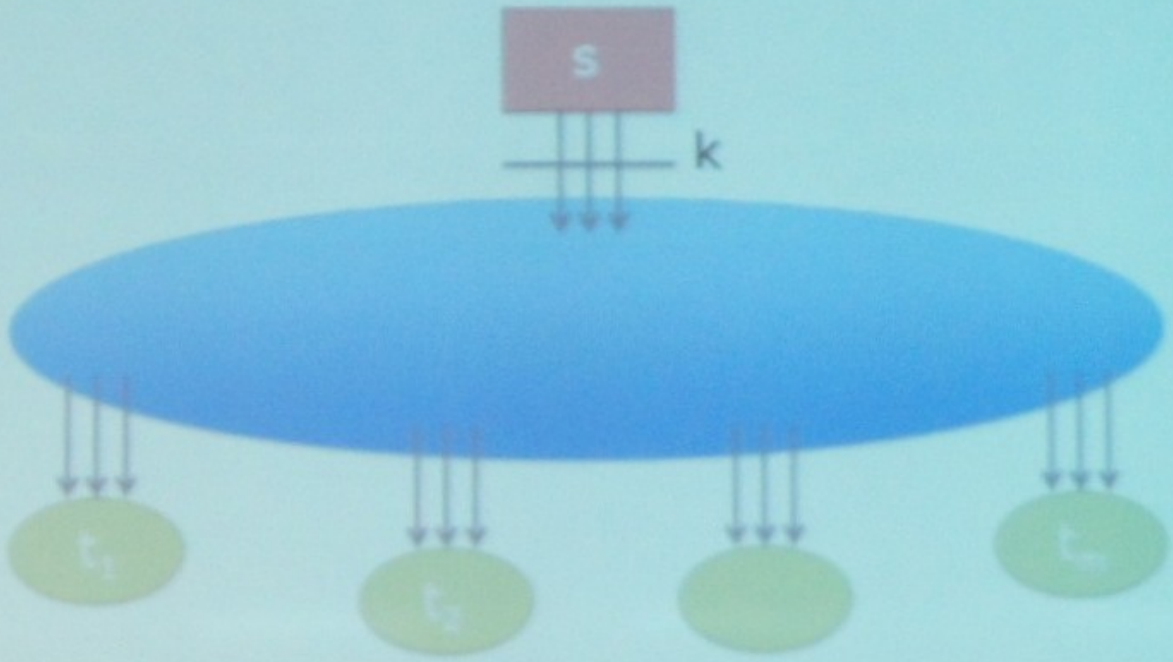
Single-Source Network Coding

Max-Flow Min-Cut: Commodity Flow

- Elias, Feinstein, and Shannon (1956)
- Ford and Fulkerson (1956)

Maximum flow = Minimum cut

Max-Flow Min-Cut: Information Flow



Max-Flow Min-Cut: Information Flow

- Ahlswede, Cai, Li, and Yeung (1998/2000)

Rate = k is achievable
by means of network coding

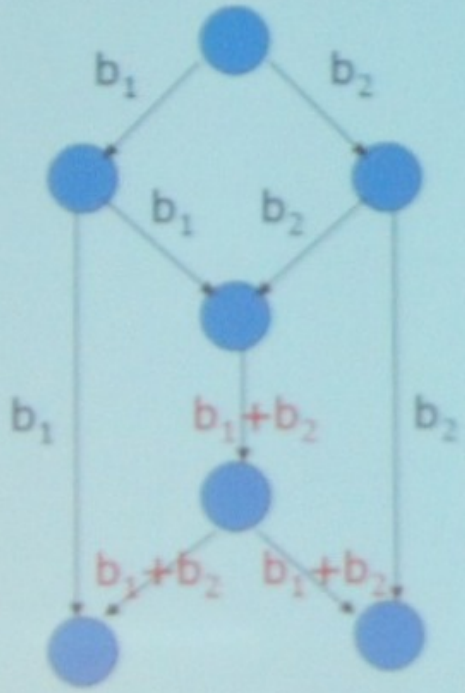
iff

$\text{maxflow}(s,t_i) \geq k$
for $i = 1, 2, \ldots, m$

Linear Network Coding

- Linear network coding suffices
  - Vector space approach: Li, Yeung and Cai (1999/2003)
  - Matrix approach: Koetter and Medard (2002/03)
- A sufficiently large finite field chosen as the base field

Example: Butterfly Network



k = 2

F = GF(2)

Random Linear Network Coding

- Ho, Koetter, Medard, Karger, Effros (2003/06)
- Random coefficients for linear network coding
- Can decode w.p.≈ 1 provided that the base field is sufficiently large
- Enables network coding in unknown network topologies
- Subspace coding: Koetter and Kschischang (2007/08)

