Information Theory for Mobile Ad-Hoc Networks (ITMANET)

Thrust I

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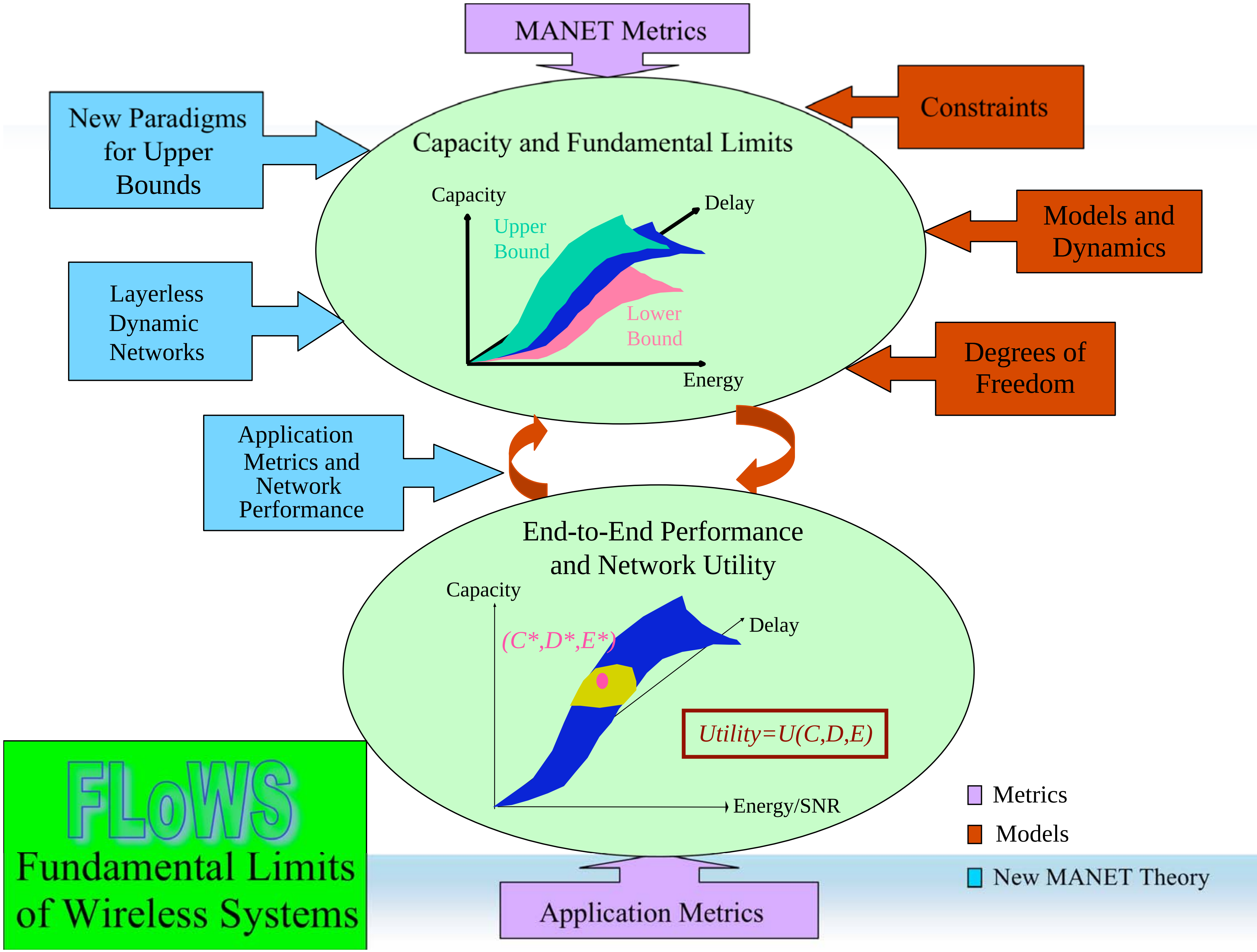
(and everyone!)


