Information Theory for Mobile Ad-Hoc Networks (ITMANET): *The FLoWS Project*

Thrust 1

Upper Bounds

Muriel Medard, Michelle Effros and Ralf Koetter

Non-Coherent Multipath Fading Relay Networks in the Wideband Regime – *Fawaz, Medard*

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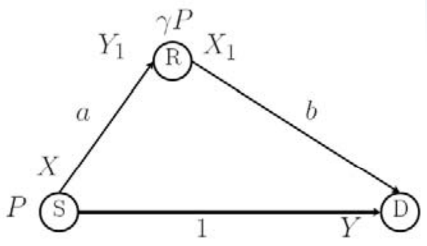
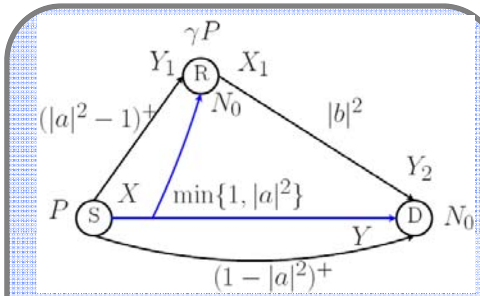


Capacity of general relay channel unknown

- *Bounds on general relay channel*
- *Bounds on AWGN relay channel*

NEW INSIGHTS



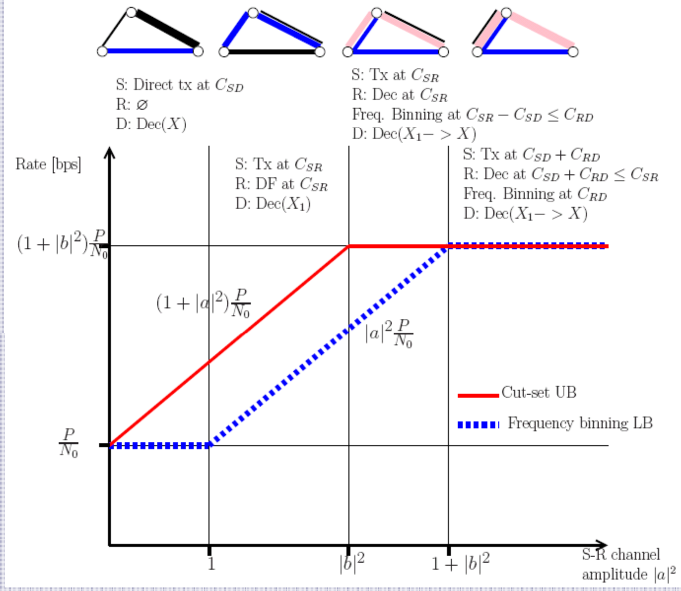
Wideband regime: not interference-limited, but energy-limited

point-to-point: $C_{Fading} = \frac{P}{N_0} = C_{AWGN}$

Hypergraph Model: min-cut on hypergraph

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:



$$R = \min\left\{\max(1,|a|^2)\frac{P}{N_0}, (1+|b|^2\gamma)\frac{P}{N_0}\right\}$$

HOW IT WORKS:

- Source: Low-duty cycle peaky FSK signaling
- Relay: Decode, Frequency Binning and Forward
- Destination: decodes relayed signal, then source signal using relayed information

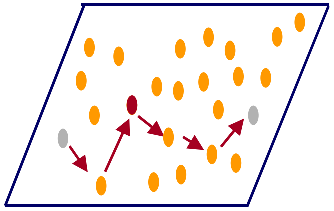
ASSUMPTIONS AND LIMITATIONS:

- Wideband regime
- Relay decodes fully

IMPACT

1) **Achievable rate in non-coherent multipath fading relay channel**
    - coincides with generalized block-Markov lower bound of AWGN-FD channel -> LB
    - coincides with cut-set upper-bound for $a^2 \geq 1+b^2\gamma$ -> Capacity
2) **Non-coherent peaky frequency binning scheme**
3) **Min-cut on hypergraph model**

NEXT-PHASE GOALS



Extension to larger networks: *multiple relays, layers...*

Open question: closing the gap to Cut-set UB?

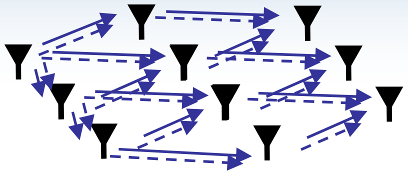
Virtual MIMO gain in the wideband regime?

Towards characterizing the capacity of the building block of MANETs

Linear Representation in Network Coding

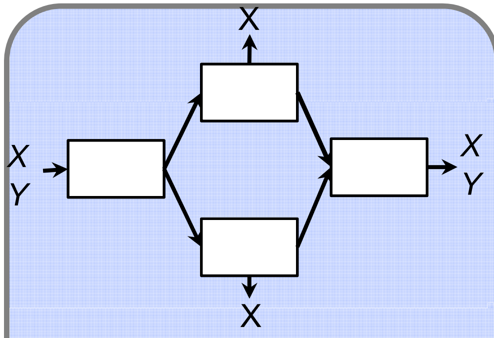
Cohen, Effros, Avestimehr, and Koetter

STATUS QUO



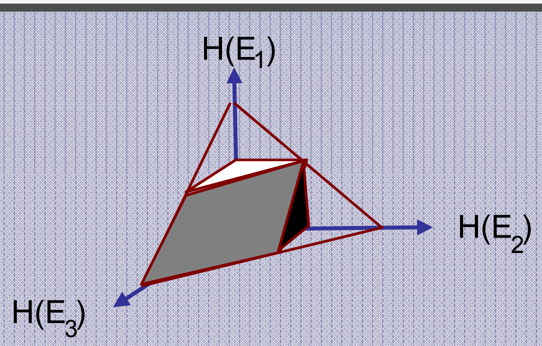
- ***Linear network codes are simple to design and operate.***
- ***Linear network codes are sufficient for multicast demands.***
- ***Linear network codes are insufficient in general.***

NEW INSIGHTS



- Linear coding is optimal at encoders and decoders of a network code only under very special circumstances.
- Studying problems where linearity suffices only at internal nodes may broaden the class of codes for which we can prove optimality.

ACHIEVEMENT DESCRIPTION



How it works:

- Characterize space of possible entropy vectors representing node inputs and outputs.
- Use nodes' functional constraints to restrict this characterization.
- If this space has a linear representation, then we can show that linear coding at all internal nodes suffices.

Assumptions and limitations:

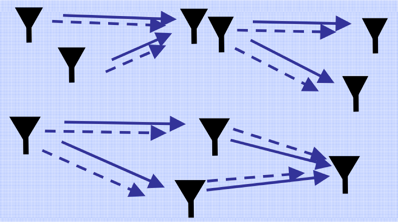
- Requires demonstration of the existence of a linear representation for the space of possible entropy vectors.
- Linear representations don't always exist.
- The complexity of finding them when they do exist restricts our attention to smaller networks.

IMPACT

Sufficient conditions under which linear operations at the internal nodes (combined with possible non-linear operations at the terminals) suffice to achieve optimality.

The same conditions are also sufficient to show that the rate region can be described without non-Shannon information inequalities.

NEXT-PHASE GOALS



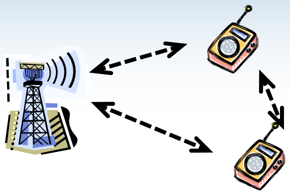
- Use the proposed tool to test small example networks for sufficiency of linear network codes
- Understand the design implications of codes with linear operations at interior nodes.

Removing the linearity constraint at edge nodes increases the family of problems for which (mostly) linear codes are optimal.

Continuity for Network Coding Capacity Regions

Gu and Effros

STATUS QUO

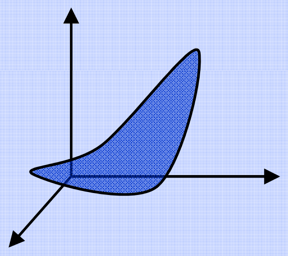


Question: Can a small change in source distribution mean a big change in capacity region?

-Previous ITMANET results:

- ***•Inner semi-continuity for many networks.***
- ***•Outer semi-continuity only for a few simple networks.***

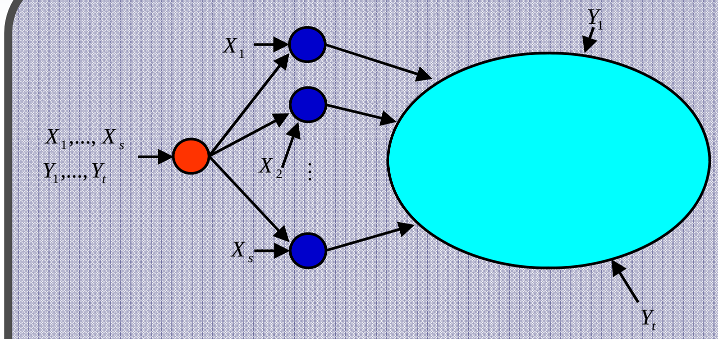
NEW INSIGHTS



- The difference between p(x)=0 and p(x)=ε can be very large.

- Capacity regions probably are NOT outer semi-continuous in the source distribution in general!

ACHIEVEMENT DESCRIPTION



How it works:

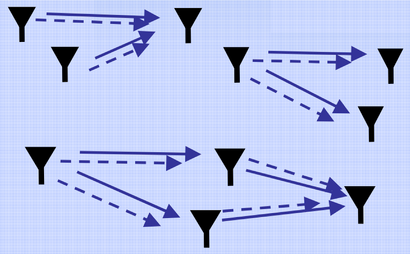
- Assume that the source alphabet is *known*.
- In this case, p(x)>0 for all x in the known alphabet.
- Prove continuity under this assumption (called S-continuity).

Assumptions and limitations:

S-continuity results apply quite generally

- Zero-error coding (arbitrary demands – including functions)
- Lossless coding (arbitrary demands – including functions)
- Lossy coding (non-functional and separable)
- Lossy coding (functional when all demands have distortion constraints greater than 0)

IMPACT



- For non-functional source coding, reliable source distribution estimations result in reliable approximations of capacity regions.

- For functional source coding, estimated source distributions should have the same support of the true distribution.

NEXT-PHASE GOALS

Upper bound approximation errors of capacity regions when using estimated source distributions.

Investigate other abstract properties (for example, strong converses) that we can possibly exploit in practical code design.

S-Continuity holds for broad classes of network coding capacity regions.

