A comparative taxonomy of wireless networks in the wideband regime - Fawaz, Thakur, Médard

**MAIN ACHIEVEMENT:**

- Hypergraph models
  - Model the broadcast nature of wireless transmission
  - Clarify correlation between messages
  - Correspondence with transmission schemes for wideband AWGN and fading models
- MAC and BC: equivalent hypergraph model
- Relay channel: comparison of min-cuts of achievable hypergraphs

**HOW IT WORKS:**

- Equivalent or achievable hypergraph models
- Transmission schemes achieving hypergraph min-cut for the AWGN and non-coherent multipath fading channels
- How does the optimal scheme for wideband BC and MAC perform in the relay channel?

**ASSUMPTIONS AND LIMITATIONS:**

- Wideband regime assumption
- Single source systems

**IMPACT:**

1. **Hypergraph = wired-like error-free models** for error-prone wireless systems => apply network optimization tools
2. Achievable hypergraphs of larger wideband networks built from hypergraphs of small blocks (Point-to-Point, BC, MAC, Relay)
3. Wideband relay channel > concatenation of wideband BC and MAC
   - Highest rate achieved by block markov DF in AGWN/peaky binning DF in fading
   - Superposition coding is suboptimal in AWGN, yet close to optimal and easy to scale
   - AF equivalent to direct transmission

**LOW SNR regime:**

- $P/W \to 0$ on all links

**NEW INSIGHTS:**

- Equivalent and achievable hypergraph models for building blocks of MANETs

**END-OF-PHASE GOALS:**

- Converse for relay channel
- Extension to optimization problem in larger networks in low SNR thanks to hypergraph model
- Optimal relay placement and geometry of wireless networks in wideband regime

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Equivalent and achievable hypergraph models for building blocks of MANETs
Optimal relay location and power allocation for low SNR broadcast relay channels - *Thakur, Fawaz, Médard*

**Main Result:**
Optimal relay positioning shows strong gains over seemingly interesting relay positions (e.g., centroid).

**Assumptions and Limitations:**
- Single source-multiple destination networks with a single relay as the only intermediate node.
- Multicast rate maximization is considered.
- Non-convex network optimization.

**How it Works:**
Using superposition coding and frequency division - a wireline-like model is created - Achievable hypergraph. 2-D plane is divided into disjoint regions for different relay positions with invariant network hypergraph (k-nearest neighbour problem). Using switch functions, a combined network optimization problem is formulated.

**New Insights:**
- Problem: relay position and power allocation to maximize multicast rate in wideband broadcast relay channel.
- Hypergraph model as a function of power allocation and relay location.
- Continuous switch functions to model varying hypergraph as relay position changes.

**End-of-Phase Goals:**
- Extension to multiple relay scenario
- Exploring geometric properties of multicast in wireless networks to significantly reduce complexity.

**Impact:**
Achievable hypergraph approach (superposition coding and frequency division) for low-SNR networks offers a simple and easily scalable network model and transmission scheme.

**Flow Achievement:**
- A comprehensive approach based on network optimization, computational geometry and information theory for optimal relay positioning is presented for low-SNR networks.
A converse for the wideband relay channel - Fawaz, Médard

**MAIN ACHIEVEMENT:**

Assuming that the relay cannot decode:
- Split total mutual information into two parts
  - contribution from relay
  - remaining contribution from source after deducting contribution from relay
- Bound contributions using equivalence theory and rate distortion theory, in particular to justify
  - Gaussian input at source
  - Estimation with distortion at relay
  - Error-free R-D link with finite capacity
- Analyze the limit of these contributions in the low SNR regime and show that the total converges to the direct link capacity

**Conclusion:** the relay should decode in the low SNR

**ASSUMPTIONS AND LIMITATIONS:**

- Low SNR assumption

**IMPACT**

1. Capacity of multipath fading /AGWN relay channel in low SNR regime
   - Hypergraph min-cut
   - Achieved by block Markov DF in AWG relay channel and simple non-coherent peaky binning DF in the fading channel

2. Network Coding in the digital domain at low SNR

3. New upper-bounding technique for capacity based on network equivalence theory

**END-OF-PHASE GOALS**

- Scalability of optimal relaying scheme
- Comparison with simpler and easy to scale linear schemes