MANET Metrics
New Paradigms for Upper Bounds
Constraints
Capacity and Fundamental Limits
Capacity
Delay
Upper Bound
Lower Bound
Energy
Models and Dynamics
Layerless Dynamic Networks
Degrees of Freedom
Application Metrics and Network Performance
End-to-End Performance and Network Utility
Capacity
(C*,D*,E*)
Delay
Utility=U(C,D,E)
Energy/SNR
Metrics
Models
New MANET Theory
FLoWS
Fundamental Limits of Wireless Systems
Application Metrics

Goals

- Characterize the performance potential of ITMANETs.
- Objectivity: Upper bounds provide an objective assessment of:
  - How well current schemes are doing
  - Where future efforts are best spent
- Utility: To be useful, upper bounds must be
  - Concrete
  - Computable
  - Helpful
  - Practical
- Generality: We seek general upper bounds to apply to
  - Arbitrary networks
  - Arbitrary demands
- Reality: Traditional assumptions are a poor match for ITMANETs.- to develop realistic upper bounds, we must master
  - Delay
  - Variability
  - Non-ergodicity

Final goal

- Final objective: Network SPICE , "SPINE"

(Simulation Program with Integrated Network Emphasis)

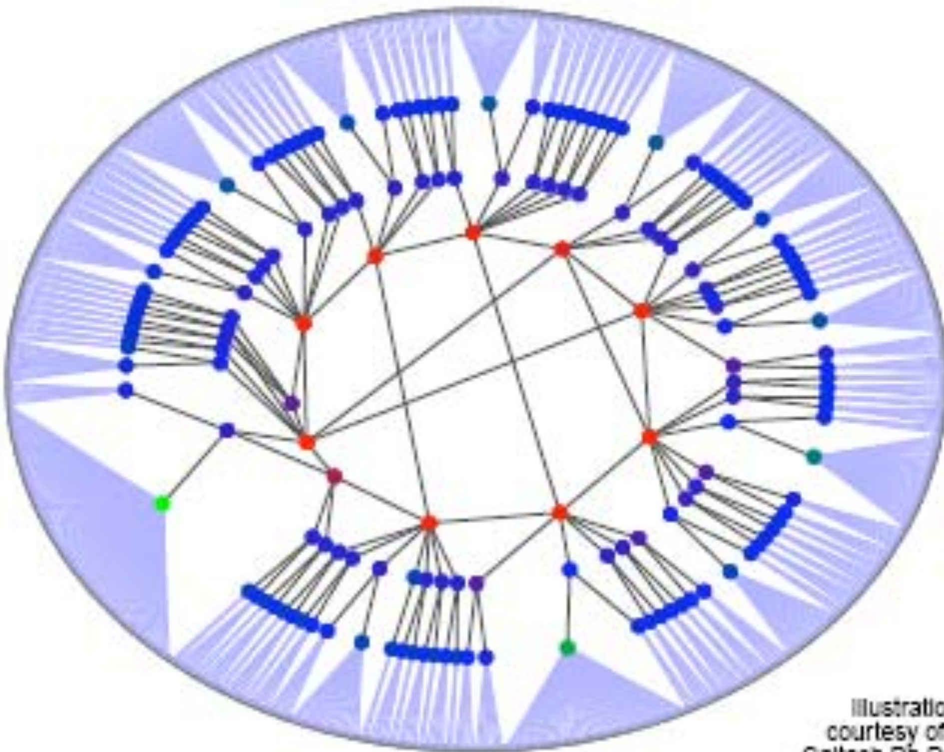


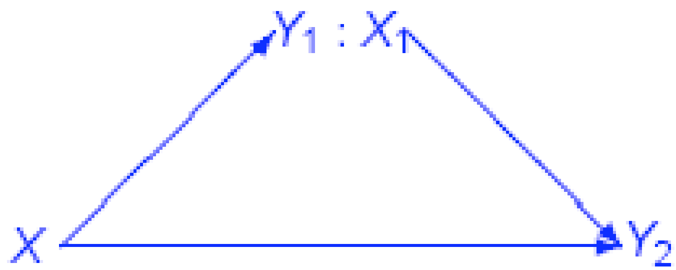
Illustration
courtesy of Lun Li
Caltech Ph.D., 2007

Traditional approaches – tools and results

- Tools:
  - Fano's Inequality
    - The information that we want to estimate must be determined by our evidence.
  - Min-cut Max-flow Theorem
    - Information flow through a network is limited by the tightest bottleneck on the best routes.
- Results:
  - Small systems (e.g., relay channel)
  - Asymptotic results under assumptions re: structure and size (e.g., scaling laws)