Information Theory for Mobile Ad-Hoc Networks (ITMANET): *The FLoWS Project*

Thrust 2

Layerless Dynamic Networks

Lizhong Zheng, Todd Coleman

Achievable Rate Regions for BC With Cognitive Relays

Goldsmith, Jiang, Maric, Cui

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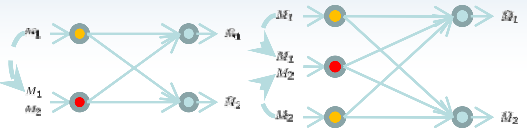
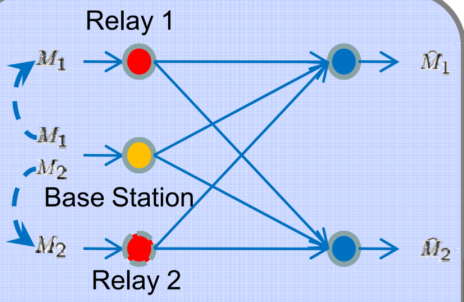


- *Cognitive radio channel (CRC) & interference channel with a cognitive relay (ICCR) have been studied as variants of the IC*
- *Known interference assumption → imposing a constraint on the encoding order → cannot include Marton's Region for the BC*

NEW INSIGHTS



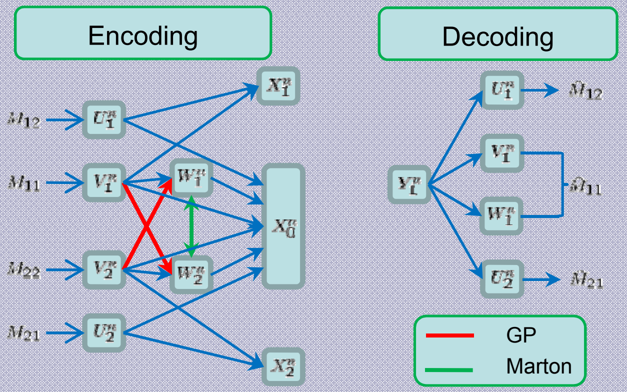
Viewing both models as variants of the broadcast channel (BC):

Both models are regarded as the BC with cognitive one relay or two relays (BCCR)

ACHIEVEMENT DESCRIPTION

MAIN RESULT:

New coding scheme effectively integrates superposition coding, Gel'fand-Pinsker coding, and Marton's binning scheme, and applies simultaneous joint decoding



HOW IT WORKS:

Rate splitting of both messages (common and private)

Private messages are encoded with two layers:

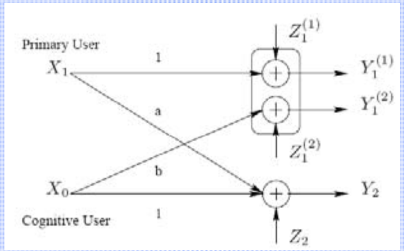
(1) Inner layer serves as cooperation base between relays and the sender

(2) Outer layer performs Generalized GP coding against each other's inner layer, and perform Marton's binning against each other

ASSUMPTIONS AND LIMITATIONS:

- Cognition is non-causal, but is practical in certain sensor network scenarios
- Region is derived in its implicit form

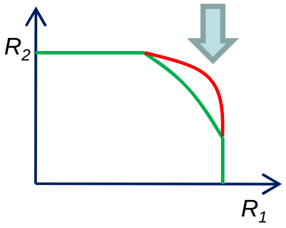
IMPACT



- New achievable rate regions for both the CRC and the BCCR
- New regions generalize Marton's region for BC
- A simple achievable rate region obtained for a special case Gaussian CRC (potentially tight)

NEXT-PHASE GOALS

To be determined



- Outer-bound of the capacity region to be developed from the BC perspective
- Special capacity results to be identified

Exploiting the broadcasting nature of CR channels leads to better achievable rates

Tilted Matching for Feedback Channels

B. Nakiboglu, L. Zheng

STATUS QUO

- *Feedback is an efficient way for error correcting, but often used for ACK/NACK and retransmissions*
- *Using feedback to guide FEC has only limited examples*
- *Performance metric for Dynamic coding is missing*

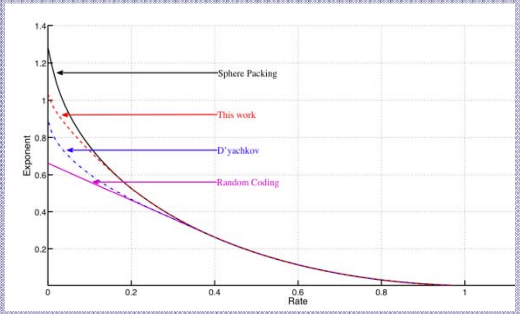
NEW INSIGHTS

By finding the a posteriori matching scheme with the optimal error exponent, we expose the limitation of error exponent optimal FB coding

ACHIEVEMENT DESCRIPTION

MAIN RESULT:

Tilted a posteriori matching achieves the best error exponent



HOW IT WORKS:

- **Smooth upper bound to error prob.**

$$P_e \le \mathbf{E}\left[\sum_k \varphi_n(k)^{1-\rho\eta}\left(\sum_{l\neq k}\varphi_n(l)^{\eta}\right)^{\rho}\right]$$

- **Make sure at each time t, conditioned on any history, the above metric decreases by a multiplicative factor;**
- **Match tilted a posteriori distribution to the desired input distribution.**

AP tilting $\varphi_t(\cdot)^\eta$ **instead of** $\varphi_t(\cdot)$

END-OF-PHASE GOAL

- Break away from uniform increment, allow coding to be considered as a dynamically changing optimization
- New performance metric and the resulting coding schemes for dynamic problems

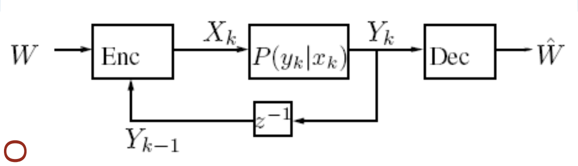
COMMUNITY CHALLENGE

The dynamic aspect of FEC coding, which is crucial in understanding dynamic information exchange requires new formulation

Uniform Belief Increment Limits Performance

Lyapunov Exponents and the Posterior Matching Scheme
Coleman

STATUS QUO



The use of feedback is of the utmost importance in designing scalable, robust, reliable communication schemes

Deep understanding of feedback is still work in progress. Are there simple provably good iterative feedback encoders/decoders/

NEW INSIGHTS

Dynamical System Encoder (2008):

p 1 = p I p i+1 = c$_{Y_i}$(p i) (1)

″ i = b$_X^{i\ 1}$(p i)

- **Converse** to coding theorem: next input should be independent of everything decoder has seen so far
- With an **optimal** decoder, such “posterior matching” schemes achieve capacity
- Does this motivate **a simple iterative decoder**, that **achieves** capacity?
- How do we analyze this easily, exploiting the dynamics?

ACHIEVEMENT DESCRIPTION

MAIN RESULT:

- For the posterior matching scheme with encoder (*), the following **dynamical system decoder** - with **arbitrary initial condition** u in (0,1) - achieves capacity:

p^ [¿j¿] = ¢L p^ [Wj¿] = c$_{Y_i}^{i\ 1}$(p^ [W+ 1j¿])L(2)

HOW IT WORKS:

- Since the **Y**’s are **independent** and identically distributed, the decoder dynamical system is a **Markov chain** and has a **Lyapunov exponent** of **–C** for any initial condition u on (0,1)

p^ [1j¿] = O$_n$(¢Lv^n)

1/¿ log (HO$_n$(¢Lv^n) / H¢) ! a:s: ¡ ' L any ¢ 2 (0L1)
3

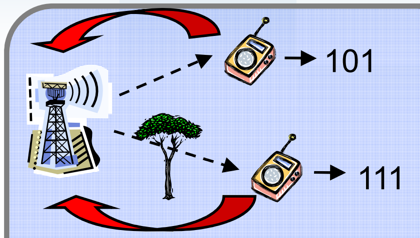
) " p ¡ p^ [1j¿] > 2$^{i\ nC}$! 0

- **Side benefit**: provides a conceptually simple understanding of how PM scheme uses feedback to achieves capacity

ASSUMPTIONS AND LIMITATIONS:

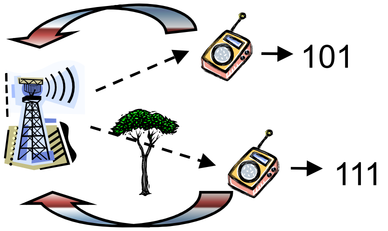
- Noiseless feedback
- Memoryless Channels

IMPACT



- Provides **explict** capacity-achieving **recursvie encoders and decoders**
- Can be extended to **networks** with tight converses

NEXT-PHASE GOALS



Use Stochastic Control methodology for a **principled, canonical approach** to address:

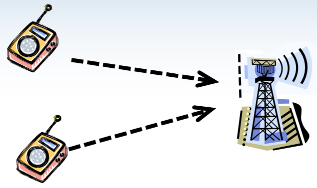
- noisy feedback (POMDP)
- Unknown channel (Q-learning)
- Delayed feedback

A Canonical Controls Methodology to Design Iterative Feedback Coding Systems in MANETs

Efficient Codes using Channel Polarization

Bakshi, Jaggi, and Effros

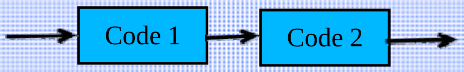
STATUS QUO



- ***Practical capacity achieving schemes are not known for general multi-input multi-output channels***

- ***Codes based on channel polarization that achieve capacity for point-to-point, degraded broadcast and MAC have poor error performance***

NEW INSIGHTS



Concatenating Polar and R-S codes gives the best properties of both

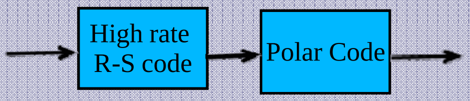
- Use Polar codes as Code 2 as they achieve capacity

- Use R-S codes as Code 1 to reduce error probability

- Complexity of encoding and decoding is almost linear in blocklength

ACHIEVEMENT DESCRIPTION

At each encoder:



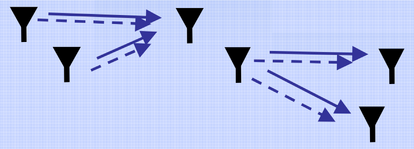
How it works:

- Divide input of blocklength N into N/f(N) sub-blocks of length f(N) each
- Apply high rate R-S code on the entire input followed by a polar code on each sub-block
- Decode the two stages one by one
- When the polar fails on few of the sub-blocks, the R-S code can correct the error
- P(error) decays as exp(-o(N)); Complexity is O(N poly log N); excess rate goes to 0 asymptotically

Assumptions and limitations:

- Works for channels where capacity-achieving codes are known (e.g. point-to-point channels, degraded broadcast channels, multiple access channels)
- Dependence of error probability on excess rate unknown

IMPACT



- Practical coding schemes for several different types of channels that have the following properties:

- Low complexity

- Low delay

- Capacity achieving

NEXT-PHASE GOALS

Find Polar codes or a modification that work for a bigger class of channels

Use insight from the two-stage design to construct a better single stage code – currently works for special cases.

