Fundamental Limits of Wireless Systems (FLoWS):

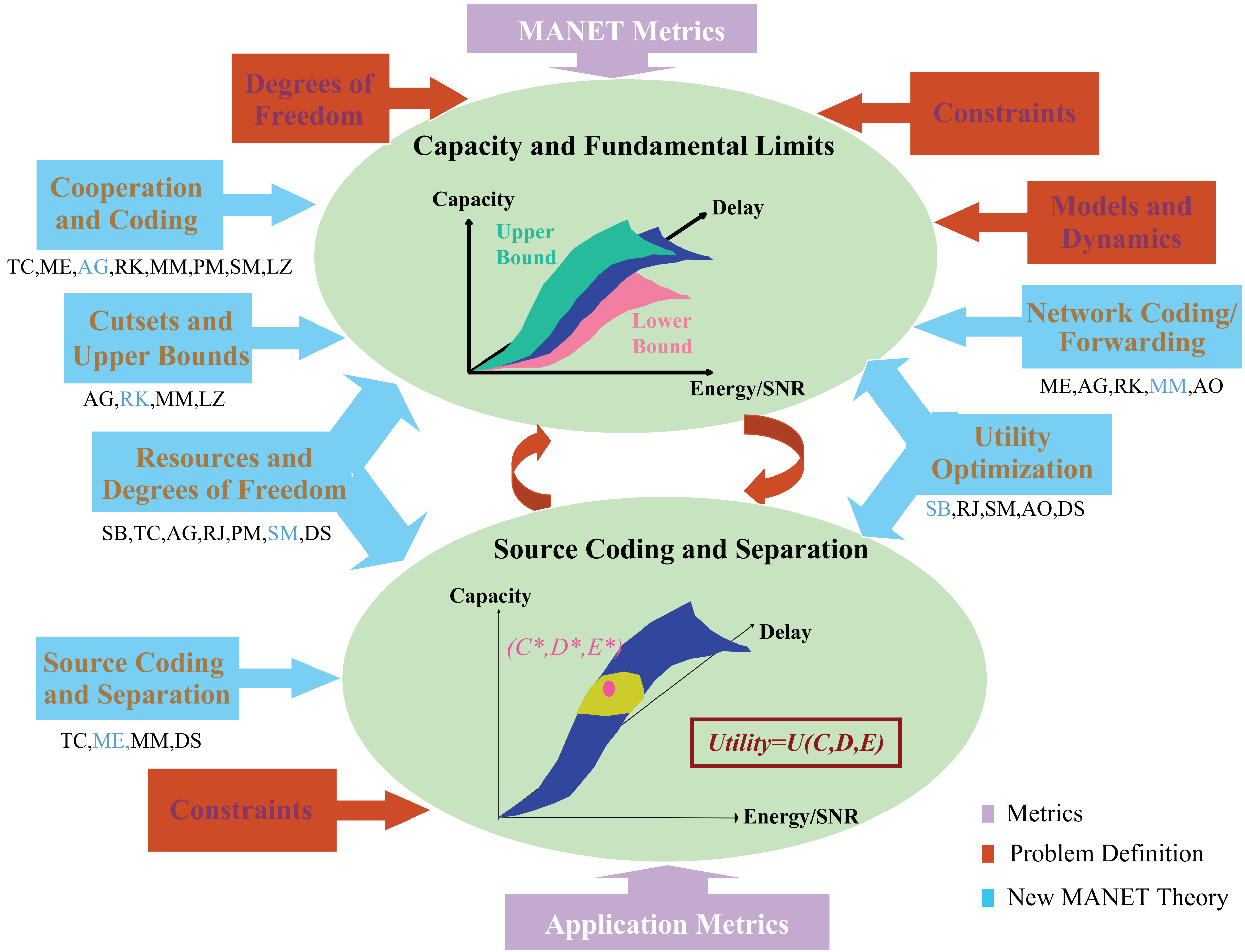
Vision, Challenges, Progress, Roadmap

Andrea Goldsmith

ITMANET PI Meeting
January 25-26, 2007
Stanford University

Program Objective

- Define the fundamental performance limits for MANETs in terms of desired metrics.
- Obtain upper and lower performance bounds for these metrics for a given set of MANET models.
- Define the negotiation between the application and network for picking the operating point.
- Bound the cost of using this set of metrics as the interface between the network and applications.
- Repeat as needed



MANET Metrics
Degrees of Freedom
Constraints
Capacity and Fundamental Limits
Capacity
Delay
Upper Bound
Lower Bound
Energy/SNR
Cooperation and Coding
TC,ME,AG,RK,MM,PM,SM,LZ
Models and Dynamics
Cutsets and Upper Bounds
AG,RK,MM,LZ
Network Coding/ Forwarding
ME,AG,RK,MM,AO
Resources and Degrees of Freedom
SB,TC,AG,RJ,PM,SM,DS
Utility Optimization
SB,RJ,SM,AO,DS
Source Coding and Separation
Capacity
(C*,D*,E*)
Delay
Utility=U(C,D,E)
Energy/SNR
Source Coding and Separation
TC,ME,MM,DS
Constraints
Application Metrics
Metrics
Problem Definition
New MANET Theory

Area Thrusts and Organization

Metrics and Problem Definition (Models, Degrees of Freedom, and Constraints)
Leads: Goldsmith and Medard
All PIs Contribute