**NEW INSIGHTS**

- Capacity of general relay channel unknown
  - Bounds on general relay channel
  - In wideband regime, cut-set upper-bound and lower bounds on AWGN/Fading relay channel

- Relay channel in low SNR /wideband regime:
  - At low SNR, cut-set upper-bound = virtual MIMO with perfect channel R-D, is not achievable
  - Block Markov DF / peaky binning hypergraph lower-bound is tight = capacity

**STATUS QUO**

**CHARACTERIZING THE CAPACITY OF THE RELAY CHANNEL IN THE WIDEBAND REGIME**
Resolution of a long-standing challenge for network & information theory ---

**Efficient, distributed wireless medium access**

**ACHIEVEMENT**

**MAIN ACHIEVEMENT:**
Efficient, distributed MAC that can deal with dynamics in demand
- Formally, it is positive recurrent
- Random access probability:
  - function of queue-size, learnt info.
  - Totally distributed, no message-passing

**HOW IT WORKS:**
- Learning rates of time varying Poisson process
  - Appropriate filter design
  - Using a clever choice of function

**ASSUMPTIONS AND LIMITATIONS:**
- Collision based model of physical layer

**IMPACT**

\[
L(t) \text{ is near } W(t) \\
\|L(t) - W(t)\| = o(W(t)) \quad \text{whp}
\]

Resolution of a long-standing problem: fully distributed, efficient MAC that is positive recurrent (can deal with dynamic demand)

New theory for learning rates of time varying Poisson process using noisy observations

**NEXT-PHASE GOALS**

Beyond Inference=Noise
- Dealing with hidden terminals
- Improving delay through utilization of geometry

Resolution of a long-standing challenge for network & information theory ---
**efficient, distributed wireless medium access**
Reduced-Dimension Multiuser Detection
Y. Xie, Y. C. Eldar and A. Goldsmith

New detection framework: compressive detection allows for lower complexity front-end for all types of MUD detectors: linear detector, decorrelator, iterative detector, maximum likelihood detector.

Other applications: Compressive ARQ protocol, wideband white space detection, multi-sensor detection

Complexity-performance tradeoff

MAIN RESULTS:
Compressive detection is done by first correlating with M sensing signals, then postprocessing to detect active users and their symbols. Sensing signals are constructed by linearly combining bi-orthogonal waveforms.

Without noise, achieve correct detection:
- \( K = 1, M = 2, \) BER = 0
- \( K > 1, \mu < 1/(D \times (2K-1)), \mu = \max a_i^*a_j \)

With noise:
- \( \mu < 1/(D \times (2K-1)) f(SNR, N) \)

Intuition: Project the original space consisting of N-dimensional waveforms onto an M-dimensional subspace.

Noise in RD-MUD is colored. How to optimally detect in colored noise

Develop tighter performance guarantee based on restricted isometry constants (RIC)

Performance guarantee based for other detectors: decorrelator, iterative detector based on OMP, maximum likelihood detector.

Low-complexity multiuser detection employs sparsity in the number of active users with analog processing
Dynamic auctions with learning have been widely studied across economics and engineering, but with little structural insight. Our work provides a simple, intuitive description of how we expect bidders to play.

**MAIN ACHIEVEMENT:**
We show there exists a structurally simple MFE of a dynamic auction with learning, where at each time step a bidder participates in a Vickrey auction. At each time step a bidder bids:

\[
\text{Expected marginal value of one additional observation of channel quality} + \text{Conditional expected value of channel quality (given posterior)}
\]

**HOW IT WORKS:**
Consider a limiting regime where the number of bidders \(N\) and number of auctions \(K\) grows large, while holding the number of bidders per auction \(\alpha\) fixed.

**ASSUMPTIONS AND LIMITATIONS:**
Our work provides existence of a simple equilibrium, but does not show how to converge to it. We are applying a form of model predictive control to show that such equilibria can be easily found by bidders.

**END-OF-PHASE GOALS**

**STATUS QUO**
Many cognitive radio models do not account for reaction of other devices to a single device’s action.

In prior work, we developed a general stochastic game model to tractably capture interactions of many devices via mean field equilibrium.

**NEW INSIGHTS**
We study a dynamic auction with learning.

Example: Multiple devices bid to share a channel; devices must learn their own channel quality.