Concatenating Polar and R-S codes leads to more efficient codes for several different channels

Information Theory for Mobile Ad-Hoc Networks (ITMANET): *The FLoWS Project*

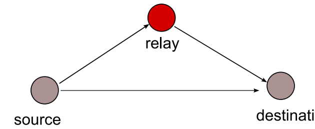
Thrusts 1& 2

Performance Bounds for the Interference Channel with a Relay

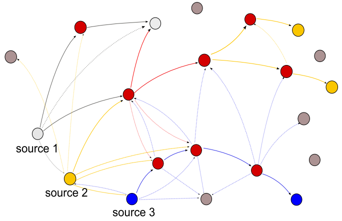
Ivana Marić, Ron Dabora and Andrea Goldsmith

STATUS QUO

Several relaying strategies for forwarding information to a single receiver exist



Capacity of networks are still unknown; one of the key obstacles: how to handle and exploit interference?



What is the performance when relaying for multiple sources?

NEW INSIGHTS

A genie-added approach for an interference channel outer bound extended to the interference channel with a relay. Genie gives a receiver noisy inputs from sources and the relay. Although inputs are dependent (unlike in interference channels), one can still optimize inputs to obtain a bound.

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:

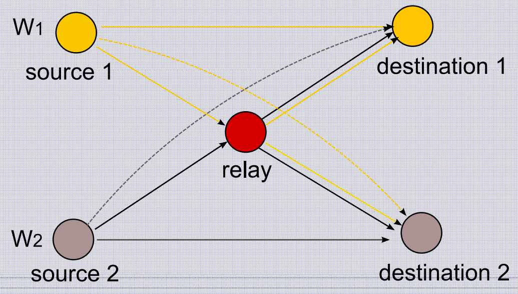
A new sum-rate outer bound to the performance of the Gaussian interference channel with a relay

HOW IT WORKS:

A genie gives to a receiver minimum information needed for decoding both messages

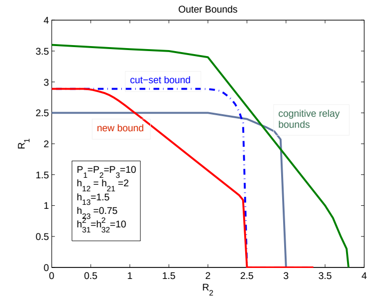
ASSUMPTIONS AND LIMITATIONS:

- The considered channel model: *the interference channel with a relay*
- The genie cannot be turned-off even when not needed i.e., in strong interference regime.

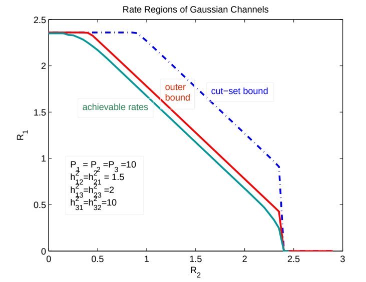


IMPACT

1) Tighter outer bound than cut-set bound and than existing cognitive ICR bounds



2) Close to achievable rates in strong interference



NEXT-PHASE GOALS

- Apply interference forwarding and the outer bound to larger networks

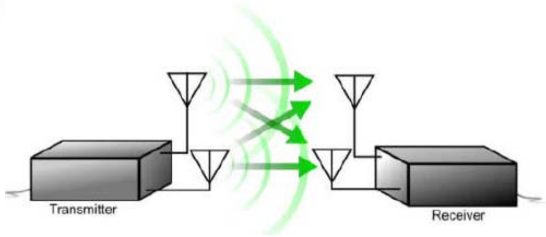
A sum-rate outer bound for the Gaussian interference channel with a relay developed

Joint Source/Channel Coding with Limited Feedback

Deniz Gündüz, Andrea Goldsmith and Vincent Poor

FLOWS & NEQUIT ACHIEVEMENT

STATUS QUO



Separate source and channel coding

Theoretically optimal for static channels

Optimality fails over fading channels with delay constraints

NEW INSIGHTS

-We study the high SNR regime

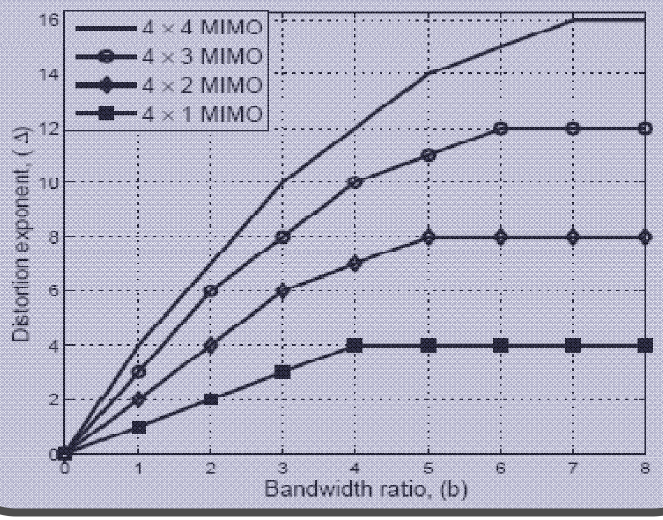
- Consider 1 bit/channel use feedback

- Use feedback as instantaneous ARQ

High SNR behavior of the average distortion in transmitting Gaussian sources over MIMO fading channels: “**distortion exponent**”

Multi-layer source coding followed by multi-rate channel coding

Each source layer is transmitted until successfully decoded by the receiver



IMPACT

- Improves our understanding of how to utilize feedback optimally in communication systems

NEXT-PHASE GOALS

To find the optimal transmission scheme when the feedback resources are limited

One-bit instantaneous feedback helps us achieve the optimal distortion exponent in MIMO systems. Feedback also helps us simplify the transmission scheme.

Capacity and Achievable Rates for the Interference Channel:

Deniz Gündüz, Nan Liu, Andrea Goldsmith and Vincent Poor

FLOWS & NEQUIT ACHIEVEMENT

STATUS QUO

Classical interference channel:

- Each user has one message destined for its own receiver

- Receivers have no side information

NEW INSIGHTS

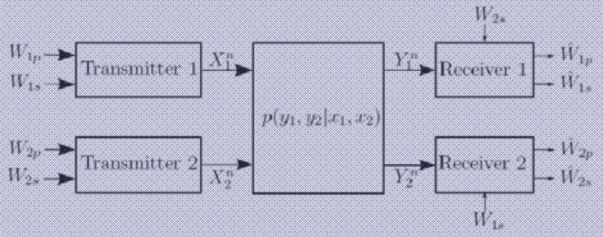
Networks are more complicated:

-Some common messages might be destined for both receivers

- Each receiver might know a part of the interfering message

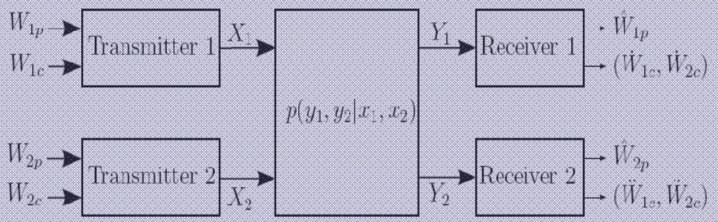
MODEL:

Interference Ch. with Message Side Information



Each receiver knows a part of the interfering message

X-Channel with Degraded Message Sets



Achievable rates for general channel models

These are shown to be capacity achieving for two special classes:

- a class of deterministic interference channels

- a special class of Z-channels

IMPACT

- More general models for interference channels are proposed
- These can model more complicated and realistic networks

NEXT-PHASE GOALS

- Extend the finite-bit capacity results for the classical Gaussian interference channel to these new models

Achievable rates for more general interference channel models.

Multicasting with a Relay

D. Gündüz, O. Simeone, A. Goldsmith, V. Poor and S. Shamai

FLOWS & NEQUIT ACHIEVEMENT

STATUS QUO

In multicasting multiple messages over a network, common strategies are:

- Routing

- Decoding both messages at the relay and using network coding

NEW INSIGHTS

Relay need not decode the messages

Design codes that enable decoding of the modulo sum of the messages at the relay:

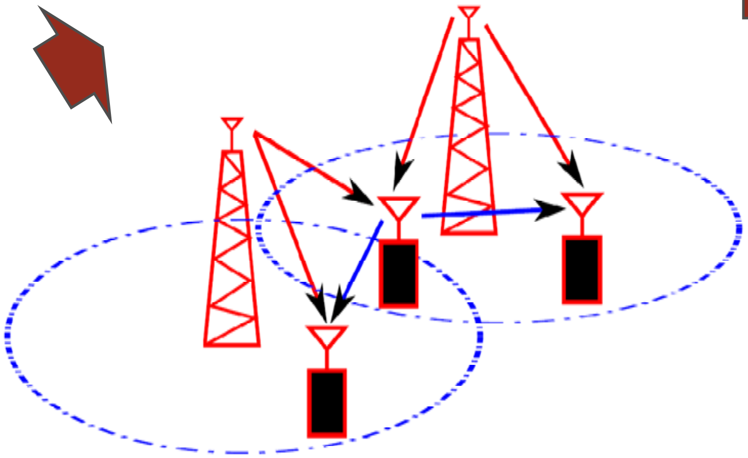
Structured coding

MAIN RESULT:

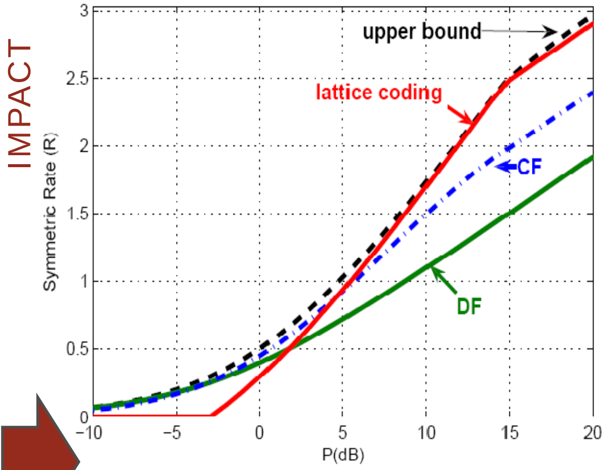
We develop structured codes that exploit the network topology such that the relay decodes and multicasts only the modulo sum of the messages

Linear codes achieve the capacity region for finite-field modulo additive channels

Nested-lattice codes for Gaussian channels: approach the upper bound and surpass standard random coding schemes.



