# Control over Lossy Networks:

# The Interplay Between Coding and Control


Babak Hassibi

Joint work with Ravi Teja Sukhavasi

Department of Electrical Engineering

California Institute of Technology, Pasadena, CA 91125


*Workshop on Interactive Information Theory*
*Banff International Research Station for Mathematical Innovation and Discovery*

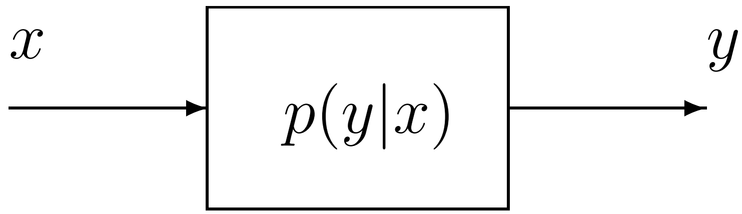
*Banff, Alberta, CANADA, January 16, 2012*

# Outline

- **Introduction**
  - information theory and coding: algebraic and graph-based codes
  - control theory: LQG control
- **Interplay between control and communication**
  - coding for interactive communications: tree codes
  - control over noisy channels: anytime capacity
  - estimation over lossy channels
- **Construction of linear tree codes**
  - existence with high probability
  - efficient decoding for erasure channels
  - examples
- **Conclusion**
  - future work and open problems

# Single-User Information Theory

Single-user information (Shannon 1948) deals with the study of the fundamental limits of reliable information transmission between a sender and a receiver over a noisy channel




$$C = \max_{p_X(\cdot)} \{H(x) + H(y) - H(x, y)\}$$

*Key idea:* Block coding

- the behavior of the channel over a single use is unpredictable
- but the behavior over many channel uses is:
  - if the channel introduces errors with probability $p$, say, over $n \gg 1$ channel uses it will introduce $\approx np$ errors

# Coding Theory

- start with $b = \{b_i\}_{i=1}^{m}$ bits (the message)
- map them to $c = \{c_i\}_{i=1}^{n}$ bits (encoding, rate = $\frac{m}{n}$)
- the set of all codewords, $c$, is denoted by $\mathcal{C}$ ($|\mathcal{C}| = 2^m$)
- if $c = \{c_i\}_{i=1}^{n}$ is transmitted across the channel and $y = \{y_i\}_{i=1}^{n}$ is received, then the maximimum likelihood decoder is

$$\hat{c} = \arg\max_{c \in \mathcal{C}} p(y|c)$$

Shannon showed that for all rates $\frac{m}{n} < C$, *there exists a sequence of codes*, such that

$$\lim_{n \to \infty} P(\hat{c} \neq c) = 0.$$

## Information Theorists Live in Asymptopia

This is nice theory and an elegant result. However,

- it may require unlimited computational resources at the transmitter and receiver (encoding and decoding may need exponential time)
- it assumes asymptotically long delays ($n \to \infty$)
  - encoding can be done only *after* all the bits $\{b_i\}_{i=1}^n$ are available
  - decoding can be done only *after* all the outputs $\{y_i\}_{i=1}^n$ are observed

## In Practice...

- one cares about the probability-of-error as a function of the rate and the length of the code (error exponents)
- one cares about codes that can be efficiently encoded and decoded
  - algebraic codes
    * Reed-Solomon, Reed-Muller, algebraic geometry
    * Berlekamp-Massey, list-decoding (Guruswamy-Sudan), etc.
  - graph-based codes
    * turbo codes, LDPC codes, expander codes
    * message-passing, bit-flipping, LP decoding, etc.
  - polar codes

In summary, after 60 years of work, we have practical codes that come close to the Shannon limits in many cases.