Cooperation and Coding
Lead: Goldsmith

— Coleman
— Effros
— Koetter
— Medard
— Meyn
— Moulin
— Zheng

Cutsets and Upper Bounds
Lead: Koetter

— Coleman
— Goldsmith
— Medard
— Zheng

Optimization
Lead: Boyd

— Johari
— Meyn
— Ozdaglar
— Shah

Source Coding and Separation
Lead: Effros

— Coleman
— Goldsmith
— Koetter
— Medard
— Shah

Network Coding and Forwarding
Lead: Medard

— Effros
— Koetter
— Ozdaglar

Resources and DoF
Lead: Meyn

— Goldsmith
— Johari
— Medard
— Moulin

Challenges

- Metrics
  - What are the right set of metrics for networks and applications in the "near" future?
  - Should there be different metrics for different systems?
  - How to capture dynamics in these metrics
    - Is averaging (e.g. average delay) good enough? If not, then what?
    - For adaptive techniques, how to quantify the impact of feedback and imperfect estimates.
- Models
  - There are many different aspects to a network model (#nodes, propagation, flows, jamming, dynamics,…)
  - Hence, there are uncountable many different models.
  - How do we find models that are tractable, yet lead to general design and performance insight?

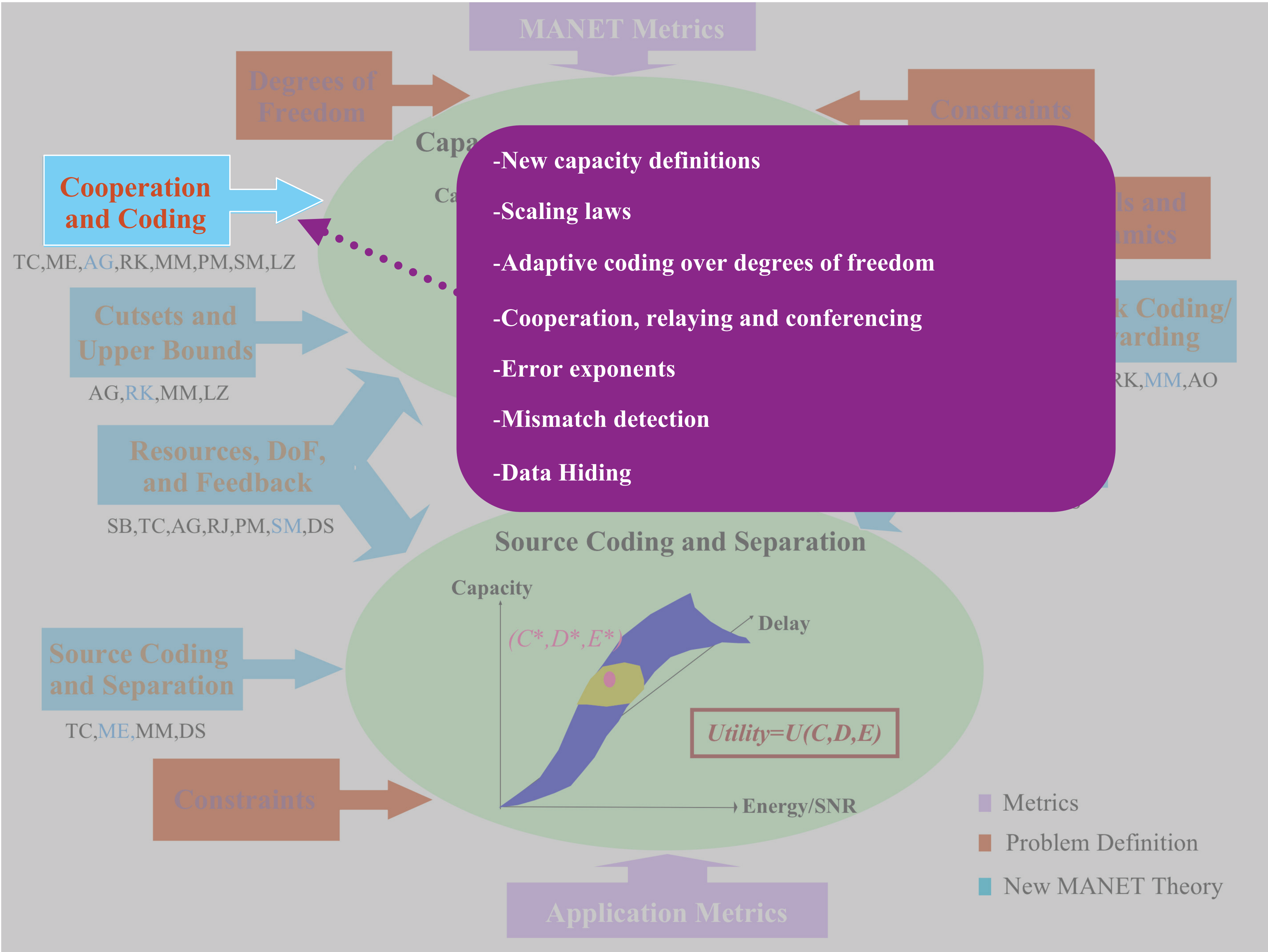
More Model Challenges

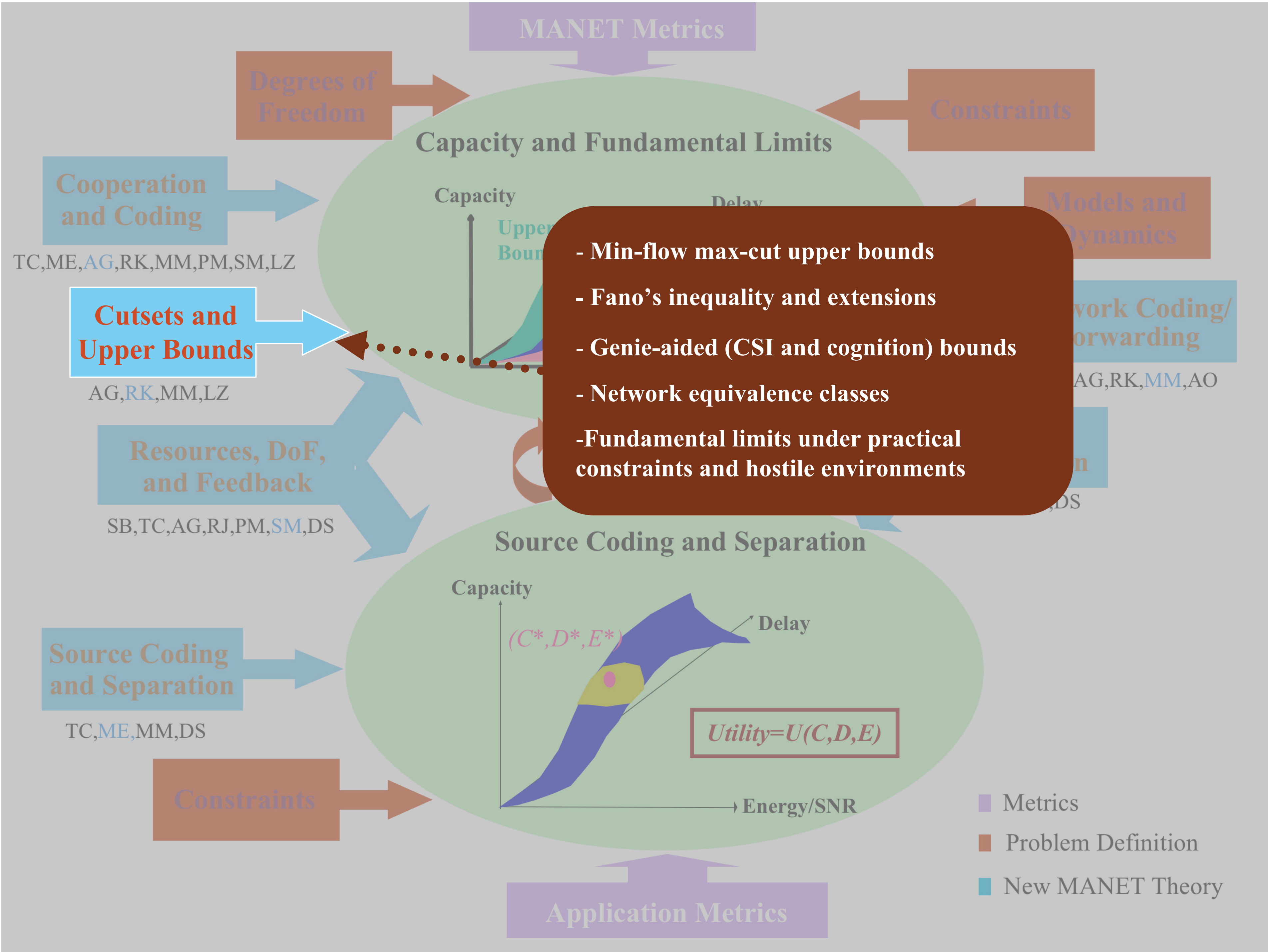
- Degrees of freedom
  - What are they?
  - How should they be used?
  - Does capacity scale with each DoF?
    - Are some more valuable than others?
    - Are there diminishing returns?