IMPACT



NEXT-PHASE GOALS

- Extension to multiple relays
- Combine structured and random codes for uniformly higher rates

Structured codes improve multicasting rates over a relay network.

The Multi-Way Relay Channel

Deniz Gündüz, Aylin Yener, Andrea Goldsmith and Vincent Poor

FLOWS & NEQUIT ACHIEVEMENT

STATUS QUO

Exact capacity regions are hard to obtain even with three nodes.

Random codes are capacity achieving for many models.

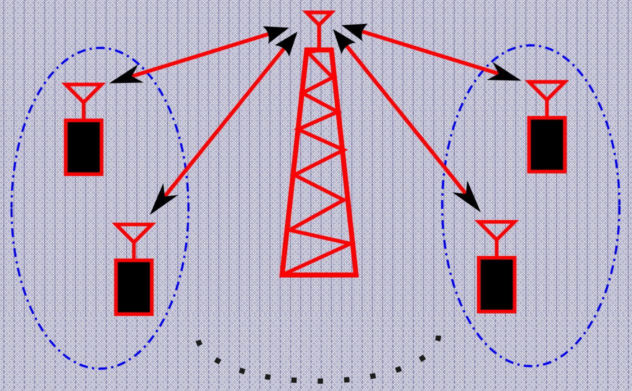
Decode-and-forward relaying used in most practical systems.

NEW INSIGHTS

Joint source-channel coding techniques to achieve higher rates

Structured codes provide higher rates than random coding in some networks

MAIN RESULT:



MODEL:

Clusters of users: Each user in a cluster wants messages of all other users in the same cluster.

Communication is enabled by the relay.

ASSUMPTIONS AND LIMITATIONS:

No signal received from other users

Symmetric capacity for a symmetric system is analyzed

* Achievable symmetric rate is characterized and compared to the upper bound

IMPACT

- Joint source/channel coding helps achieve higher rates in networks
- Compress and forward relaying outperforms other strategies for this network topology

NEXT-PHASE GOALS

- Consider inter and/or intra cluster reception
- Combine structured and random codes
- Characterize non-symmetric achievable rate points

Both compress-and-forward relaying and lattice coding achieve symmetric rates within a constant gap of capacity.

Communication Requirements for Inducing Cooperation

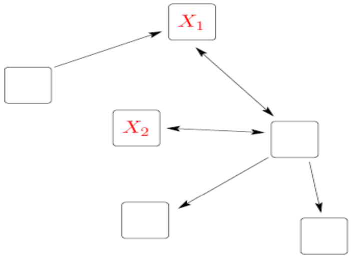
Paul Cuff, Haim Permuter and Thomas Cover

FLoWS

ACHIEVEMENT DESCRIPTION

STATUS QUO

Network information theory is a theory of exchange of information among nodes.



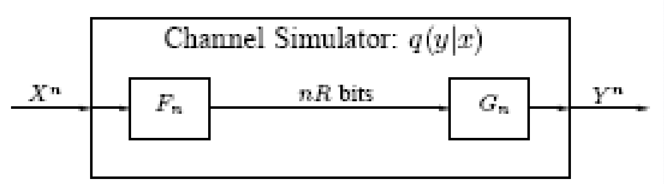
NEW INSIGHTS

We shift emphasis away from information exchange. One of the main purposes of distributed communication is the induced cooperation of the nodes of the network. How much dependence can be set up with a given set of communication constraints?

MAIN ACHIEVEMENT:

Mutual information I(X;Y) characterizes the amount of information that must be sent in order to generate a desired joint distribution.

We characterize the tradeoff between the rate of available common randomness and the communication needed for achieving the desired coordination.



The coordination scheme requires randomization at both encoder and decoder. A codebook of independently drawn sequences U^n is overpopulated so that the encoder can choose one randomly from many that are jointly typical with X^n. The decoder then randomly generates Y^n conditioned on U^n.

ASSUMPTIONS AND LIMITATIONS:

We assume that the desired joint distribution is known.

IMPACT

The result yields results in distributed game theory, task assignment and rate distortion theory. Specifically what is the set of all distributions $p(x_1,x_2,\ldots,x_m)$ inducible under communication rate constraints R_{ij}, $i,j = 1,2,\ldots,m$?

NEXT-PHASE GOALS

We propose investigation of universal coordination schemes that work uniformly well over a family of problems.

We seek a theory of dependence and cooperation in mobile ad hoc networks.

There exists an optimal tradeoff between the amount of common randomness used and the required communication rate

3-Receiver Broadcast Channels with Confidential Messages

Y.K. Chia, A. El Gamal

STATUS QUO

•Information-theoretic secrecy provides a strong notion of secrecy.

•But, capacity results are known only for a small number of setups (the wiretap channel and 2 receivers broadcast channels with degraded message set)

NEW INSIGHTS

•Use a newly introduced technique of "indirect decoding" and the standard techniques of random binning, Marton binning and superposition coding to obtain new bounds on secrecy capacity that are tight is several cases of interest.

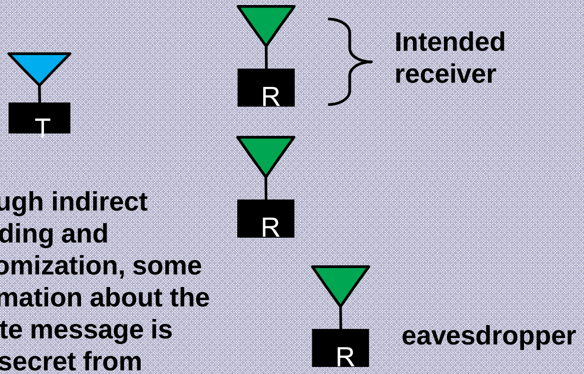
ACHIEVEMENT DESCRIPTION

MAIN RESULT:

- **New rate-equivocation tradeoff regions for 3 receivers broadcast channels with 1 and 2 eavesdroppers**
- **Achieves capacity for several nontrivial special cases**
- **Generalizes inner bounds obtained in previous work**

HOW IT WORKS:

- **Via indirect decoding, legitimate receivers can decode a larger set of messages carried by auxiliary random variables. This improves the rate region**
- **Coding scheme uses randomization to confuse the eavesdropper but in a way which makes the message still decodable by the legitimate receiver**



Through indirect decoding and randomization, some information about the private message is kept secret from eavesdropper

IMPACT

•Secrecy capacity regions for new classes of networks

• New coding techniques for secrecy capacity

NEXT-PHASE GOALS

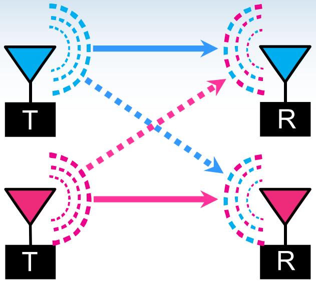
Secret message and key capacities for general network of legitimate receivers and eavesdroppers

Indirect coding is the key to secrecy

Sum Rate of Cyclically Symmetric Interference Channels

Bernd Bandemer, Gonzalo Vazquez-Vilar, Abbas El Gamal

STATUS QUO



- *The Gaussian interference channel (IC) is practically relevant*
- *Its capacity is a long-standing open problem*
- *Asymptotic results and bounds with constant gap have been obtained*

NEW INSIGHTS

A finite-field deterministic IC correctly reflects the asymptotic behavior of Gaussian IC.

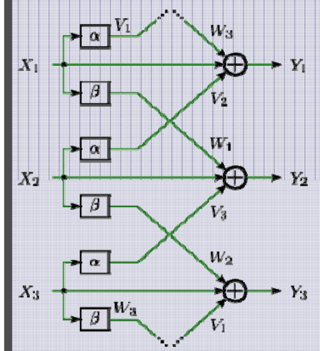
Coding in this model takes the form of simple single-letter bit pipe assignments.

The sum capacity for a cyclically symmetric, locally connected interference channel has been found using this model.

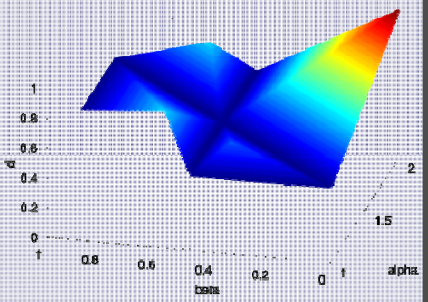
ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:

Sum capacity is established for a K-user-pair, cyclically symmetric, deterministic interference channel with local interference (Wyner model).



Channel model with cross gain shifts alpha and beta



Normalized symmetric capacity as function of cross gains

HOW IT WORKS:

Achievability: Established using bit pipe assignments that depend on the interference parameters α,β.

Converse: The optimality of the assignments is proved via standard weak converse techniques.

ASSUMPTIONS AND LIMITATIONS:

Channel gains are known globally. Symmetry is assumed in the channel and the data rates.