## A Critique...

An early criticism (albeit philosphical) of information was that it *did not involve time*

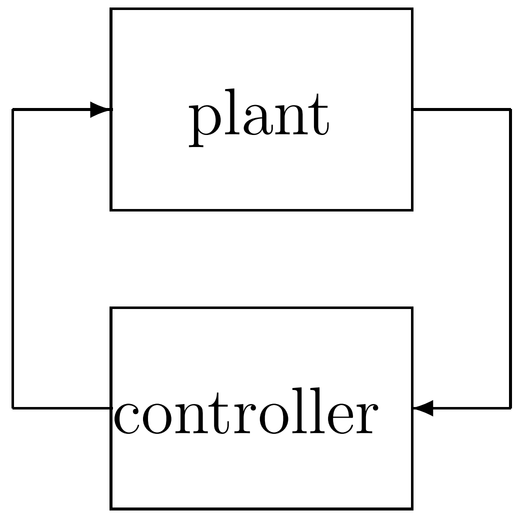
- the "information" obtained about knowledge of an event, depends only on the probability of that event

$$\log \frac{1}{p},$$

  not on *when* this knowledge is revealed or when we want to take action on this knowledge

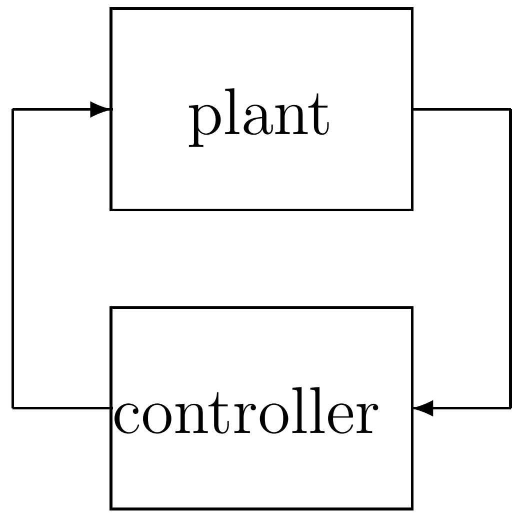
- issue never quite resolved (things like directed mutual information, or the entropy rate of a random process don't quite cut it)
- problem is that information-theoretic quantities often require some form of ergodicity to have operational significance

# Control Theory



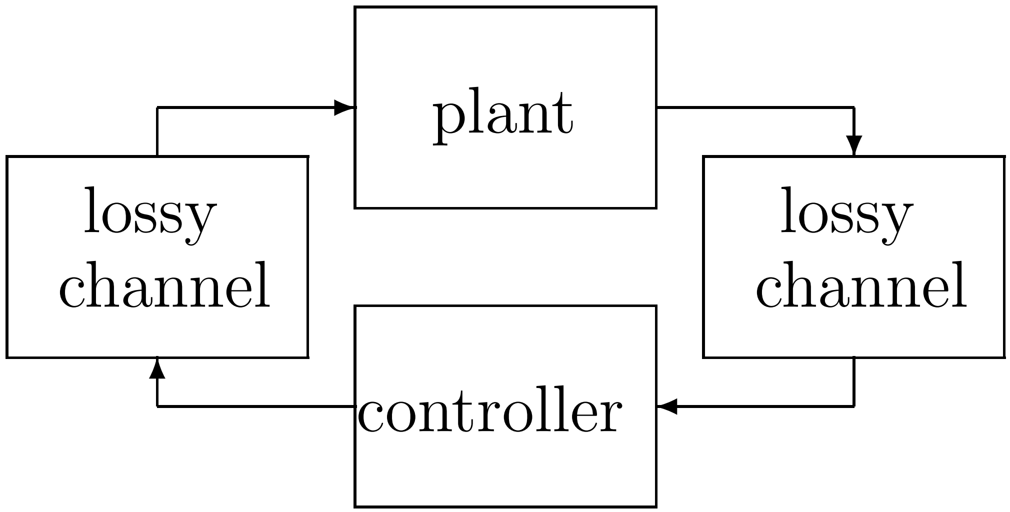

- in control theory we observe the output of a dynamical system (plant) and design a controller to regulate its behavior
- controller needs to react and generate control signals on the fly (*in real-time*)
- the introduction of delay can result in loss of performance and/or instability