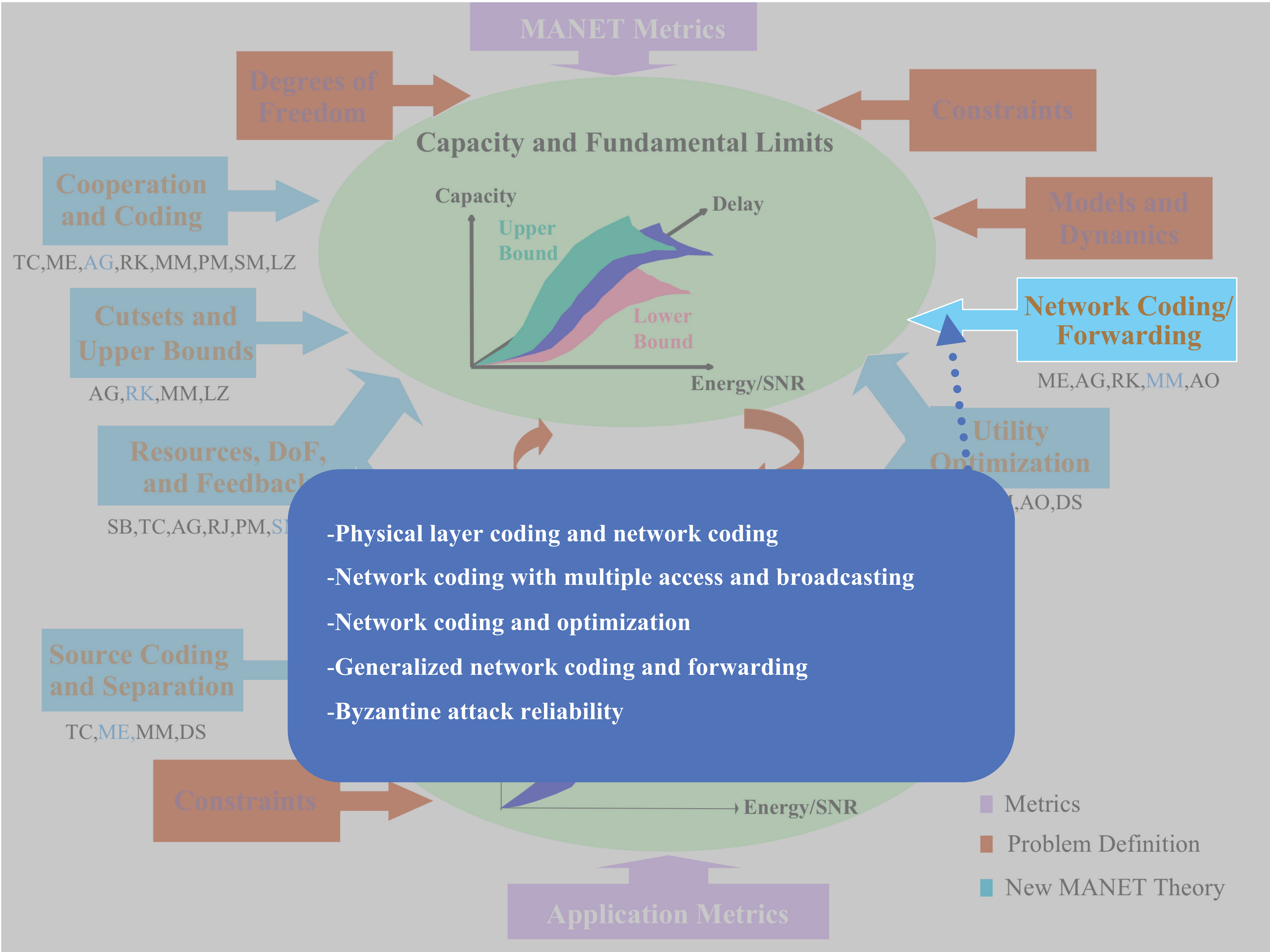
- Constraints
  - What defines the network constraints (e.g. security, robustness)?
  - How are constraints incorporated into our framework?
  - What is the relationship between DoF and constraints?