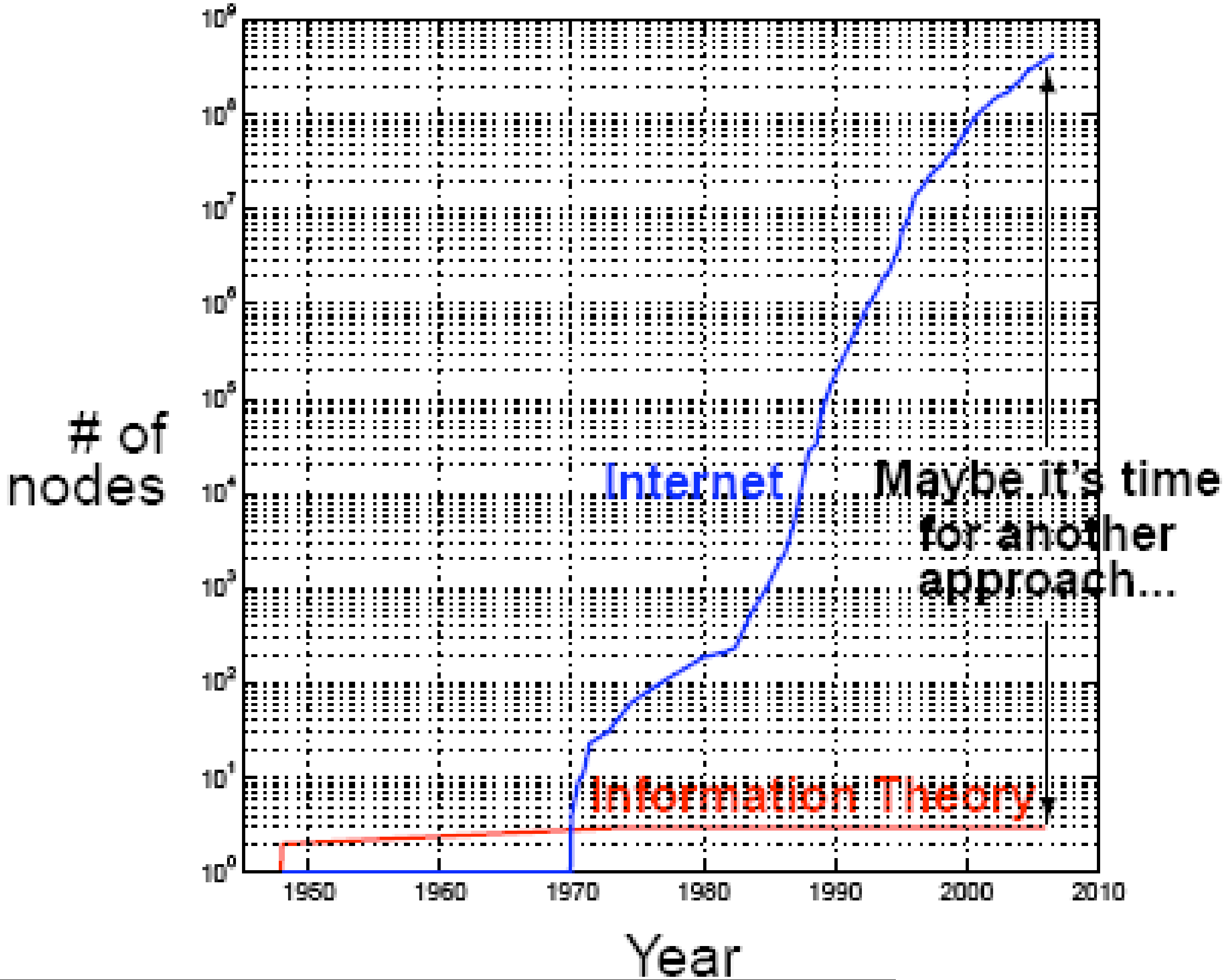
Traditional approaches - results

- A simple 3-node network (Kramer et al.)



$$
\begin{aligned}
R_0 &\leq \min\{I(T;Y_1|X_1), I(T,X_1;Y_2)\} \\
R_0 + R_1 &\leq I(X;Y_1|X_1) \\
R_0 + R_2 &\leq \min\{I(T,U,X_1;Y_2), I(X,X_1;Y_2)\} \\
R_0 + R_1 + R_2 &\leq I(T;Y_1|X_1) + I(X;Y_1|T,U,X_1) + I(U;Y_2|T,X_1) \\
R_0 + R_1 + R_2 &\leq I(T;Y_1|T,U,X_1) + I(T,U,X_1;Y_2) \\
R_0 + R_1 + R_2 &\leq I(T;Y_1,Y_2|X_1)
\end{aligned}
$$