# Control Theory



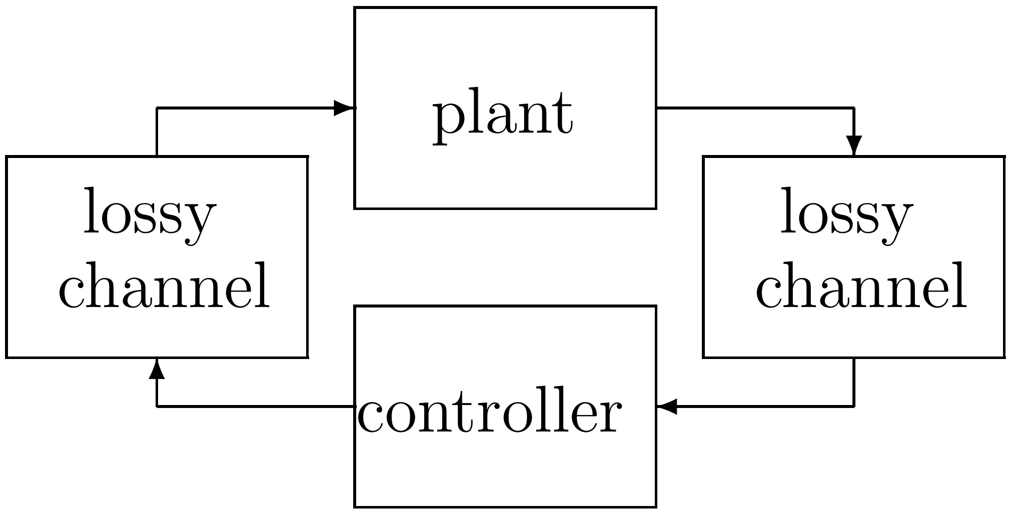

- very rich theory has been developed (especially in the LTI case)
  - LQG control, $H^\infty$ control, Kalman filtering, separation principle
- virtually no interaction with information theory
  - plant and controller often co-located, no measurement loss

# But what if...?



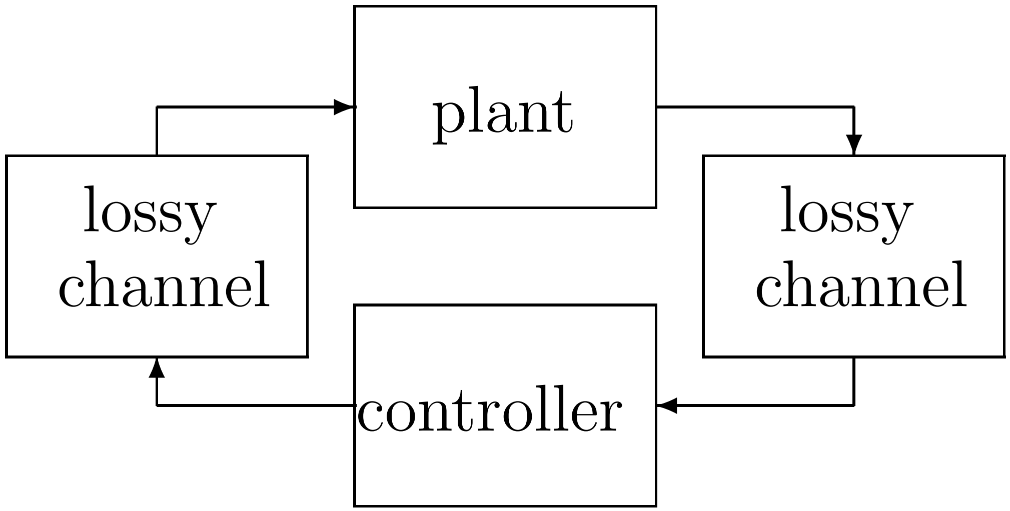

- increasingly we have applications where systems (autonomous agents, sensor/actuator networks, smart grid, etc.) are remotely controlled and where measurement and control signals are transmitted across noisy channels
- conventional channel coding does not work - the ensuing delay may lead to instability

## Living with the Noisy Channels...?




- if the noisy channels are erasure channels, Sinopoli et al (2005) showed that if the erasure probability is high enough then the closed loop system will be unstable
- similar results hold for other classes of channels

## What to Do?




- the problem is that if we cannot tolerate large delays, we cannot make the noisy channels reliable
- but do we need to do that?
- what do we need to guarantee the stability of the closed loop system?