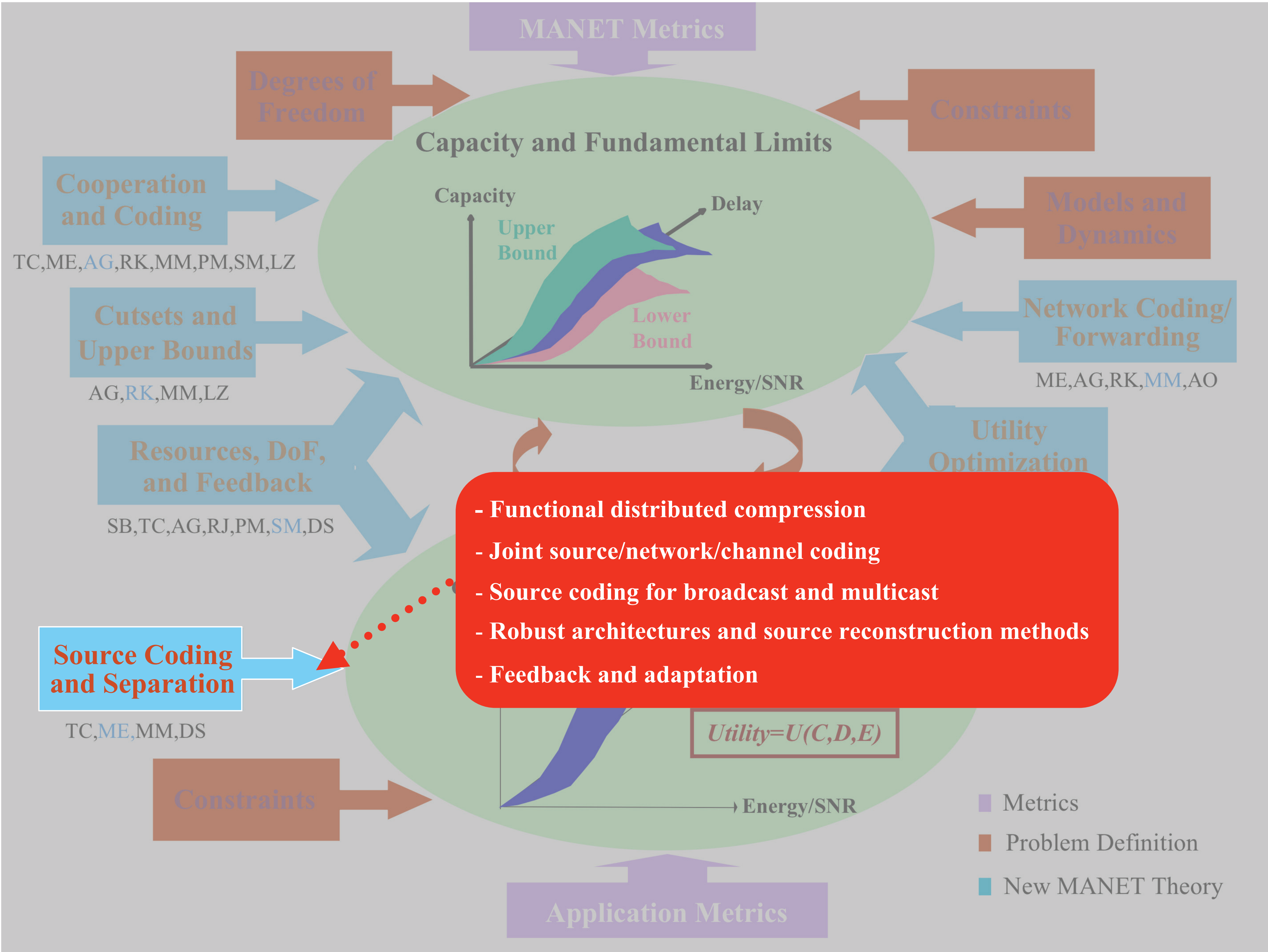
MANET Research Challenges

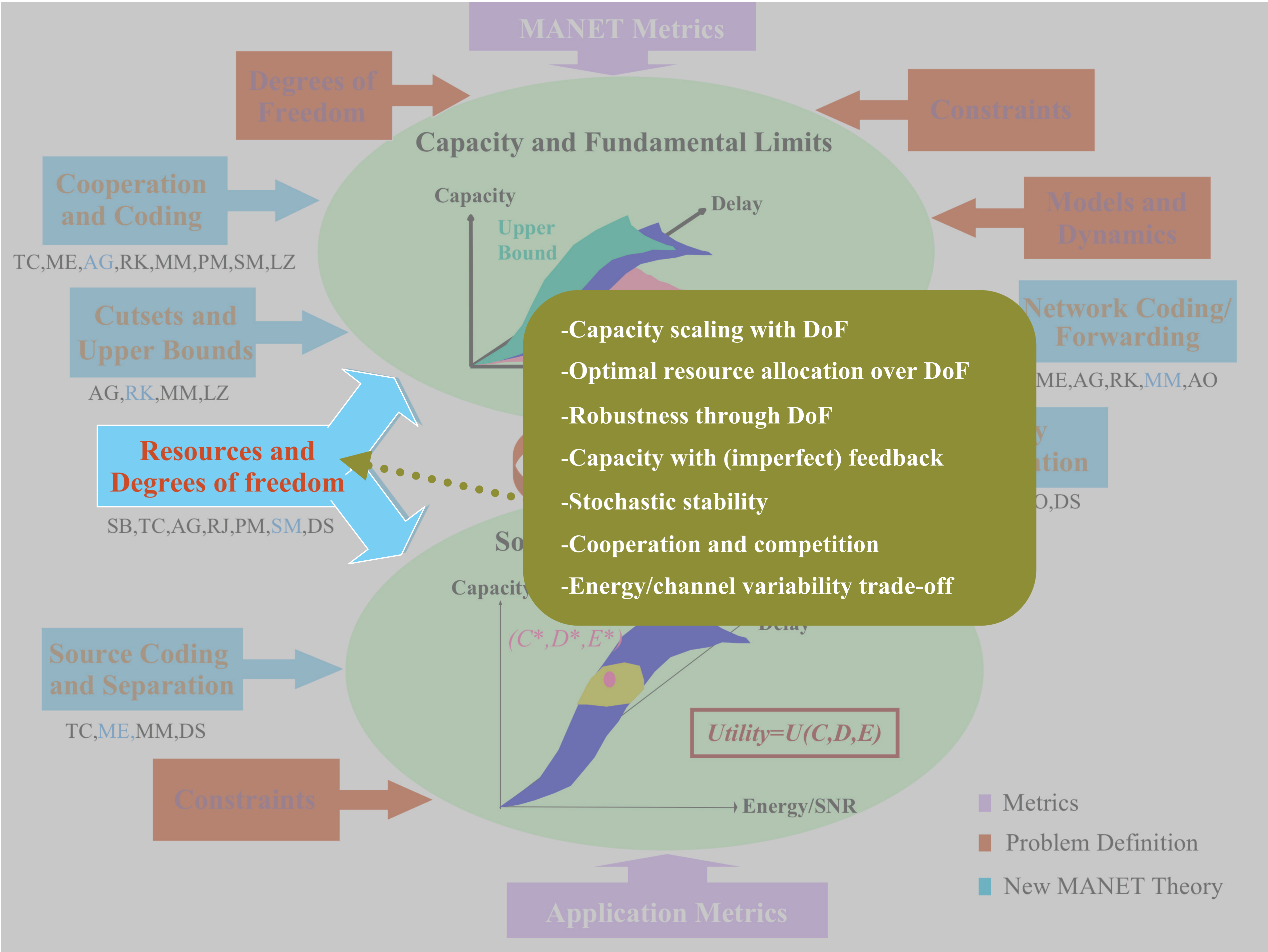
- Area talks
- Focus talks
- Posters

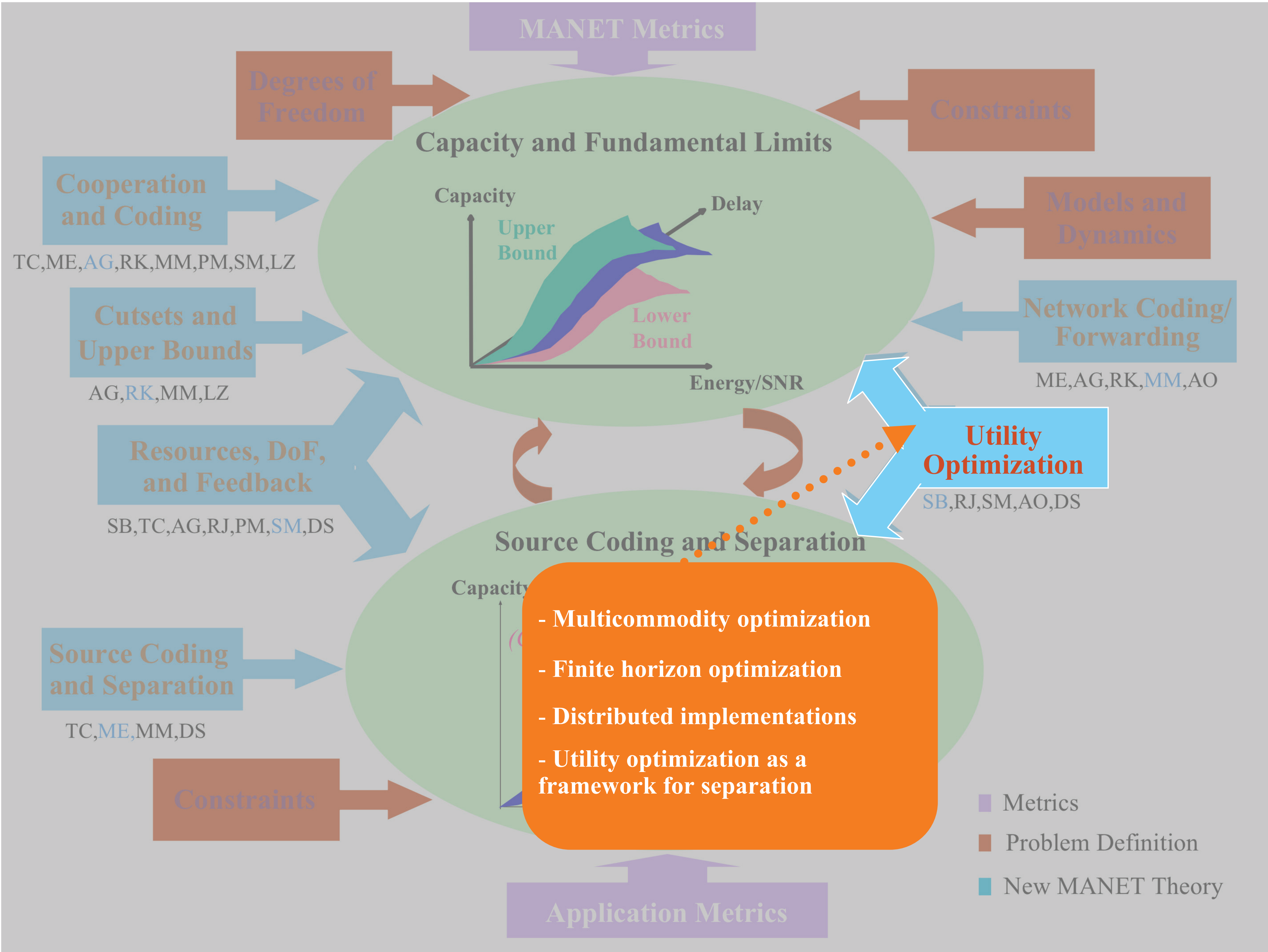

MANET Metrics
Degrees of Freedom
Constraints
Cooperation and Coding
TC,ME,AG,RK,MM,PM,SM,LZ
Cutsets and Upper Bounds
AG,RK,MM,LZ
Resources, DoF, and Feedback
SB,TC,AG,RJ,PM,SM,DS
-New capacity definitions
-Scaling laws
-Adaptive coding over degrees of freedom
-Cooperation, relaying and conferencing
-Error exponents
-Mismatch detection
-Data Hiding
RK,MM,AO
Source Coding and Separation
Capacity
Delay
(C*,D*,E*)
Utility=U(C,D,E)
Energy/SNR
Source Coding and Separation
TC,ME,MM,DS
Constraints
Application Metrics
Metrics
Problem Definition
New MANET Theory


MANET Metrics
Degrees of Freedom
Constraints
Capacity and Fundamental Limits
Cooperation and Coding
TC,ME,AG,RK,MM,PM,SM,LZ
Capacity
Cutsets and Upper Bounds
AG,RK,MM,LZ
- Min-flow max-cut upper bounds
- Fano's inequality and extensions
- Genie-aided (CSI and cognition) bounds