IMPACT

Progress has been made in understanding the capacity of the Gaussian interference channel

Worst- and best-case interference conditions can be identified

Immediate practical implications in full-reuse multi-user wireless systems

NEXT-PHASE GOALS

- *Transform asymptotic result into upper and lower bound on capacity with finite gap*
- *Extension to*
  - *Non-symmetric rates*
  - *Non-symmetric channel*
  - *Fully connected channel*
- *Systematic ways to find optimal assignments*

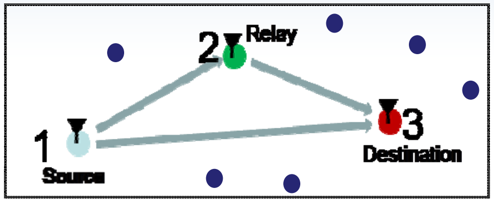
We compute the sum capacity of a K-user deterministic interference channel

Towards Harnessing Relay Mobility in MANETs

Naini, Moulin

ACHIEVEMENT DESCRIPTION

STATUS QUO

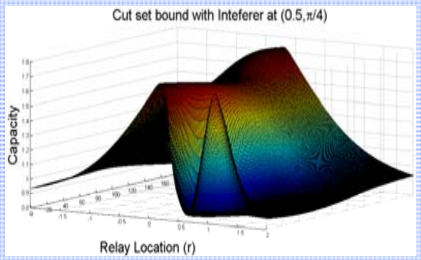


Relay Locations are taken as a given

Link-level Relaying Protocol is independent of network configuration

Mobility of nodes viewed in a passive setting

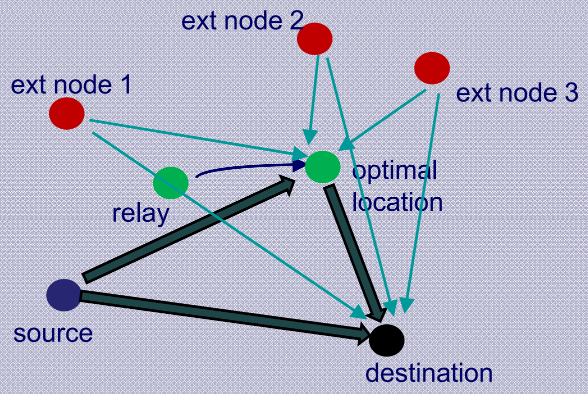
NEW INSIGHTS



Relay location and scheme are crucial especially in a network with other interfering nodes

MAIN RESULT:

Network configuration dependent Optimal Relay Locations and Schemes under restricted mobility



HOW IT WORKS:

Correlated Noise at the Relay and the Destination due to the rest of the network

Optimal Location chosen based on available mobility region

Certain scenarios favor Decode-Forward while others entail Interference Mitigation through Compress-Forward

ASSUMPTIONS AND LIMITATIONS:

Gaussian Channel Models are assumed

An adjusted Quadratic Path Loss exponent is used

Network Configuration should be known to the relay

IMPACT

A step towards establishing optimal node locations to maximize throughput in a large network

Illustrates the potential of Compress-Forward scheme in a highly correlated noise regime

Establishes need for node cooperation in a large network with multiple end-end streams to maximize throughput

NEXT-PHASE GOALS

Investigate parallel data-streams with dedicated mobile relays in a multi-objective game-theoretic setting.

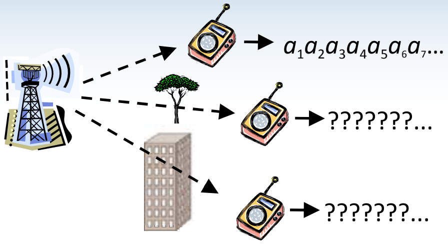
Understand the role of mobility in other adhoc network blocks.

Devise mobility strategies for cooperative multi-hop relaying

Relay mobility can improve Network Capacity

Transmission over composite channels with combined source-channel outage: *Goldsmith and Mirghaderi*

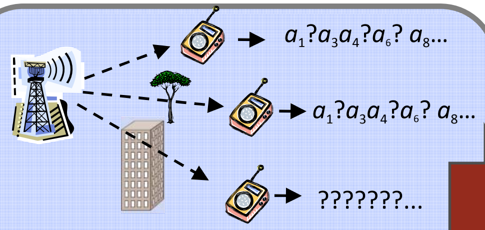
STATUS QUO



Composite channel model captures non-ergodic nature of MANET

Transmission with channel outage over a composite channel leads to the total loss of data with a certain probability in exchange for higher rates in non-outage states

NEW INSIGHTS



Allow partial loss in each block of data to lower the probability of total loss.

Tx. declares ***source outage*** *with certain probability to avoid "high rate" source outputs,Less distortion for other outputs.*

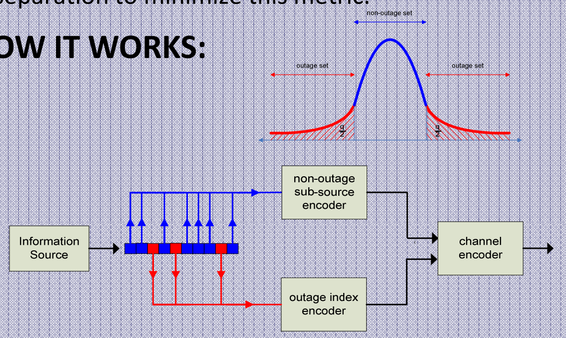
Does separation theorem hold in a combined source-channel outage scenario?

ACHIEVEMENT DESCRIPTION

MAIN RESULT:

We define an end-to-end distortion metric, Distortion vs. Combined Outage and prove the optimality of source and channel code separation to minimize this metric.

HOW IT WORKS:

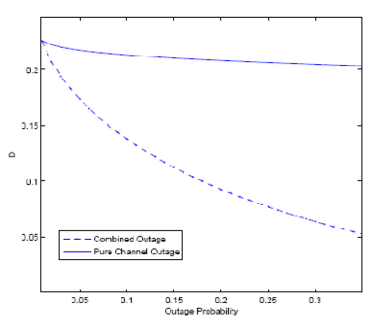


- Useful when partial loss of information is acceptable and only the low distortion of the retrieved data is concerned.
- Select the optimal source outage set (with prob. q_s) from the source alphabet and also the channel outage set (prob. q_c).
- Compress the non-outage subsequence of the source output and transmit along with the source outage indices using a separate channel code.
- In non-outage channel states, identify the source outage indices and then reconstruct the non-outage subsequence.

ASSUMPTIONS AND LIMITATIONS:

- Perfect CSI at Rx., Statistics (channel capacity vs. outage) known at Tx. Given a certain loss prob. trade-off b/w q_s and q_c
- Source is stationary and ergodic

IMPACT



Considerably lower distortion as compared with pure channel outage

Design flexibility provided by source channel code separation

NEXT-PHASE GOALS

Consider a more general case with different end-to-end distortion requirements for different subsets of the source alphabet.

Extend the work to a network scenario where different reconstructions of a common information source are available at multiple nodes and are to be transmitted to a single receiver

Investigate the effect of a feedback channel to this problem

Combination of source and channel outage can improve the performance of lossy transmission systems

Information Theory for Mobile Ad-Hoc Networks (ITMANET): *The FLoWS Project*

Thrust 3

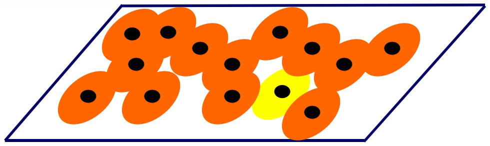
Application Metrics and Network Performance

Asu Ozdaglar and Devavrat Shah

Asymptotic Analysis for Large Scale Dynamic Stochastic Games

S. Adlakha, R. Johari, G. Weintraub, A. Goldsmith

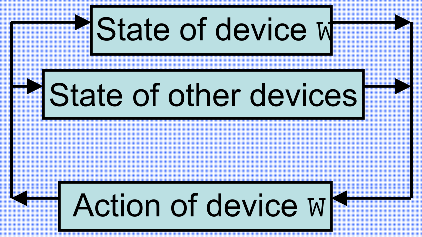
STATUS QUO



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.

NEW INSIGHTS

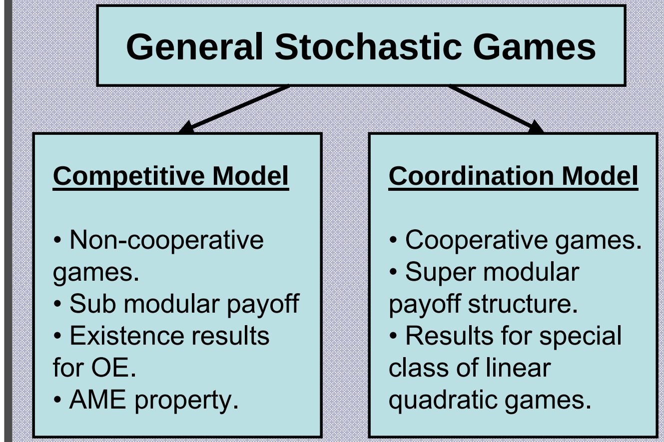


In principle, tracking state of other devices is ***complex.***

We approximate state of other devices via a ***mean field limit.***

ACHIEVEMENT DESCRIPTION

MAIN RESULT: Taxonomy of Stochastic Games



General Stochastic Games

Competitive Model

- Non-cooperative games.
- Sub modular payoff
- Existence results for OE.
- AME property.

Coordination Model

- Cooperative games.
- Super modular payoff structure.
- Results for special class of linear quadratic games.

HOW IT WORKS:

- Existence results for competitive model are based on continuity arguments.
- AME property for a competitive model is derived from the fact that opponents at higher states lead to lower payoff.

ASSUMPTIONS AND LIMITATIONS:

- Mean field requires all nodes to interact with each other – applies to Dense networks only
- Coordination model requires different existence proof

IMPACT

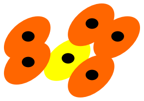
General Framework for interaction of multiple devices

Further, our results:

- provide common thread to analyze both competitive and coordination models.
- provide exogenous conditions for existence and AME for competitive models
- provide results on a special class of coordination model – linear quadratic tracking games.

NEXT-PHASE GOALS

Provide existence and AME results for general class of coordination games.