# Coding for Interactive Communications

Consider a two-party communication system

Alice, $x$ Bob, $y$

$$s_1 = f_1(x)$$

$$- - - - - - - \longrightarrow$$

$$s_2 = f_2(y, s_1)$$

$$\longleftarrow - - - - - - -$$

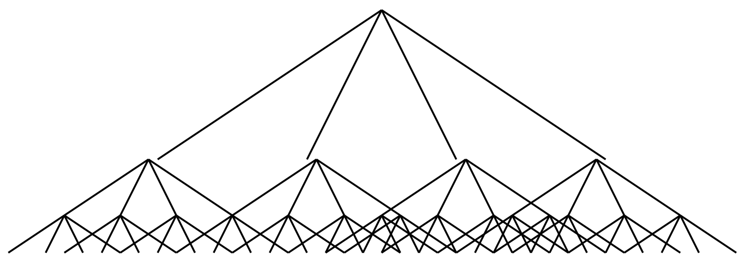
$$s_3 = f_3(x, s_1, s_2)$$

$$- - - - - - - \longrightarrow$$

$$\vdots$$

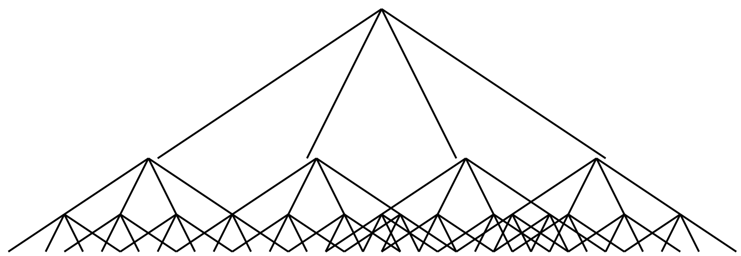
Can one do this reliably over noisy links?

# Tree Codes (Schulman, 1993)



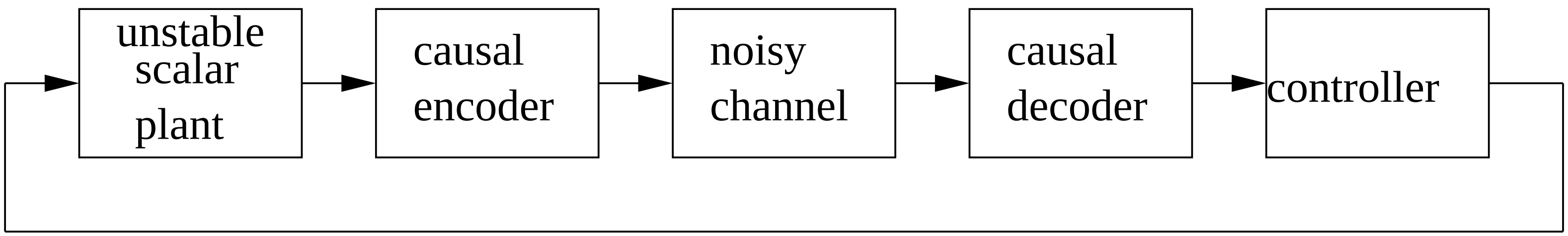
- semi-infinite $d$-ary tree
- each edge labeled by a symbol in an alphabet of size $d' > d$
- maps a sequence $\{s_i\}_{i=1}^{\infty}$ to a sequence $\{c_i\}_{i=1}^{\infty}$, where $s_i \in \{0, 1, \ldots, d-1\}$ and $c_i \in \{0, 1, \ldots, d'-1\}$
- represents a *causal* code; each path is a codeword; $R = \frac{\log d}{\log d'}$

# Tree Codes (Schulman, 1993)



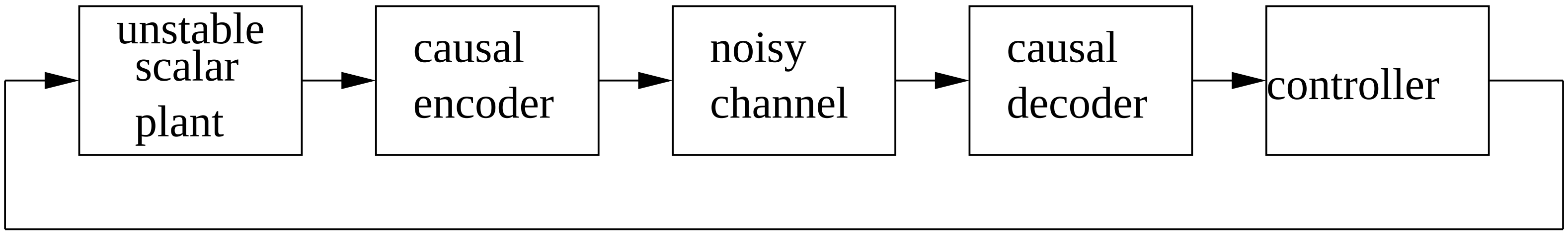
- for *every* pair of paths with a common ancestor and length $n$, say, we require that the "Hamming distance" between the paths be *at least a fixed proportion of* $n$
- Schulman proved the existence of tree codes
- along with ML decoding, allows reliable interactive communication over a noisy link
- **Problem:** No explicit constructions; no tractable decoding; existence result is not with high probability