- Network equivalence classes
-Fundamental limits under practical constraints and hostile environments
AG,RK,MM,AO
Resources, DoF, and Feedback
SB,TC,AG,RJ,PM,SM,DS
Source Coding and Separation
Capacity
Delay
(C*,D*,E*)
Utility=U(C,D,E)
Energy/SNR
Source Coding and Separation
TC,ME,MM,DS
Constraints
Metrics
Problem Definition
New MANET Theory
Application Metrics


MANET Metrics
Degrees of Freedom
Constraints
Capacity and Fundamental Limits
Capacity
Delay
Upper Bound
Lower Bound
Energy/SNR
Cooperation and Coding
TC,ME,AG,RK,MM,PM,SM,LZ
Models and Dynamics
Network Coding/ Forwarding
ME,AG,RK,MM,AO
Cutsets and Upper Bounds
AG,RK,MM,LZ
Resources, DoF, and Feedback
SB,TC,AG,RJ,PM,
Utility Optimization
,AO,DS
-Physical layer coding and network coding
-Network coding with multiple access and broadcasting
-Network coding and optimization
-Generalized network coding and forwarding
-Byzantine attack reliability
Source Coding and Separation
TC,ME,MM,DS
Constraints
Energy/SNR
Metrics
Problem Definition
New MANET Theory
Application Metrics