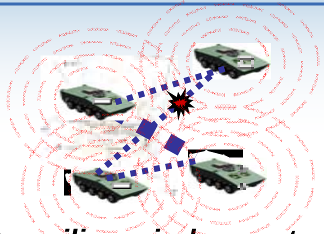


Our main goal is to develop a related model that applies when a **single node interacts with a small number of other nodes each period.**

New Paradigm for analyzing large scale competitive and coordination games

Adaptive modulation with smoothed flow utility
Boyd, Akuiyibo, O'Neill

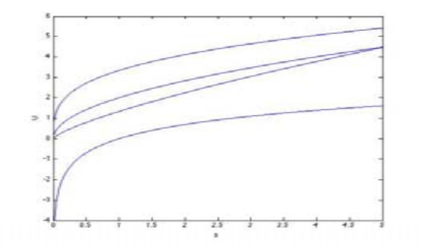
STATUS QUO



Prevailing wireless network utility maximization and resource allocation methods focus on per period optimization

These methods ignore the heterogeneous time scales over which network applications need resources

NEW INSIGHTS



- *Derive network utility from smoothed flows*
- *Smoothing allows us to model the demands of an application that can tolerate variations in flow it receives over a time interval*

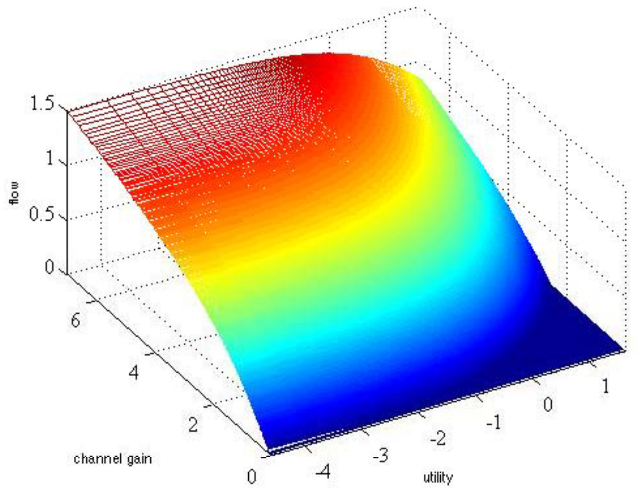
ACHIEVEMENT DESCRIPTION

MAIN RESULT:

Flow allocation to optimally trade off average smoothed flow utility and power.

HOW IT WORKS:

Optimal flow policy is a complicated function of smoothed flow and channel gain

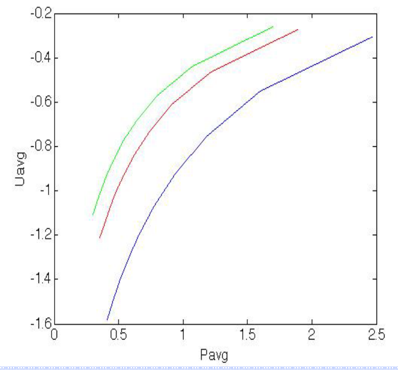


ASSUMPTIONS AND LIMITATIONS:

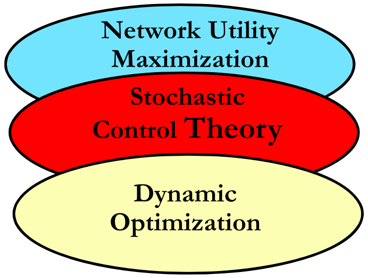
- Utilities are strictly concave, power is strictly convex; linear dynamics represent time averaging
- At each time period, assumes the transmitter learns random channel state through feedback

IMPACT

Different levels of smoothing lead to different optimal policies; different trade offs



NEXT-PHASE GOALS



Network Utility Maximization

Stochastic Control Theory

Dynamic Optimization

Approximate dynamic programming (ADP) for MANETs

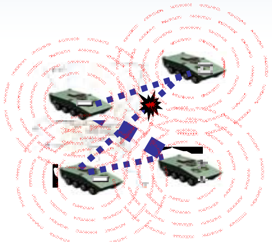
- *computationally tractable*

Optimally trade off average utility and power using smoothed flow utilities

Network Aware Design: Dynamic/Stochastic NUM

Boyd, Goldsmith, ONeill

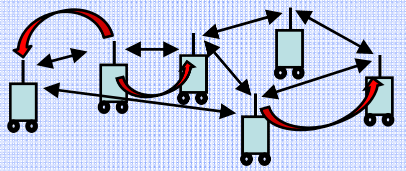
STATUS QUO



MANET performance sub-optimal. Not linked to changes in

- *Tactical wireless environment*
- *Traffic needs: Delay, Throughput, Priority.*

NEW INSIGHTS



Complex dynamics

- *Random time varying RF environment – new opportunities*
- *Time based QoS*

New tools based on

- *Stochastic Optimization*
- *Approx MDP*
- *Model Predictive Control*

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:

Wireless NUM – Learning Based

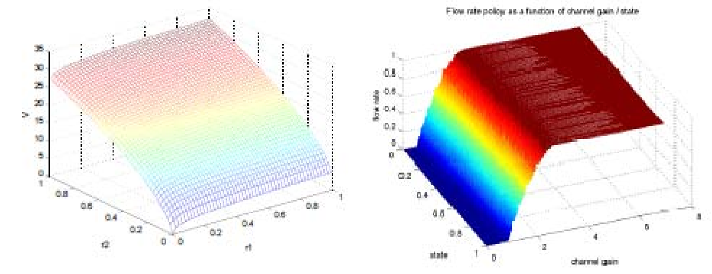
- Data Delivery Contracts and prioritization
- Distributed approaches
- Multi-time scale convergence applications

Multi-Period NUM

- Optimal control policies for infinite horizons
- Average cost infinite horizon Markov models
- Approximate relative value functions

HOW IT WORKS:

- Multi-period statistical approach to model properties of environment and traffic learn parameters



ASSUMPTIONS AND LIMITATIONS:

Unbiased CSI

Explicit QoS requirements

IMPACT

$$\max \ \lim \frac{1}{N}\sum E\Big[\sum_m U(r_m(G),\phi_m(G))\Big]$$

subject to

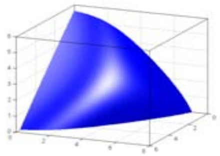
$$\begin{aligned}
&\lim \frac{1}{N}\sum \ E\big[S_l(G)\big]-\bar{S}_l \le 0\\
&\lim \frac{1}{N}\sum \ E\big[Ar\big]-E\big[Diag(\theta(G))R(S(G),G)\big]\le 0\\
&\lim \frac{1}{N}\sum \ E\big[\phi(G)\big]-(1-E\big[A^T\vartheta(\theta(G))\big])\le 0\\
&0\le\theta(G)\le 1\\
&0\le\phi(G)\le 1
\end{aligned}$$

Improved performance and optimal resource allocation.

Quantify cost of traffic (QoS)

Explore rate-delay-energy trade-offs

NEXT-PHASE GOALS



Performance on Energy-Delay-Capacity Surface

- Approx MDP -Dimensionality reduction, Value function approximation and online learning
- Approx. optimal policies

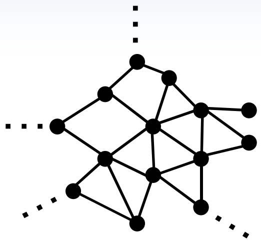
Dynamically Optimize Network Resources to Match Traffic Needs

Supermodular Network Games

V. Manshadi and R. Johari

ACHIEVEMENT DESCRIPTION

STATUS QUO

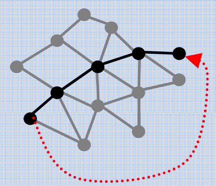


Supermodular games:
Games where nodes have strategic complementarities

Network (or graphical) games:
Games where nodes interact through network structure

NEW INSIGHTS

A node's actions can have significant effects on *distant* nodes.



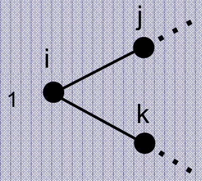
Centrality, coreness: **Global** measures of power of a node

We characterize equilibria in terms of such global measures

MAIN RESULT:

Payoff of agent i:

$\Pi_i(x_i, x_j, x_k) =$
$u(x_i, x_j+x_k) - c(x_i)$



We assume utility exhibits *strategic complementarities.*

We show:

- Membership in larger k-core implies higher actions in equilibrium
- Higher centrality measure implies higher actions in equilibrium
- If nodes don't know network structure, largest equilibrium depends on *edge perspective* degree distribution

HOW IT WORKS:

We exploit *monotonicity* of the best response to prove our results:

The best action for node i is
increasing in its neighbor's actions.

ASSUMPTIONS AND LIMITATIONS:

We study equilibria of a *static* game between nodes.

The eventual goal is to understand *dynamic* network games.

IMPACT

Local interaction does **not** imply weak correlation between far away nodes in cooperation settings.

Centrality measures need to be used to quantify the effect of the network.

NEXT-PHASE GOALS

This model assumed a *static* interaction between the nodes.

Our end-of-phase goal is to develop *dynamic* game models of coordination on networks.

The power of a node in a networked coordination system depends on its centrality (global properties) not just on its degree (a local property)

Q-learning Techniques for Network Optmization: W. Chen & S. Meyn

STATUS QUO

What is the state of the art and what are its limitations?

Control by learning: obtain a routing/scheduling policy for the network that is approximately optimal with respect to delay & throughput.

Can these techniques be extended to wireless models?

NEW INSIGHTS

KEY NEW INSIGHTS:

- Extend to wireless? YES

Complexity is similar to MaxWeight. Policies are distributed and throughput optimal.

- Learn the approximately optimal solution by Q-learning is feasible, even for complex networks.
- New application: Q-learning and TD-learning for power control.

ACHIEVEMENT DESCRIPTION

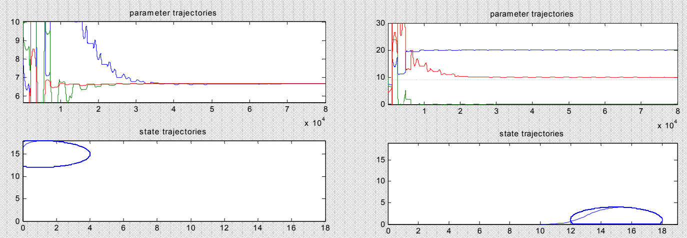
MAIN RESULT:

Q-Learning for network routing: by observing the network behavior, we can learn the optimal priority for each buffer or a small class of buffers, depending on the range of available local information.

Near optimal performance with simple solution:

Q-learning with steepest descent or Newton Raphson Method via stochastic approximation

- Theoretical analysis for the convergence and properties.
- Simulation experiments are on-going.



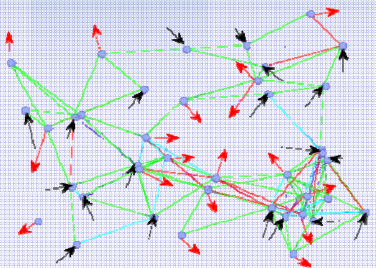
HOW IT WORKS:

Step 1: Generate a state trajectory.

Step 2: Learn the best value function approximation by stochastic approximation.