# Anytime Capacity (Sahai, 2001)




- scalar unstable LTI system
- noisy channel from plant output to controller
- each measured output quantized to $k$ bits; *causally* encoded and transmitted across channel
- controller attempts to *causally* decode transmitted bits, estimate state of the system and generate a control signal to stabilize the plant

# Anytime Capacity (Sahai, 2001)




- how big should $k$ be?
- given that we cannot reliably recover the transmitted bits, can we even stabilize the system?
- what sort of fidelity do we need?

## Toy Example: Tracking an Unstable Plant

$$x_{i+1} = ax_i + w_i, \quad |a| > 1, \quad w_i \in \{-1, 1\} \text{ (unknown)}$$

Assume the initial state $x_0 = 0$ is known to the encoder and controller.

- clearly, at each time instant, the encoder should try to convey 1 bit of information to the controller indicating whether $w_i = 1$ or $w_i = -1$
- the encoder will causally encode this sequence of bits $\{b_i\}_{i=0}^{\infty}$ and send them across the channel
- the decoder, at each time instant $i$, will attempt to decode the *entire* bit sequence $\{b_j\}_{j=0}^{i}$ and obtain $\{\hat{b}_{j|i}\}_{j=0}^{i}$

# Toy Example: Tracking an Unstable Plant

Define

$$P_e(i,d) = \text{Prob}(\hat{b}_{j|i} = b_j, \forall j < i-d, \hat{b}_{i-d|i} \neq b_{i-d})$$

This is the probability that the first error happens $d$ time steps in the past.

- Then the mean-square error is bounded by

$$E(x_{i+1} - \hat{x}_{i+1|i})^2 \leq \sum_{d=1}^{i} \left( \frac{a^d - 1}{a-1} \right)^2 P_e(i,d) < \frac{1}{(a-1)^2} \sum_{d=1}^{\infty} |a|^{2d} P_e(i,d).$$

- Clearly, if there exists $K$, $\epsilon$ and $\Delta$, such that for all $i$ and $d > \Delta$:

$$P_e(i,d) < K|a|^{-2d-\epsilon},$$

  we will have $E(x_{i+1} - \hat{x}_{i+1|i})^2 < \infty$, for all $i$, i.e., we will have *mean-square stability.*

- **Remark:** For mean absolute stability, we just need $P_e(i, d) < K|a|^{-d-\epsilon}$

**Conclusion:** We do not need arbitrary reliability. Only a reliability that decays appropriately exponentially fast with the delay.

# Anytime Capacity

- *Definition:* A channel will be said to have "anytime capacity" $C_{any}(\lambda)$, for some parameter $\lambda > 1$, if for all rates $R < C_{any}(\lambda)$, there exists causal encoding and decoding schemes such that

$$P_e(i,d) < K\lambda^{-d-\epsilon}, \quad \forall i,\ \forall d > \Delta$$

- *Theorem:* Consider a scalar LTI system

$$\begin{cases} x_{i+1} & = ax_i + w_i + u_i \\ y_i & = x_i + v_i \end{cases} \qquad |\lambda| > 1$$

  where $w_i$ and $v_i$ are *bounded* disturbances. Then to stabilize this system over a noisy channel it is necessary and sufficient that

  1. $k > \log|\lambda|$
  2. $R = \frac{k}{n} < C_{any}(|\lambda|)$

- The theorem is based on the use of tree codes

# Some Problems

This is an elegant result, but...