We apply mean field equilibrium to obtain structural insights.

**IMPACT**
Dynamic auctions with learning have been widely studied across economics and engineering, but with little structural insight.

Our work provides a simple, intuitive description of how we expect bidders to play.

Provide a mechanism to converge to MFE.

- Leverage methodology developed in earlier work on stochastic games with complementarities
- Also study how equilibria vary as parameters of the system are changed (i.e., # of bidders per auction)

**A sentence why it is important/useful**

Many cognitive radio models do not account for reaction of other devices to a single device’s action. In prior work, we developed a general stochastic game model to tractably capture interactions of many devices via mean field equilibrium.
Instantaneous Efficiency of Communication
L. Zheng

**ACHIEVEMENT DESCRIPTION**

**MAIN RESULT:**
- Capacity and Error exponent optimal random coding schemes can be viewed as instantaneous optimization of certain metrics;
- Family of Renyi divergences measure information according to the urgency of decision making;
- Instantaneous efficiency particularly applicable for lossy processing.

**NEW INSIGHTS**
- Information measured in rate and error exponent, lack of measure of soft information exchange
- Optimality in terms of long time average performance, not necessarily efficient at every time instance

**STATUS QUO**
- Information transmission with a single observation can be described as splitting of posterior distribution over messages, the measure of efficiency is however not unique, depends on how the information is combined with other observations

**COMMUNITY CHALLENGE**
- Two elements in designing of instantaneously efficient signaling
  - Choice of metrics
  - Progress balancing

**END-OF-PHASE GOAL**
- Demonstrate the power of instantaneous designs in coded transmissions
- Apply to classical problems such as distributed hypothesis testing

General design based on instantaneous efficiency should have broader applications in networked problems, utilizing all the temporal information

Different coding metrics at different time of a block
Separation of Source-Network Coding and Channel Coding in Wireline Networks: Effros and Jalali

MAIN RESULT:
Source-network coding and channel coding can be separated in wireline networks with correlated sources, and lossless or lossy reconstructions.

HOW IT WORKS:
- Given a code that achieves small distortion for some source-sink pair, by treating the reconstruction block generated by the code as side information, the extra rate required for lossless reconstruction of the source at the sink is negligible.

ASSUMPTIONS AND LIMITATIONS:
- Channels are single-input single-output
- Channels are memoryless

END-OF-PHASE GOALS:
- Channels with memory: Does separation still hold for acyclic networks where channels have memory?
- Multi-user channels: Can we use the techniques used for deriving these results to general wireless networks and derive bounds?

This result shows that in wireline networks, with lossy or lossless reconstructions, even when the sources are correlated, source-network codes and channel codes can be designed separately without any loss in the performance. For computing the distortion region of such a network, this result shows that it suffices to study the distortion region of an equivalent network of bit-pipes.

Source-network coding and channel coding separate in a wireline network.
Collision-based approach:

- Binary idle/busy model of the state of the network
- Specifically designed to avoid interference (collision assumption)

Cognitive network Problem:
- primary source: dumb ARQ protocol with random arrivals
- secondary source: optimizes its own throughput with constraints on primary source’s throughput

Compact representation of the state space:

- No a priori knowledge of Statistics
- Iteratively learns from experience
- Automatically adapts to variations
- Having a single constraint on degradation of the primary user’s performance, the global optimum solution can be found.

Reinforcement learning based on the aggregated state space (coarse empty/non empty primary users’ queue representation and retransmission state):

- Channel sensing can be extended to manage advanced communication techniques
- Nodes can sense the Channel, and possibly use information collected by decoding control messages, headers, etc

Impact:

- We proposed an on line learning algorithm for optimizing the channel access strategy of the cognitive network under some constraints on the performance degradation of primary users’ performance and showed that the performance of the learning algorithm is close to the case where we have full-knowledge of the network statistics

End-of-phase goals:

- How can we generalize it to a network of primary/secondary users
- What is the effect of noise in observing the state of the system?
  (Noisy packet decoding/loss of the header/Channel sensing error, etc.)
Metrics and Control Algorithms for Media Streaming in Heterogeneous Environments: Medard and Ozdaglar

The availability of the helper server significantly improves the user experience, not its usage!