Step 3: Policy for routing: *h-MW policy derived from value function approximation*

NEXT PHASE GOAL



- Implementation – Consensus algorithms & Information distribution
- Adaptation – kernel based TD-learning and Q-learning
- Integration with Network Coding projects: *Code around network hot-spots*

IMPACT

- Un-consummated union challenge: Integrate coding and resource allocation
- Generally, solutions to fluid model should offer insight for the stochastic model

Algorithms for dynamic routing: Visualization and Optimization

Distributed Scheduling via Reversible Dynamics

Devavrat Shah Jinwoo Shin

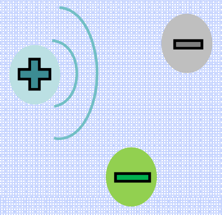
STATUS QUO

Medium Access Control (MAC) is fundamental protocol of modern wireless communication

•Random backoff protocols popular

•But, they usually perform poorly

NEW INSIGHTS



Distributed Algorithms via Reversible Dynamics

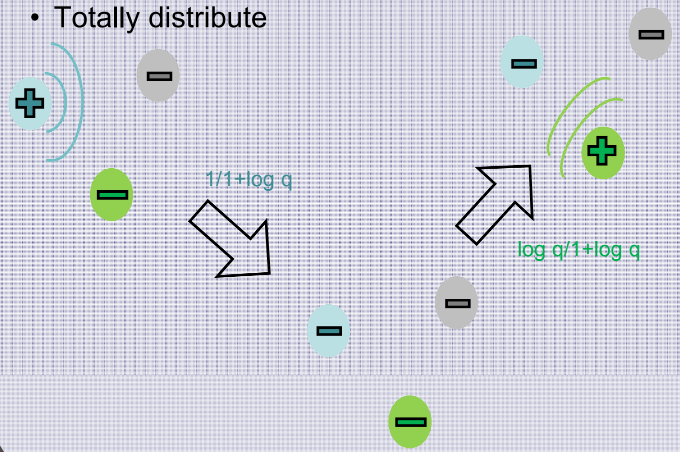
- A new theory for efficient distributed, simple network algorithm design

ACHIEVEMENT

MAIN ACHIEVEMENT:

An *efficient* MAC protocol

- Random backoff style with access probability function of queue-size
- Totally distribute



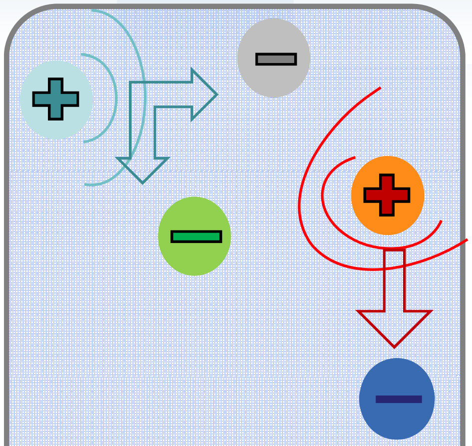
HOW IT WORKS:

- Random backoff probability proportion to the logarithm of queue-size
- Performs literally unit amount of computation per time step

ASSUMPTIONS AND LIMITATIONS:

- Carrier sensing information

IMPACT



Finally, after a long history, we have a fully distributed MAC protocol that is indeed optimal

New theory for distributed algorithm design

NEXT-PHASE GOALS

Beyond oblivious MAC

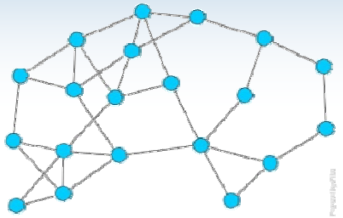
- dealing with hidden terminal
- Improving delay through utilization of geometry

Resolution of a long standing challenge for network & info. Th.: efficient MAC protocol

A Distributed Newton Method for Network Utility Maximization

(*Wei , Ozdaglar, Jadbabaie*)

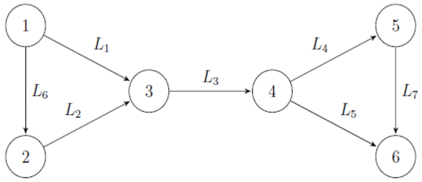
STATUS QUO



Most existing distributed optimization algorithms rely on first order methods

- *These algorithms are easy to distribute*
- *However, they can be quite slow to converge, limiting their use in rapidly changing dynamic networks*

NEW INSIGHTS

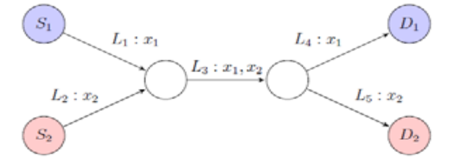


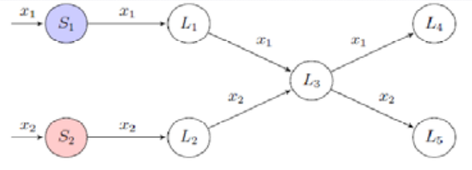
Combine Newton (second order) methods with consensus policies to distribute the computations associated with the dual Newton step

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:

- A Newton method that solves general network utility maximization problems in a distributed manner
- Simulations indicate the superiority of the distributed Newton method over dual subgradient methods





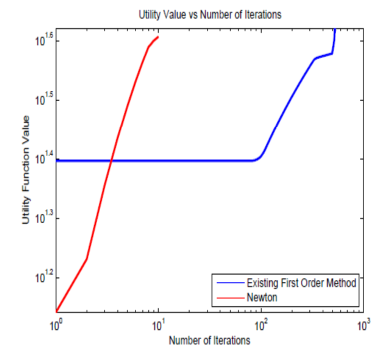
HOW IT WORKS:

- Turning inequality constraints into barrier functions
- Employing matrix splitting techniques on the dual graph to solve the dual Newton step
- Using a consensus-based local averaging scheme, which requires local information only

ASSUMPTIONS AND LIMITATIONS:

- Routing information and capacity constraints are fixed
- Dual and primal steps are computed separately

IMPACT



Significant improvements with the distributed Newton method compared to subgradient methods

NEXT-PHASE GOALS

Second order methods for distributed network utility maximization

- Prove convergence and rate of convergence of our methods
- Understand the impact of network topology on algorithm performance
- Design algorithms that compute primal and dual steps simultaneously

Novel Distributed Second Order Methods for Network Utility Maximization Problems

Dynamic Resource Allocation for Delay-Sensitive Applications
(Menache, Ozdaglar, Shimkin)

STATUS QUO

Most existing work on resource allocation in networks considers:

- *“Static” scenarios*

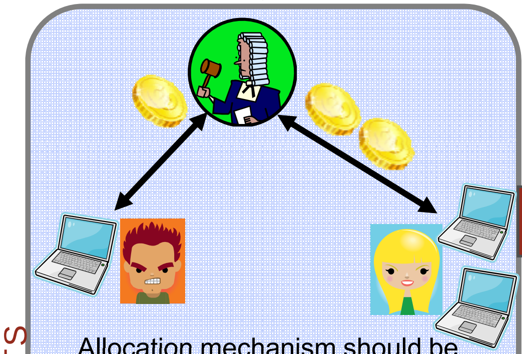
•*Rate (throughput) related performance metrics*

However, in many applications:

•Resource not required when *“job is done”* -> Dynamic resource allocation

•Relevant performance metric: Delay or Completion Time

NEW INSIGHTS



Allocation mechanism should be simple; users should have a clear notion of price.

•*Natural candidate: Proportional fair mechanism, where the allocated capacity remains **constant** and is proportional to the bid.*

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:

A tractable and general framework for the analysis of delay performance of a dynamic resource allocation mechanism.

➢*Existence and uniqueness of a Nash equilibrium*

➢*Preliminary results on efficiency loss*

HOW IT WORKS

- Each (price-taker) user solves a simple optimization problem, accounting for a delay-price tradeoff.
- We employ a **fluid-scale approximation** of the stochastic service system.
- Under the approximation, queue sizes “freeze”, giving rise to a fixed steady-state price.

ASSUMPTIONS AND LIMITATIONS:

While the proposed fluid model is motivated by the stochastic system, we do not provide here a formal convergence result that relates the two.

IMPACT

•Our model allows for fairly general dependence of delay on the allocated resource, thus suitable for different applications.

•The fluid approximation is appropriate under overloaded systems, where the user arrival rate and system resources become large.

•Possible applications:

➢Cloud-computing facility

➢Dynamic spectrum access in wireless networks

NEXT-PHASE GOALS

•Efficiency loss bounds for different delay functions.

•Dynamic stability properties

Higher-level goals:

•Comparisons with other resource allocation mechanisms.

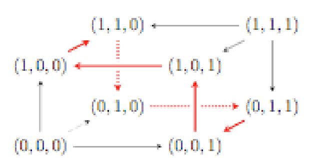
•General network architectures

A fluid-Scale approximation is used to gain insights on the equilibrium of a *dynamic* resource allocation mechanism

Canonical Decompositions of Games and Near Potential Games (Candogan, Menache, Ozdaglar, Parrilo)

FLoWS

STATUS QUO



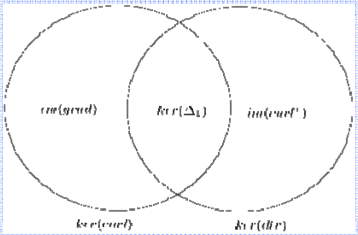
The analysis of the dynamic properties of non-cooperative user interaction is usually hard.

-Potential games is a class of games in which natural dynamics converge to a Nash equilibrium

-However, potential games is a small subset of games.

-Can we extend the class of games with desirable properties?

NEW INSIGHTS



Helmholtz decomposition of vector fields

- Analysis of the global structure of preferences in games
- *Canonical decomposition*
- *Approximating any game with its closest potential game*

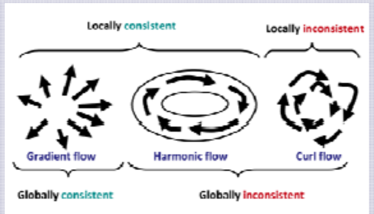
ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:

- *Any game can be decomposed to 3 orthogonal components*: ***Nonstrategic, Potential, Harmonic***
- *The dynamic properties of near potential games are analyzed by considering the properties of their potential component*

HOW IT WORKS

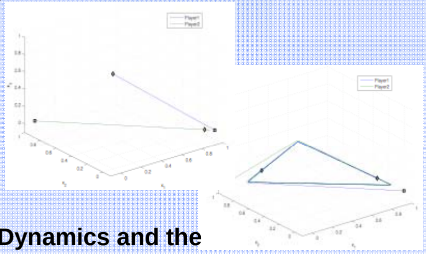
- Decomposition of the vector flows of any game to gradient, harmonic and curl flows.