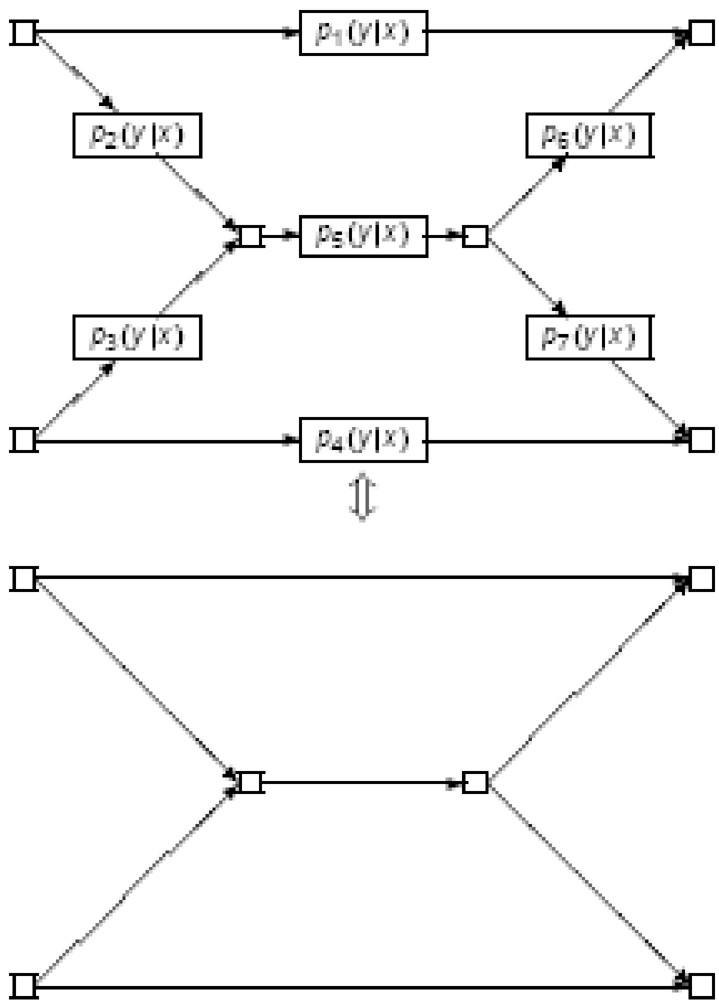
Traditional approaches - results



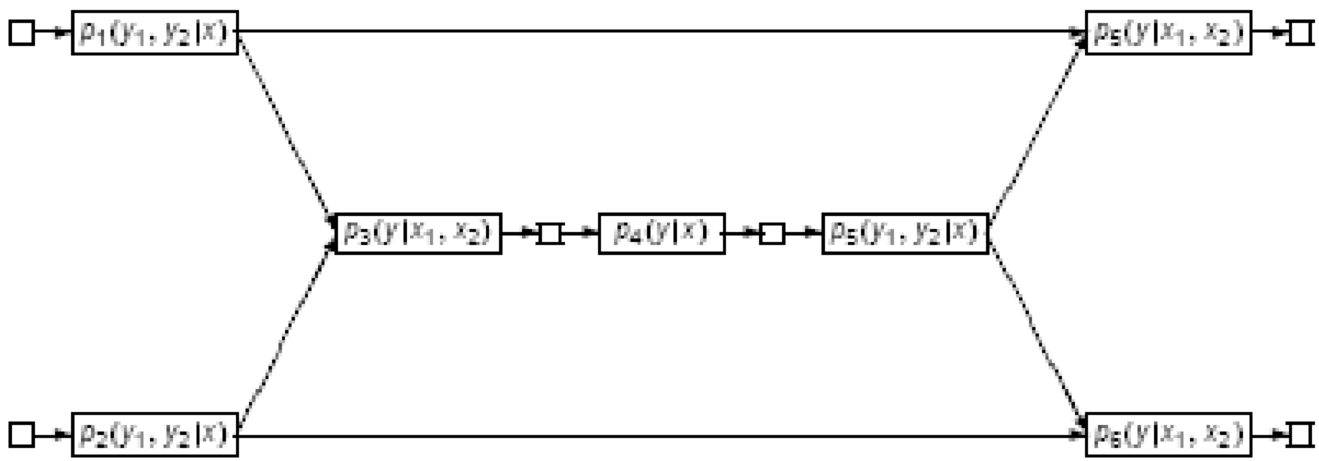
New approaches – overview and progress

- Network equivalences
- Code type equivalences
- Conflict graph presentation
- Hierarchical analyses