- there are no explicit constructions of tree codes with efficient decoding
- there is very little hope of actually computing $C_{any}(\lambda)$
  - this requires computing optimal error exponents for tree codes
  - even for block codes optimal error exponents have not been computed
- there are no "necessary and sufficient" conditions for systems with vector states

What to do...?

## Linear Tree Codes

- linear codes can be represented by *generator* or, equivalently, *parity check* matrices
- a linear tree code will thus clearly have a lower triangular generator matrix

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \vdots \end{bmatrix} = \begin{bmatrix} G_{11} & & & \\ G_{21} & G_{22} & & \\ G_{31} & G_{32} & G_{33} & \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ \vdots \end{bmatrix},$$

where $b_i \in GF_2^k$, $c_i \in GF_2^n$ and $G_{ij} \in GF_2^{n \times k}$

- equivalently, the parity check matrix can be made lower triangular

$$\begin{bmatrix} P_{11} & & & \\ P_{21} & P_{22} & & \\ P_{31} & P_{32} & P_{33} & \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \vdots \end{bmatrix} = 0$$

  where $P_{ij} \in GF_2^{(n-k)\times n}$

- *Do linear tree codes exist?* Requires $P_e(i,d) < K\lambda^{-d-\epsilon}$, for all $i$ and $d > \Delta$. This requires two union bounds (which kills things)—hence Schulman's approach

# Toeplitz Linear Tree Codes

- trick is to make the code Toeplitz

$$\begin{bmatrix} G_0 & & & \\ G_1 & G_0 & & \\ G_2 & G_1 & G_0 & \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

  and

$$\begin{bmatrix} P_0 & & & \\ P_1 & P_0 & & \\ P_2 & P_1 & P_0 & \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

- this makes the code "look the same" at all times $i$, and so we avoid the union bound over $i$

# Existence of Tree Codes with High Probability

**Theorem:** Choose the entries of the entries of the matrices $\{G_i\}_{i=1}^{\infty}$ independently from Bernouli($\frac{1}{2}$) and consider a binary-input channel with Bhattacharya parameter

$$\zeta = \int_{-\infty}^{\infty} \sqrt{p(y|b=1)p(y|b=0)}dy.$$

Then with probability $1 - 2^{-\Omega(n\Delta)}$, for all rates satisfing

$$R < 1 - \log(1+\zeta),$$

there exists a $K$ such that the probability of ML decoding satisfies

$$P_e(i,d) < K2^{-\beta d}, \quad \forall i,\ \forall d > \Delta$$

where

$$\beta < H^{-1}(1-R)\left(\log\frac{1}{\zeta} + \log(2^{1-R}-1)\right).$$

- The theorem holds exactly if we choose the entries of the $\{P_i\}_{i=0}^{\infty}$ from Bernouli($\frac{1}{2}$)
- For the BSC($p$), the Bhattacharya parameter is $2\sqrt{p(1-p)}$ and therefore

$$R < 1 - \log(1 + 2\sqrt{p(1-p)}) = 1 - 2\log(\sqrt{p} + \sqrt{1-p}).$$

- For the BEC($\epsilon$), the Bhattacharya parameter is $\epsilon$ and therefore

$$R < 1 - \log(1 + \epsilon).$$

## But What to do About ML Decoding?

- to get the error performance we need, we must do ML decoding *at each time instant*
- for block codes doing this even once is too hard....

# But not for Erasure Channels

- Consider a random block linear code with $(N-K)\times N$ parity check matrix $P$ ($R=\frac{K}{N}$)
- Suppose the codeword $c$ is transmitted and partition it onto the observed entries $c_o$ and the erased entries $c_e$, i.e., $c=\begin{bmatrix} c_o \\ c_e \end{bmatrix}$.
- Now due to the parity check condition $Pc=\begin{bmatrix} P_o & P_e \end{bmatrix}\begin{bmatrix} c_o \\ c_e \end{bmatrix}=0$, we have

$$P_e c_e = P_o c_o$$

- $$P_e c_e = P_o c_o$$

  If the erasure probability of the channel is $\epsilon$, then $c_e$ will have size $\approx N\epsilon$

- If $R = \frac{K}{N} < C = 1 - \epsilon$, then $N - K > N\epsilon$ and the system of linear equations $P_e c_e = P_o c_o$, will, with high probability, have a unique solution.