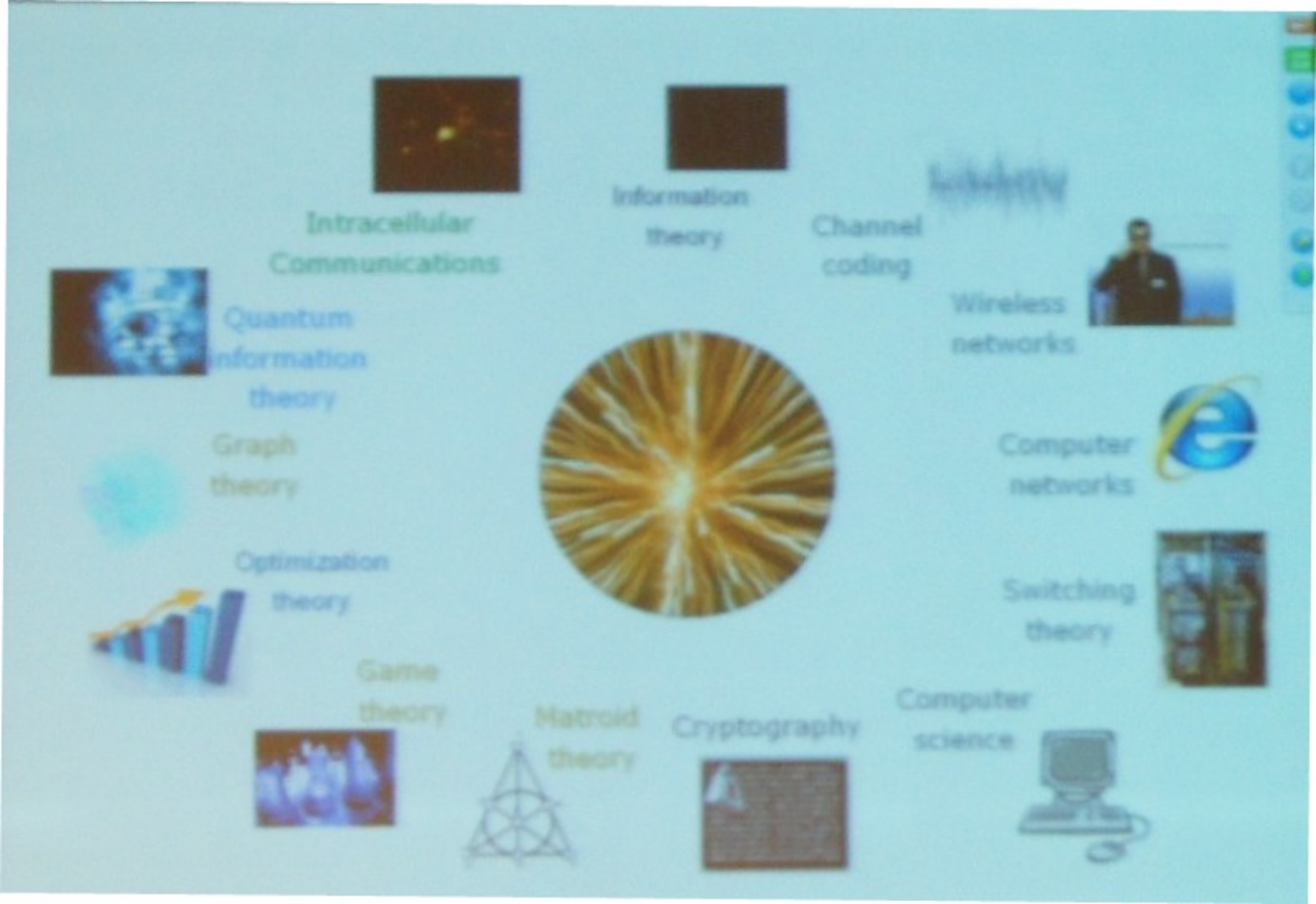
Recent Developments

Publications & Conferences

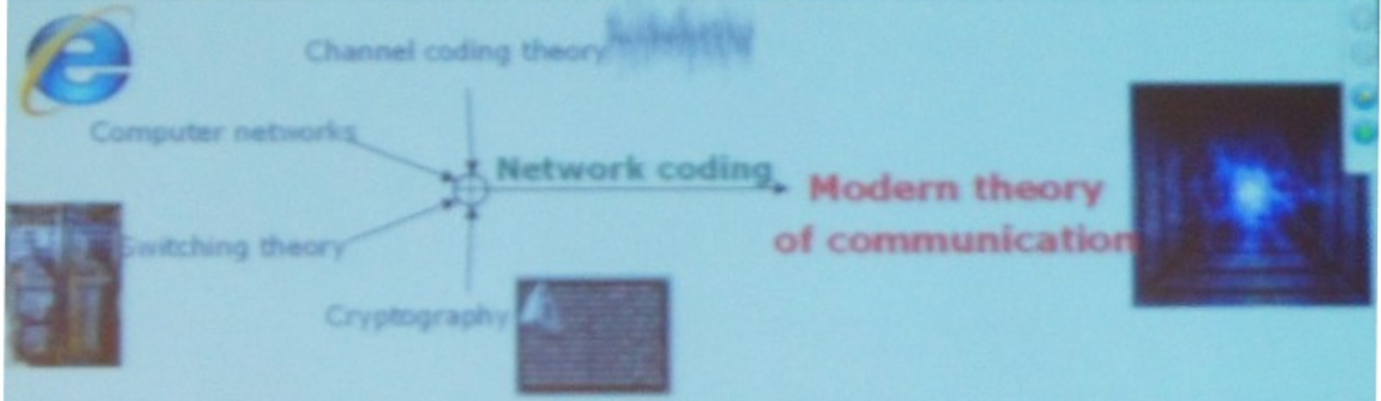
- > 2,000 citations (Google Scholar)
- > 600 citations for past 12 months
- 4 books
- ~ 8 special journal issues related to NC
- ~ 8 journal & conference paper awards
- 2 annual conferences: NetCod (since 2005), WiNC (since 2008)