Network equivalences – original results



Network equivalences - progress



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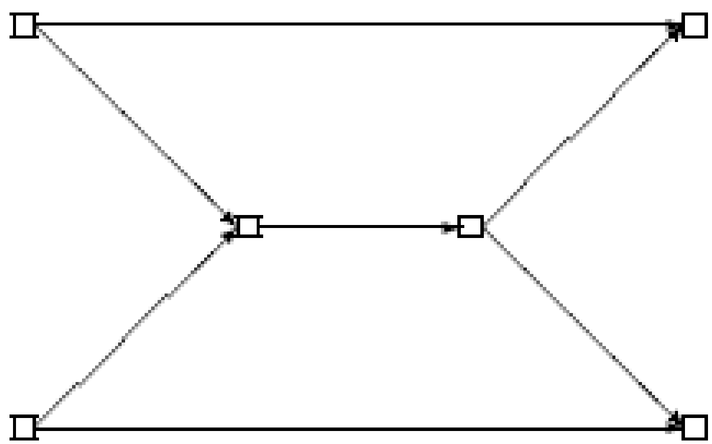
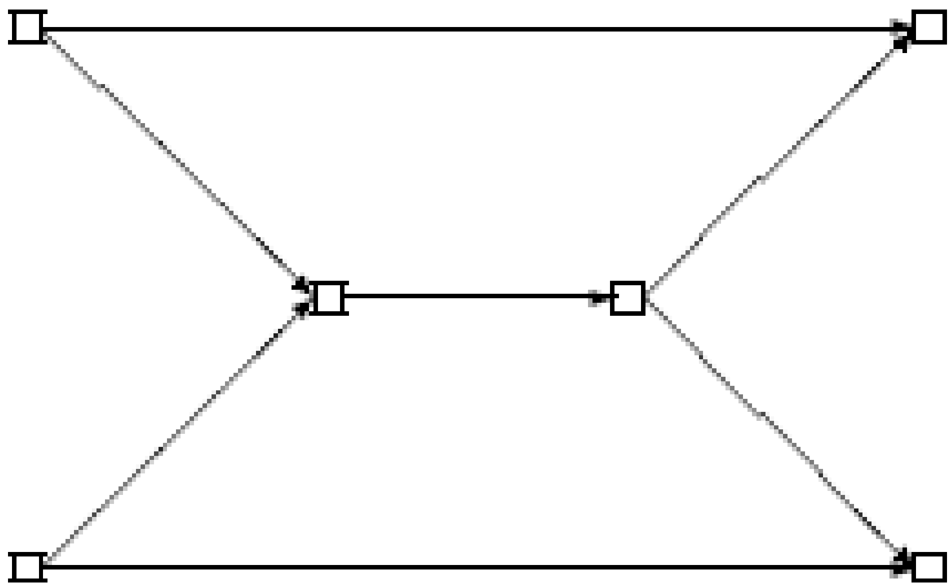


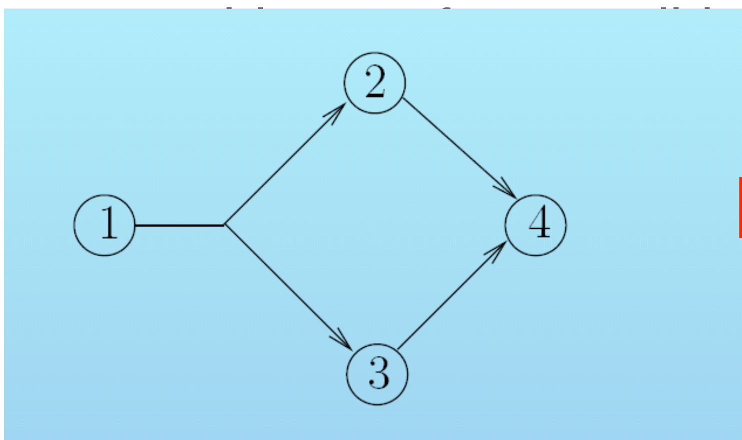
Code type equivalencies - conjecture

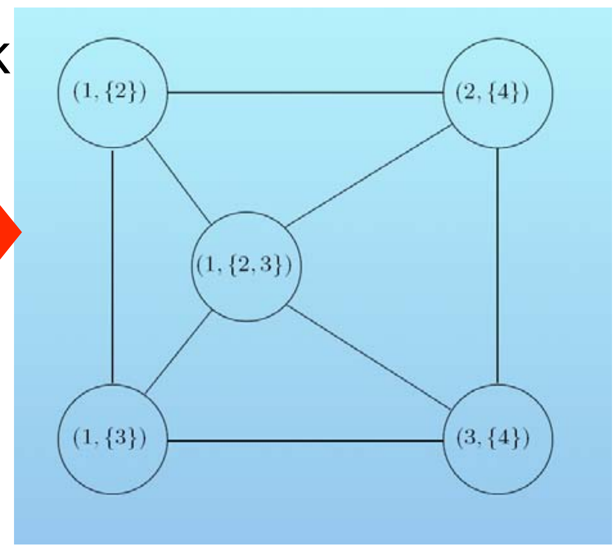


- Goal: Show that restricting the code type at all nodes of the network does not reduce the space of achievable results.