MANET Metrics
Degrees of Freedom
Constraints
Capacity and Fundamental Limits
Capacity
Delay
Upper Bound
Lower Bound
Energy/SNR
Cooperation and Coding
TC,ME,AG,RK,MM,PM,SM,LZ
Models and Dynamics
Cutsets and Upper Bounds
AG,RK,MM,LZ
Network Coding/ Forwarding
ME,AG,RK,MM,AO
Resources, DoF, and Feedback
SB,TC,AG,RJ,PM,SM,DS
Utility Optimization
- Functional distributed compression
- Joint source/network/channel coding
- Source coding for broadcast and multicast
- Robust architectures and source reconstruction methods
- Feedback and adaptation
Source Coding and Separation
TC,ME,MM,DS
Utility=U(C,D,E)
Energy/SNR
Constraints
Metrics
Problem Definition
New MANET Theory
Application Metrics


MANET Metrics
Degrees of Freedom
Constraints
Capacity and Fundamental Limits
Capacity
Delay
Upper Bound
Cooperation and Coding
TC,ME,AG,RK,MM,PM,SM,LZ
Models and Dynamics
Cutsets and Upper Bounds
AG,RK,MM,LZ
Network Coding/ Forwarding
ME,AG,RK,MM,AO
Resources and Degrees of freedom
SB,TC,AG,RJ,PM,SM,DS
-Capacity scaling with DoF
-Optimal resource allocation over DoF
-Robustness through DoF
-Capacity with (imperfect) feedback
-Stochastic stability
-Cooperation and competition
-Energy/channel variability trade-off
Capacity
(C*,D*,E*)
Source Coding and Separation
TC,ME,MM,DS
Utility=U(C,D,E)
Constraints
Energy/SNR
Metrics
Problem Definition
New MANET Theory
Application Metrics


MANET Metrics
Degrees of Freedom
Constraints
Capacity and Fundamental Limits
Capacity
Delay
Upper Bound
Lower Bound
Energy/SNR
Cooperation and Coding
TC,ME,AG,RK,MM,PM,SM,LZ
Models and Dynamics
Cutsets and Upper Bounds
AG,RK,MM,LZ
Network Coding/ Forwarding
ME,AG,RK,MM,AO
Resources, DoF, and Feedback
SB,TC,AG,RJ,PM,SM,DS
Utility Optimization
SB,RJ,SM,AO,DS
Source Coding and Separation
Capacity
- Multicommodity optimization
- Finite horizon optimization
- Distributed implementations
- Utility optimization as a framework for separation
Source Coding and Separation
TC,ME,MM,DS
Constraints
Metrics
Problem Definition
New MANET Theory
Application Metrics

New theory since kickoff

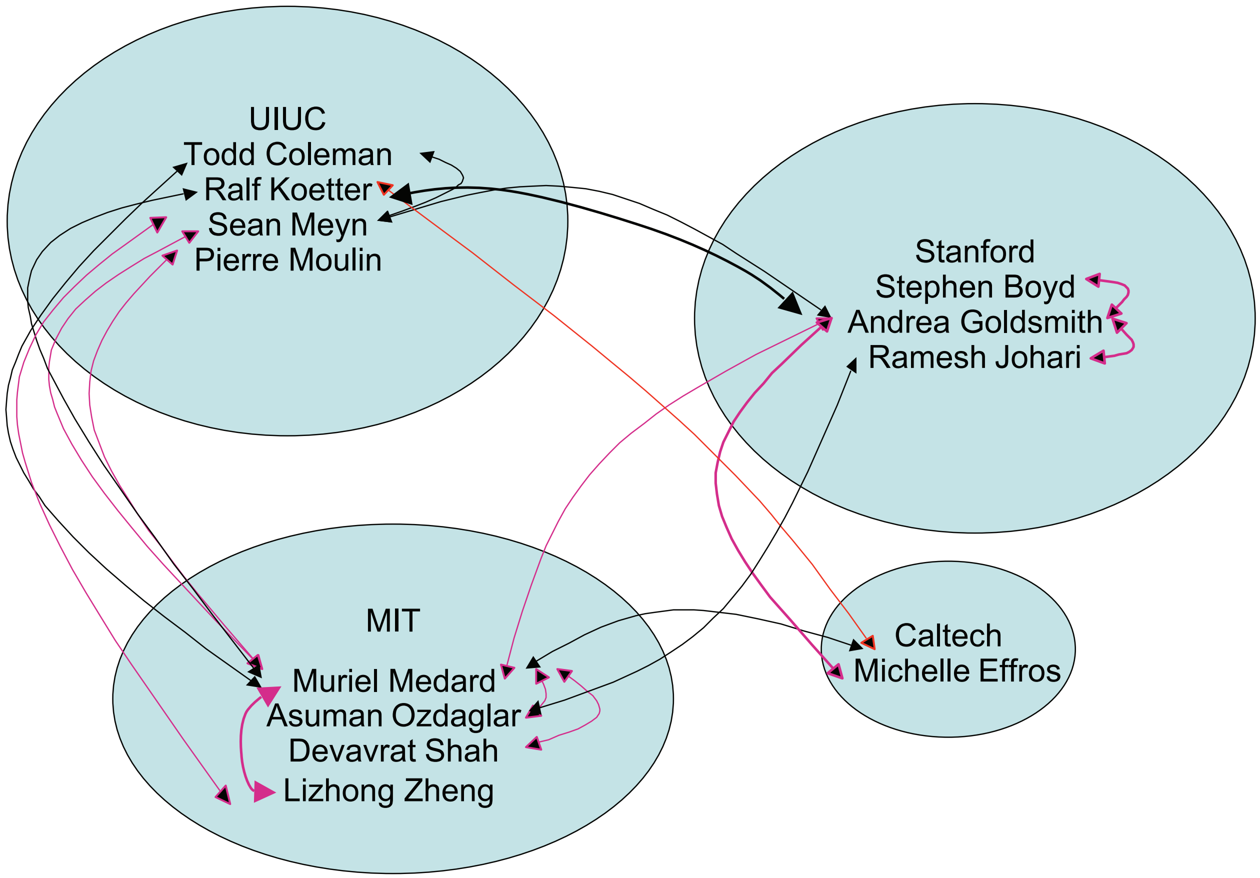
- Utility optimization and separation
- Generalized capacity
- Capacity under mismatch detection
- Network coding with relays and/or noisy links
- Cooperation in BCs, virtual MIMO and cognitive radios
- Jamming and degrees of freedom
- Stability and optimization of dynamic resource allocation
- Spectrum allocation/topology formation via game theory
- Distributed compression and joint source/network codes
- Distributed and centralized utility optimization