MAIN ACHIEVEMENT:
• Designed several access control policies for a system with two classes of servers (costly and free)
  1. Off-line policy: Queue-length not observable
  2. On-line Safe policy: Use the costly server until the safety threshold is crossed
  3. On-line Risky policy: Use the costly server only when the queue crosses the low-buffer threshold
• Explicit performance characterization of these policies

HOW IT WORKS:
• Using random linear network coding allows us to model the receiver’s buffer as an M/D/1 queue
• Problem formulated as an MDP with a probabilistic constraint: optimal policy not necessarily Markov
• Dynamic programming equation for the problem is achieved by state-space expansion

ASSUMPTIONS AND LIMITATIONS:
• Packet arrivals are assumed to be a Poisson process

IMPACT:
• We take into account more realistic user experience metrics for media streaming applications to capture their transient behavior
• Using proper dynamic control algorithms, we may decrease the usage cost of expensive equipments
• Less usage of costly back-up servers also results in larger capacity of such servers, hence fewer servers need to be installed to achieve a reasonable quality of service

NEW INSIGHTS
• Some resources are more costly or limited compared to the others
• Consider the initial buffer size and the interruption probability as Quality of user Experience metrics
• Goal: Design resource allocation policies that minimize the access cost given QoE requirements

END-OF-PHASE GOALS
• Design optimal resource allocation policies for multiple users with heterogeneous interruption probability and initial waiting time targets
• Design resource allocation algorithms when broadcasting delay-sensitive content to multiple cooperative users

FLoWS ACHIEVEMENT
• Quality of user Experience (QoE) for streaming applications is captured by initial waiting time and interruptions in media playback.
• Use random linear network coding to combine streams and avoid duplicate packet reception at the receiver
A poly-time scheduling algorithm for the multi-user, multi-channel system with a provably good worst-case delay performance.

Brings the new intuition of iterative resource allocation, that may be applicable to a wider class of problems.

**MAIN ACHIEVEMENT:**
Polynomial-time resource allocation algorithm (K-MTLB) that is **throughput-optimal**, and yields provably good per-user **delay performance**.

MTLB: Max Throughput, Load-Balancing

**HOW IT WORKS:**
- OFDM-based system: one freq. band can serve only one mobile user.
- Channels are “ON-OFF” type (the only interesting case).
- In each timeslot, allocate freq. bands to users with preference to longer backlogs (user-queues at the base-station).

**ASSUMPTIONS AND LIMITATIONS:**
- Equal priority for all users
- Poly-time complexity, but somewhat higher exponent: $O(n^3)$ computations per time-slot

**NEW INSIGHTS**
Throughput and delay are not conflicting requirements. Iterative resource allocation algorithms yield good throughput and small per-user delay.

**END-OF-PHASE GOALS**
Extensions to multi-source networks
- Femto/Pico-cell networks
- Minimal coordination

**Iterative resource allocation schemes ➔ Low per-user delay, in addition to network stability**
Network Equivalence in the Presence of Adversary - Effros

MAIN ACHIEVEMENT:
- First prove equivalence between the original network and a “stacked network” consisting of $N$ copies of the original network. Unlike in the non-adversarial case, errors for different layers are dependent. Upper bound the error probability by considering the worst case adversarial strategy and using an error correcting code with a hamming distance based decoding.
- A code $C_{\text{noiseless}}$ for the noiseless networks can be used on the noisy network by adding a channel code at each link.
- A code $C_{\text{noisy}}$ for noisy network can be modified to a code $C_{\text{noiseless}}$ for noiseless network:
  - Randomly design a source code for the noiseless link.
  - Remove those outputs from the source code for which the error probability for any message exceeds a threshold.

ASSUMPTIONS AND LIMITATIONS:
- Memoryless, point-to-point channels, acyclic network.
- Sum of rates of messages is less than capacity of the noisy link under consideration.
- Adversary can see links in a causal order.

FLOWS ACHIEVEMENT
- Equivalence between noisy and noiseless known in networks of independent point-to-point channels - relies on the random nature of errors.
- Adversary can introduce errors that are not independent of each other.

NEW INSIGHTS
- When the sum of rates of all messages is less than the capacity of a noisy link, the noisy link is equivalent to noiseless link.
- Noise is emulated on the noisy link by source coding and randomly choosing a codebook from a set of possibilities.