Conflict graph representation – connecting elements through codes

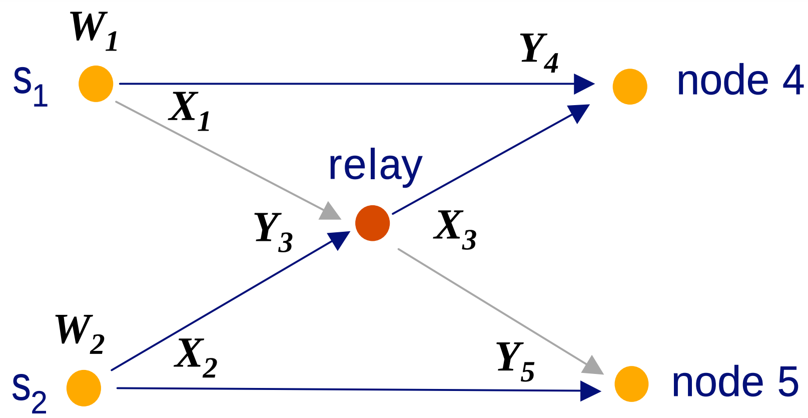
- A vertex represents a configuration of the network in terms of codes among components of the network
  - An edge between two vertices if the two configuration cause conflict (i.e. They cannot be served simultaneously).
- Stable Set: no edge connecting any pair of vertices in the set
  - etwork

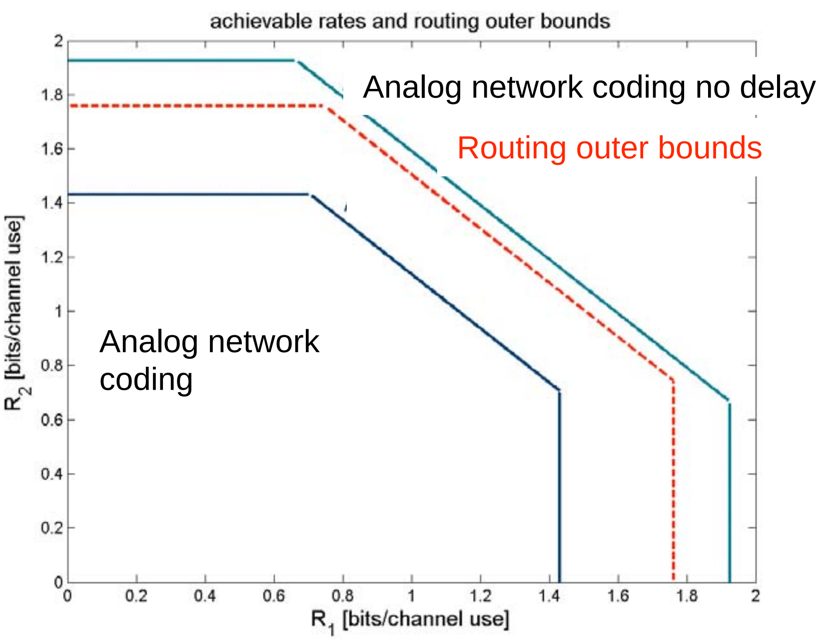




Koetter, Medard et al.