- The potential component corresponds to the gradient flow
- The dynamic and equilibrium properties of potential games are approximately carried over to near potential games

ASSUMPTIONS AND LIMITATIONS:
It is not clear how to find the closest **ordinal** potential game to a given game

IMPACT

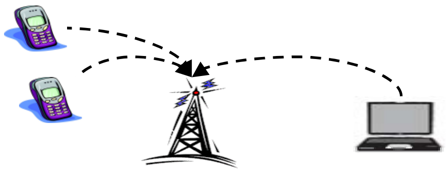


Dynamics and the potential component

Simpler analysis of dynamics and equilibrium properties in general games

Natural dynamics converge to a small neighborhood of a pure equilibrium

NEXT-PHASE GOALS



Applications of the paradigm to non-cooperative scenarios in networks:

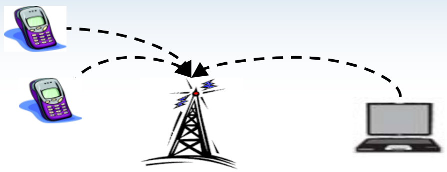
- Implications in the design of network protocols.
- Supplemental mechanisms for regulating networks to desirable working points (e.g., pricing)

The canonical decompositions of games are useful for understanding their static and dynamic equilibrium properties

Near-Optimal Power Control in Wireless Networks: A Potential Game Approach (Candogan, Menache, Ozdaglar, Parrilo)

FLoWS

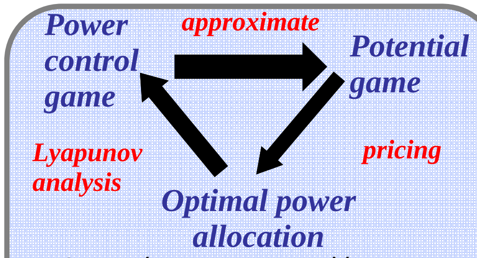
STATUS QUO



Most work on wireless games focus on static equilibrium properties without establishing convergence of distributed dynamics.

-There is no systematic framework for providing simple incentive mechanisms that can achieve an arbitrary system objective.

NEW INSIGHTS



Power control game

approximate

Potential game

Lyapunov analysis

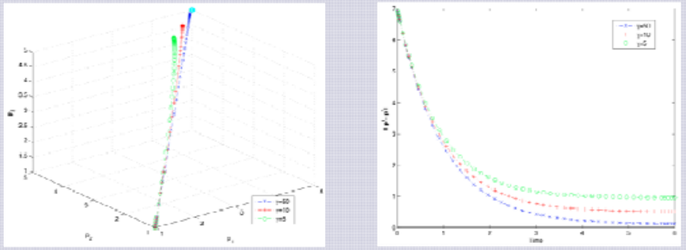
pricing

Optimal power allocation

- *Approximate a game with a "close" potential game*
- *Exploit the appealing properties of potential games, such as convergence of* ***distributed*** *(best-response) dynamics*

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:



The evolution of power levels

Distance between current and desired power allocation

The *Potential-Game Approach* *(approximately) enforces any power-dependent system-objective among competing users under natural dynamics.*

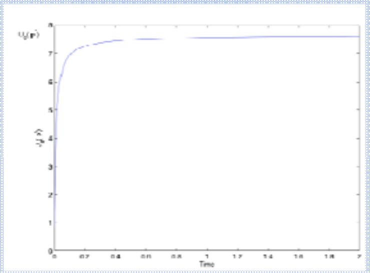
HOW IT WORKS:

- *Approximate the underlying power control game with a* "close" potential game
- Derive prices that induce an optimal power allocation in the potential game
- The proximity between the two games establishes near optimal performance in the original game in the limit of distributed dynamics.

ASSUMPTIONS AND LIMITATIONS:

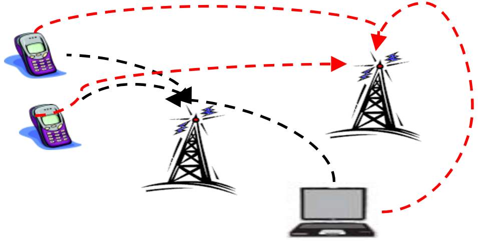
- Single-band networks
- Approximation is better for high-SINRs

IMPACT



- Simple pricing scheme that can be used for any system objective
- Performance guarantees in the dynamical sense.
- A new paradigm for regulation of wireless networks

NEXT-PHASE GOALS



- Multichannel networks
- Enhanced pricing schemes for low-SINR regime
- Distributed implementation of price generation

Potential-game approximations lead to simple pricing schemes for any system objective.

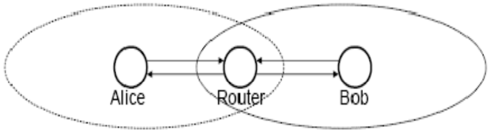
Information Theory for Mobile Ad-Hoc Networks (ITMANET): *The FLoWS Project*

Thrusts 1 & 3

On the stability region of networks with instantaneous decoding *Traskov, Medard, Sadeghi, Koetter*

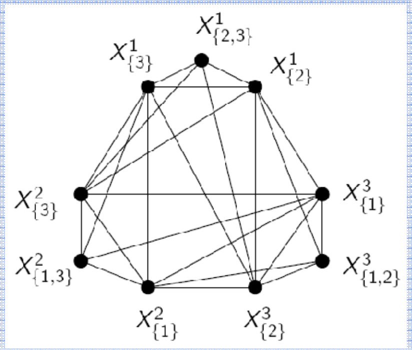
ACHIEVEMENT DESCRIPTION

STATUS QUO



- Opportunistic XOR-coding shows significant gains.
- However, stability region of instantenous decoding is not known.

NEW INSIGHTS

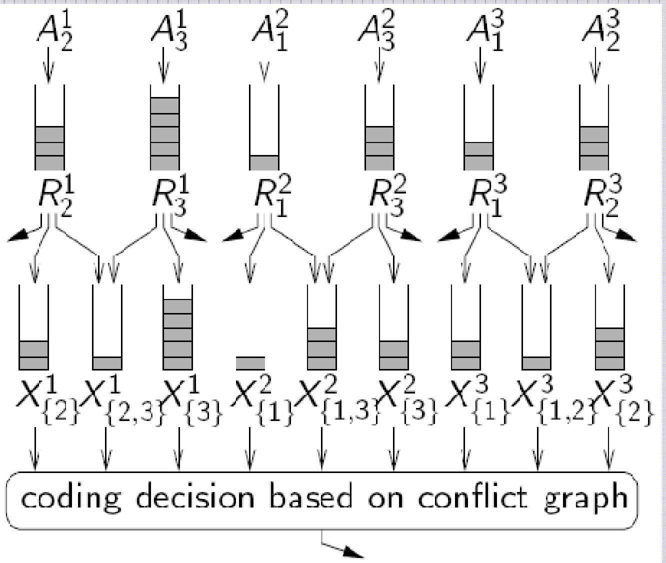


- Can formulate decoding constraints in a graphical model
- Constrained queuing system

MAIN ACHIEVEMENT:

Derive **stability region** under instantaneous decoding and provide **online scheduling and network coding** algorithm.

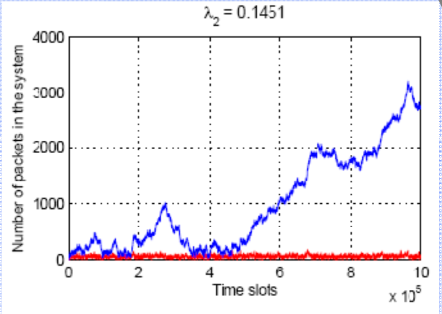
HOW IT WORKS:



ASSUMPTIONS AND LIMITATIONS:

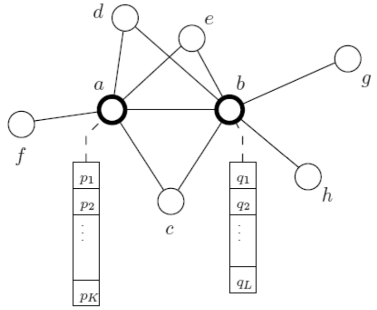
- Need ACKs or NACKs
- Network coding limited to relay

IMPACT



Network coding (red) increases the stability region over routing (blue) and leads, on average, to smaller delays.

NEXT-PHASE GOALS



- Include analog network coding. Here, nodes *a* and *b* coordinate their transmission.

Instantaneous decoding increases the stability region and reduces delay.

Information Theory for Mobile Ad-Hoc Networks (ITMANET): *The FLoWS Project*

Thrusts 1, 2 & 3

Distributed Lossy Averaging

Han-I Su and Abbas El Gamal

STATUS QUO

- *Most work on distributed averaging has involved the noiseless communication and computation of real numbers, which is unrealistic.*
- *The distributed lossy averaging problem is a generalization of the CEO problem, for which the rate region is known for Gaussian sources and MSE distortion. The averaging protocol in our setting is more complex since it allows for interactivity, relaying, and local computing, in addition to multiple access.*

NEW INSIGHTS

- **We present a lossy source coding formulation of the distributed lossy averaging problem.**
- **The information-theoretic results shed light on the fundamental tradeoff in distributed computing between communication and computation accuracy.**

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:

- Found the rate distortion function for 2-node network with correlated Gaussian sources
- A cutset lower bound on the network rate distortion function for general networks with independent white Gaussian noise sources
- A centralized protocol over a star network which achieves the cutset bound within a factor of 2
- A lower bound on the network rate distortion function for *distributed weighted-sum protocols*, which is larger then the cutset bound by a factor of (log m) in order
- An upper bound on the expected weighted-sum network rate distortion function for gossip-based weighted-sum protocols, which is at most (log log m) larger than the above lower bound

HOW IT WORKS:

The bounds are obtained using a mix of information theory, linear systems and results from gossip protocols.

ASSUMPTIONS AND LIMITATIONS:

- The upper bounds generalize to non-Gaussian sources, but the lower bounds do not.

IMPACT

- **New problem formulation**
- **Upper and lower bounds on the network rate distortion function for centralized and distributed protocols are given**
- **The results suggest that using distributed protocols results in a factor of (log m) increase in order relative to centralized protocols.**

NEXT-PHASE GOALS

- *Characterize the improvement of using the correlation (side information) between the node estimates*
- *Establish bounds for computing general functions*

An information-theoretic formulation of the distributed lossy averaging is presented.