Posters

- Cutsets and Upper Bounds
  - “On MANET jamming,” P. Moulin
  - “Finding the best mismatch detector for capacity and hypothesis testing,” S. Meyn, L. Zheng, and M. Medard.
  - "Information Geometry and Capacity Limits" L. Zheng
- Network Coding and Forwarding
  - "Joint Relaying and Network Coding in Wireless Networks," I. Maric, M. Medard, A. Goldsmith
  - “Network coding on noisy links,” Ralf Koetter
- Cooperation and Coding
  - "Capacity Gain from Transmitter and Receiver Cooperation," C. Ng. and A. Goldsmith
  - "Fundamental Limits of Networks with Cognitive Users," I. Maric and A. Goldsmith
  - "Capacity Definitions of General Channels with Receiver Side Information,” M. Effros, A. Goldsmith, and Y. Liang
  - "Crosslayer Cooperative Broadcast Communication via Dualized Erasure Correction Codes", T. Coleman

- **Source Coding, Separation, and Feedback for MANETs**
  - "Distributed Functional Compression Through Coloring," D. Shah and M. Medard
  - "Optimal Power Distribution and Minimum Expected Distortion in Gaussian Layered Broadcast Coding," C. Ng, D. Gunduz, A. Goldsmith, and E. Erkip
  - "On joint source and network coding" by A. Lee, M. M´edard, K. Z. Haigh, S. Gowan and P. Rubel.
- **Resource Allocation and Degrees of Freedom**
  - "Dynamic Spectrum Management for Cognitive Radios." S. Adlakha, R. Johari, and A. Goldsmith
  - "Stochastic Stability Under Fair Bandwidth Allocation," D. Shah
  - Topology formation: when can local competition yield global cooperation, R. Johari
  - "Generalized Maxweight for resource allocation" S. Meyn
- **Optimization in MANETs**
  - "Rolling Horizon Control for Networks with Random Link Capacities," S. Boyd, A. Zymnis, D. O'Neill, and A. Goldsmith
  - "Iterative Power Control in Wireless Networks with Interference" S. Boyd and N. Tricharis
  - "Distributed optimization for nonseparable utilities," A. Ozdaglar

Team Collaborations



Collaborative mechanisms: Existing collaborations, student/postdoc exchanges, faculty visits, workshops

18 Month Roadmap

1/07 – 7/07

- Problem definition
- Thrust area progress
- Demonstrated gains
- New ideas/synergies

7/07 – 1/08

- More complex models
- Thrust area progress
- New ideas/synergies
- Demonstrated gains across thrust areas
- Utility maximization as separation principle

1/08 – 7/08

- New capacity regions
- Utility maximization/SC over these regions
- Synergies w/ CBMANET

1/07 7/07 1/08 7/08

Project Roadmap

	Period 1 1/07-6/08			Period 2 7/08-6/09	Period 3 7/09-6/10	Period 4 7/10-6/11
MANET Capacity	Formulate Problems	Prelim Results	Final Results			
Small networks, known CSI, MIMO Robustness to uncertainty						
large networks with fading, imperfect CSI, mobility						
Energy/Delay Tradeoffs						
Throughput/stability results Scheduling						
Integrated coding and queuing						
Node Cooperation						
Virtual MIMO, cooperation diversity, conferencing, relaying						
High/low/moderate SNR regimes						
Resource Allocation						
Rate, power, spectrum, antennas						
Routing, end-to-end metrics						
Security and Robustness						
Jamming w/wout cooperation						
Capacity limits w/ inside attacks						
Joint S/C/N Coding & Sep.						
Src-chan. and Src-netw. codes						
Source/channel/network codes						
Network App., Utility, Opt.						
Optimal operating pt on cap. reg.						
More complex nets and app. reqts						
Experiments (Sec. II.H)						

Goals for next meeting

- Baseline consensus on models, metrics, DoF, and constraints
- Progress in thrust areas (possibly merge resource allocation/DoF and optimization)
- New capacity theory with demonstrated performance gains
- Synergistic developments across thrust areas
- Mini-workshop co-located with ISIT

Summary

- We have made progress on defining the problem and refining the area thrusts.
- We have developed new theory in each of the area thrusts.
- We have made progress in determining the interface between networks and applications that incorporates all area thrusts.