Analog network coding





Channel outputs

relay $Y_3 = h_{13}X_1 + h_{23}X_2 + Z_3$

node 4 $Y_4 = h_{14}X_1 + h_{24}X_2 + h_{34}X_3 + Z_4$

node 5 $Y_5 = h_{15}X_1 + h_{25}X_2 + h_{35}X_3 + Z_5$

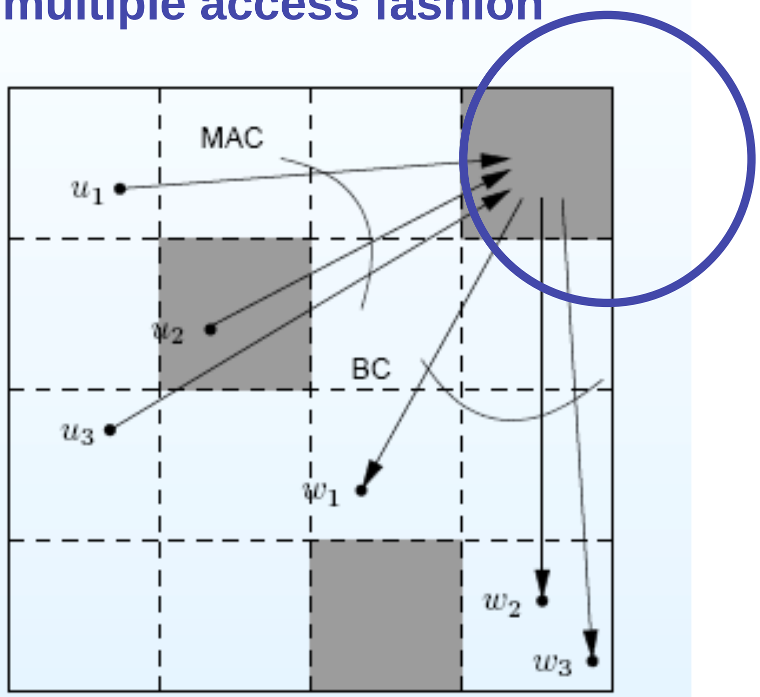
Channel input at the relay

$$X_{3,n} = f_n(Y_{3,n-1} \ldots, Y_{3,1})$$

Goldsmith, Medard, et al.

Scaling laws using multiple access

Squarelet acts as a component and interconnections occur among components, albeit in a multiple access fashion



• Source-destination pairs relay traffic over dense squarelets

• Induces virtual multiple antenna multiple access and broadcast channels

• For the best communication scheme

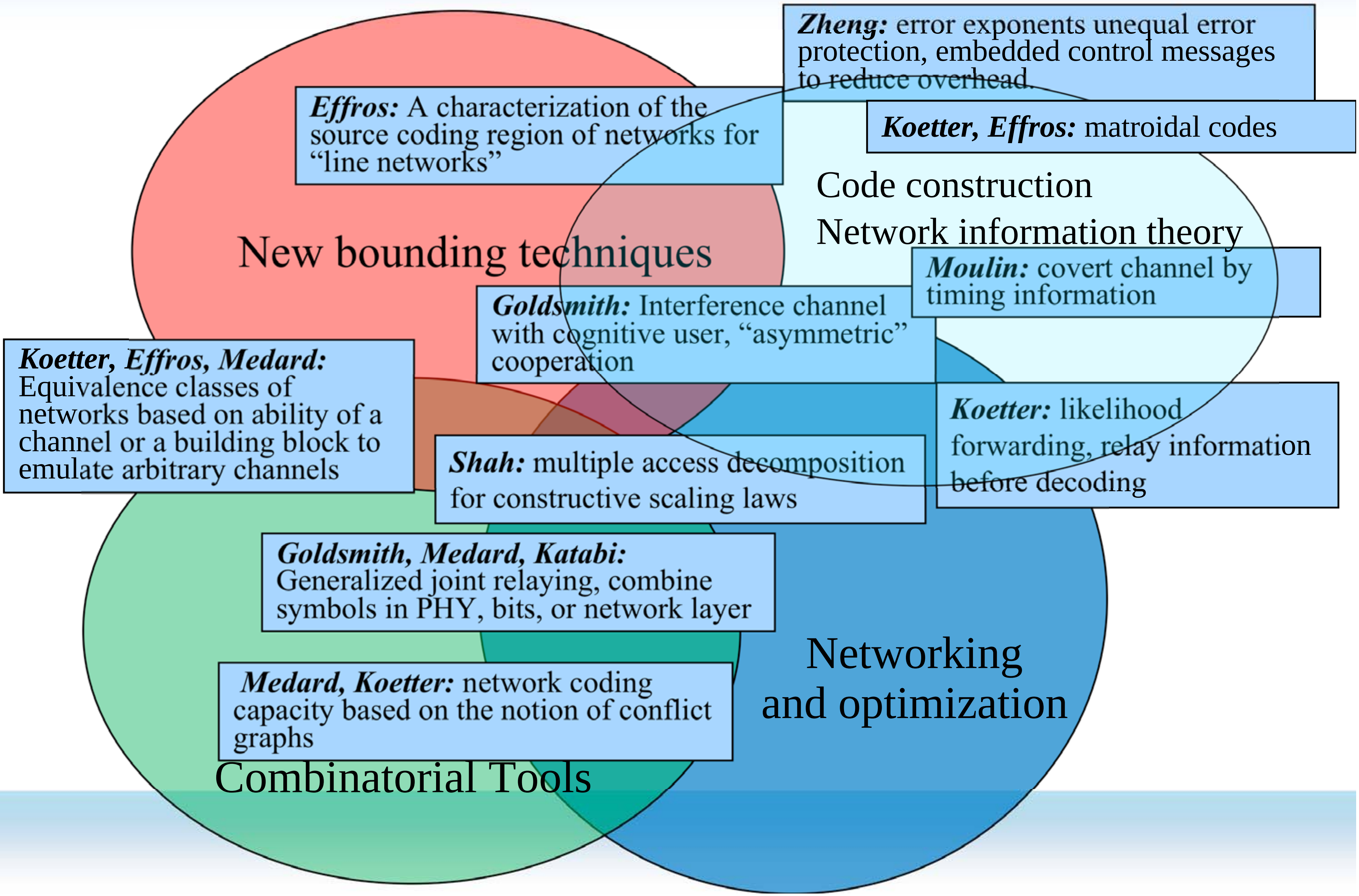
$$\rho^*(n) = O\left(n^{1-\frac{\alpha}{2}+\varepsilon}\right)$$