STATUS QUO
- Equivalence between noisy and noiseless known in networks of independent point-to-point channels - relies on the random nature of errors.
- Adversary can introduce errors that are not independent of each other.

END-OF-PHASE GOALS
- Remove the sum rate Constraint on messages.
- Extend beyond the point-to-point case – MAC, Broadcast etc.
- Other transmission models?

IMPACT
- Simplifies capacity calculations - noiseless networks with adversaries are better understood than noisy networks with adversaries.
- Simplifies code design for the class of adversarial networks where this applies by enabling a two step design - network code followed by channel code.
- By removing the assumption of independence of noise on links, this result opens the door to extending equivalence to more general cases.

Network Equivalence extends to networks with Adversaries.
Shannon meets Nyquist --- Capacity Limits of Sampled Analog Channels

Yuxin Chen, Andrea J. Goldsmith and Yonina C. Eldar

**ACHIEVEMENT**

Single-channel Prefiltered Uniform Sampling

- $x(t) \rightarrow h(t) \rightarrow y(t)$
- $\eta(t)$
- $s(t) \rightarrow y[n]$
- $z = nT_s$

Theorem 1: The sampled channel capacity is

$$C(f_s) = \frac{1}{2} \int_{f \in P(f)} \log \left( \frac{\sum_{n=\text{even}} |H_c(f-iT_s)|^2}{\sum_{n=\text{odd}} |S_c(f-iT_s)|^2} \right) df$$

MISO Interpretations:
- Filtered channel, colored noise
- Combining (due to uniform sampling)
- Maximum Ratio Combining

Optimal Prefilter:

- $S_{\text{opt}}(f_kT_s)$
- $\text{SNR}(f-kT_s)$
- $\text{SNR}(f)$

Non-monotonicity:
- due to UNIFORM sampling grid

Multi-channel Prefiltered Uniform Sampling

- $x(t) \rightarrow h(t) \rightarrow y(t)$
- $\eta(t)$
- $s(t) \rightarrow y[n]$
- $z = nT_s$

Theorem 2: The sampled capacity with multi-channel sampling is:

$$C(f_s) = \frac{1}{2} \max_{Q \text{ diagonal}} \int_{f \in P(f)} \frac{1}{m} \log \left( \text{det} \left( I + \frac{1}{Q} \int_{f \in P(f)} \text{H}_c(f) Q^{-1} \text{H}_c(f)^T df \right) \right) df$$

MIMO Interpretation:
- $x(t)$
- $y(t)$
- $h(t)$
- $z = nT_s$

**NEW INSIGHTS**

- Information Theory
  - Traditional Shannon framework deals with continuous domain.
  - Optimize input for a given channel $N(f)$

- Sampling Theory
  - Analog signals $\rightarrow$ digital sequences (Nyquist rate sampling)
  - Optimize sampling mechanisms for given input

- Info Theory meets Sampling Theory
  - What is the capacity limit of the sampled analog channel
  - What is the tradeoff between capacity and sampling rate
  - How to jointly optimize input and sampling methods

**NEXT-PHASE GOALS**

- Extension to Network Info. Theory
  - Example: (Broadcast Channel)
  - Gaussian MIMO Broadcast Channel

- Connection between IT and Sampling theory
- Sufficient Statistics (that favors the channel structure)

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A first attempt to study the tradeoff between data rate and hardware complexity
A Network Equivalence-Based Analysis of the Multiple Access and Broadcast Channels: Calmon and Médard

MAIN ACHIEVEMENT:
• An effective approach for finding capacity region bounds for discrete and memoryless multiterminal channels as components of larger networks.
• This method also provides valuable insights when applied to channels in isolation.
• Precise bounds for the multiple access AWGN channel within a larger network.
• Alternative look at the MAC with correlated sources and at the broadcast channel.

HOW IT WORKS:
• If a network can reproduce the same input-output relation of a given channel, it represents an upper bound model for the capacity region of the channel.
• Furthermore, if this upper bound consists of independent, point-to-point links, we can determine the upper bounding capacity region.
• By taking the intersection of different bounds we can find better results.

ASSUMPTIONS AND LIMITATIONS:
• Only useful for discrete memoryless channels.
• Difficult to determine tightness of bounds.

Bounding multiterminal channels by point-to-point models can be an effective approach!