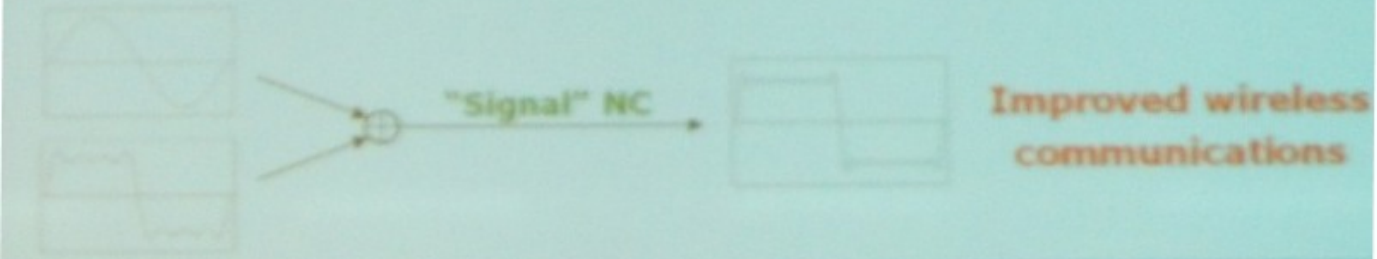
Major Research Projects

- USA: IT-MANET, CB-MANET (DARPA)
- Europe: N-CRAVE (European Commission)
- Hong Kong: Institute of Network Coding (HK Government)
  - Funded for 8 years
  - Conduct research in different aspects of NC
  - Train postdocs and PhDs
  - Protyping and implemention


Intracellular
Communications
Information
theory
Channel
coding
Wireless
networks
Quantum
information
theory
Graph
theory
Computer
networks
Optimization
theory
Switching
theory
Game
theory
Matroid
theory
Cryptography
Computer
science

Network Coding Roadmap





Network Error Correction

- Cai and Yeung (2002/2006)
- Use network coding for error correction
- Generalizes classical algebraic coding to networks:
  - Bounds: Hamming, Gilbert-Varshamov, Singleton
  - Network Singleton bound achievable
- Can correct random errors and neutralize malicious nodes

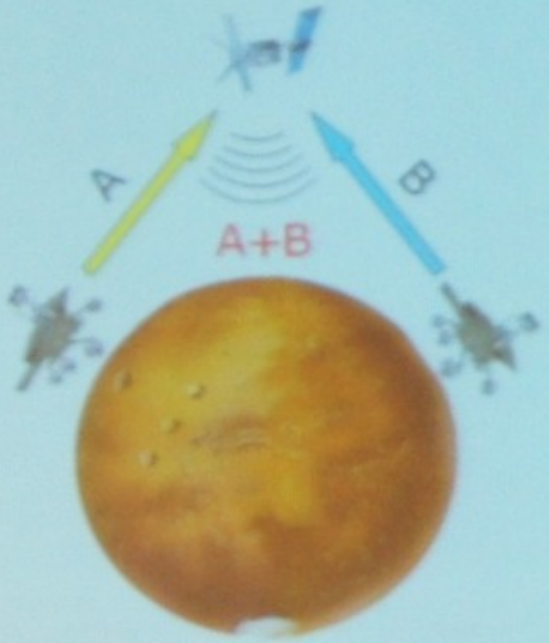
Secure Network Coding

- Cai and Yeung (2002/2007)
- Uses network coding against wiretapping
- Subsumes secret sharing in cryptography
- Information-theoretic bounds achievable for some important special cases

Signal-Level Network Coding

- Allows wireless signals to add up physically
- Can further improve the efficiency of wireless network coding
- Physical-Layer NC: Zhang, Liew, and Lam (2006)
- Analog NC: Katti, Gollakota, and Katabi (2007)

Illustration of PNC/ANC



PNC

- Estimates A+B

ANC

- Amplify and forward

Concluding Remarks

- For decades, network communication has been based on point-to-point solutions + routing
- Network coding fundamentally changes the concept of network communications
- Can apply to any communication system that can be modeled as a network
- Researchers are investigating and re-investigating different aspects of network communications
- A new information infrastructure for transmission, storage, security, etc, is underway
- Network coding will continue to interact with different fields of research

Thank you