for ε > 0 arbitrarily small and for any2 < α 3

• Thus scheme is order optimal for 2 < α < 3, so that decomposition is not detrimental in an order sense

Shah, Gupta et al.

Achievements Overview



Thrust Synergies: An Example

Koetter, Effros, Medard: Equivalence classes of networks based on ability of a channel or a building block to emulate arbitrary channels

Goldsmith, Medard, Katabi: Generalized joint relaying, combine symbols in PHY, bits, or network layer

Koetter: likelihood forwarding, relay information before decoding

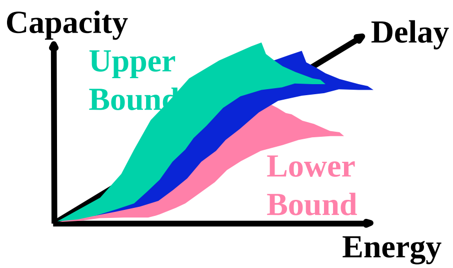
Thrust 1
Upper Bounds

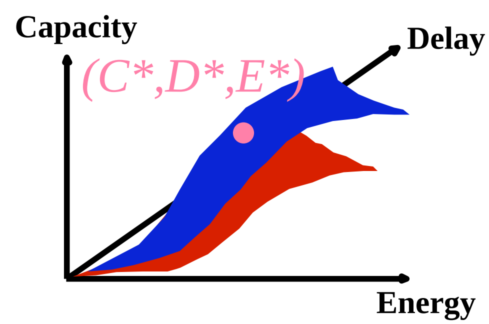
Thrust 2
Layerless Dynamic Networks

Shah: multiple access decomposition for constructive scaling laws

Medard, Koetter: network coding capacity based on the notion of conflict graphs

Thrust 3
Application Metrics and Network Performance





Roadmap

- Generalized equivalence results beyond point –to-point multiple access and broadcast components
- Derive bounds in cases where equivalence fails
- Conflict graphs for soft constraints such as multiple access constraints
- Schedule creation from conflict graph (thrust 3 interaction)
- Explore code-type equivalence conjecture
- Investigate code design implications of restricted code types

Publications

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- J.-K. Sundararajan, Médard, M., Kim, M., Eryilmaz, A., Shah, D., and Koetter, R., "Network Coding in a Multicast Switch," Proceeding of *INFOCOM* 2007, pp. 1145-1153.
- M. Kim, Sundararajan, J.-K., and Médard, M., "Network Coding for Speedup in Switches," *International Symposium on Information Theory (ISIT)*,2007, Nice, France
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- V. Doshi, D. Shah, M. Médard, S. Jaggi, "Distributed Functional Compression through Graph Coloring", *Data Compression Conference (DCC)*, 2007, Snowbird, UT.
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- Y. Liang, A Goldsmith, M. Effros, "Distortion Metrics of Composite Channels with Receiver Side Information".
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- Chris T. K. Ng and Andrea J. Goldsmith,"The Impact of CSI and Power Allocation on Relay Channel Capacity and Cooperation Strategies," submitted to IEEE Transactions on Information Theory, 2007.
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