**Conclusion:** For erasure channels ML decoding is simply matrix inversion

# But What About the Lower Triangular Case?

- for tree codes the matrices $P_e$ and $P_o$ are lower triangular
- therefore even though the matrix $P_e$ has more rows/equations $(N-K)$ than columns/unknowns ($\approx N\epsilon$), the system of equations

$$P_e c_e = P_o c_o,$$

  will most likely *not* have a unique solution (otherwise tree codes would have the same performance of block codes!)
- however, if the tree code corrects all errors above a delay of $d$, this means that if we partition $c_e = \begin{bmatrix} c_{e1} \\ c_{e2} \end{bmatrix}$, where $c_e$ are all the erased entries with delay more than $d$, we must have

$$P_e c_e' = P_e c_e'' \quad \text{implies} \quad c_{e1}' = c_{e2}''$$

- partitioning $P_e$, $P_o$ and $c_o$ similarly, we have

$$\begin{bmatrix} P_{e11} & \\ P_{e21} & P_{e22} \end{bmatrix} \begin{bmatrix} c_{e1} \\ c_{e2} \end{bmatrix} = \begin{bmatrix} P_{o11} & \\ P_{o21} & P_{o22} \end{bmatrix} \begin{bmatrix} c_{o1} \\ c_{o2} \end{bmatrix}$$

or

$$\begin{bmatrix} P_{e11}c_{e1} \\ P_{e21}c_{e1} + P_{e22}c_{e2} \end{bmatrix} = \begin{bmatrix} P_{o11}c_{o1} \\ P_{o21}c_{o1} + P_{o22}c_{o2} \end{bmatrix}$$

pre-multiplying the second set of equations by $P_{e22}^{\perp}$, the orthogonal complement of $P_{e22}$ yields

$$\begin{bmatrix} P_{e1} \\ P_{e22}^{\perp}P_{e21} \end{bmatrix} c_{e1} = \begin{bmatrix} P_{o11}c_{o1} \\ P_{e22}^{\perp}P_{o21}c_{o1} + P_{e22}^{\perp}P_{o22}c_{o2} \end{bmatrix}$$

But this latter system of equations must have a *unique solution* for $c_{e1}$.

# An Efficient Algorithm

1. suppose at time $i$ the bits up to delay $d$ have not yet been decoded (this happens with probability $P_e(i,d) < K\lambda^{-d}$)

2. for these bits, partition $c = \begin{bmatrix} c_e \\ c_o \end{bmatrix}$ and $P = \begin{bmatrix} P_e & P_o \end{bmatrix}$

3. starting with delays $d' = 1, 2, \ldots, d$ check whether the matrix

$$\begin{bmatrix} P_{e1} \\ P_{e22}^{\perp} P_{e21} \end{bmatrix}$$

   has full column rank

4. if so, solve for $c_{e1}$ in the system of equations

$$\begin{bmatrix} P_{e1} \\ P_{e22}^{\perp} P_{e21} \end{bmatrix} c_{e1} = \begin{bmatrix} P_{o11} c_{o1} \\ P_{e22}^{\perp} P_{o21} c_{o1} + P_{e22}^{\perp} P_{o22} c_{o2} \end{bmatrix}$$

5. if this does not happen for any $d' = 1, 2, \ldots d$, go to next time instant

The expected complexity per time instant is constant:

$$\sum_{d=1}^{\infty} K' d^3 \lambda^{-d}$$

Furthermore, the probability that the complexity at any given time instant exceeds $O(d^3)$ decays as $O(\lambda^{-d})$.

**Remark:** With feedback, encoding can also be done with constant expected complexity.

# A Scalar Example

- Take the scalar LTI system

$$\begin{cases} x_{i+1} &= 2x_i + w_i + u_i \\ y_i &= x_i + v_i \end{cases}$$

  where $w_i$ is uniform over $[-30, 30]$ and $v_i$ is uniform over $[-1, 1]$.

- Suppose we want to stabilize this over an erasure channel with erasure probability $\epsilon = 0.3$ and that we have $n = 15$ bits per measurement at our disposal.

- We need an error exponent $2^{-\beta} < \frac{1}{2}$. Using the theorem we can see that we need a rate less than $R < 0.40$, i.e., we should quantize the measurements to at most $k = 5$ bits.

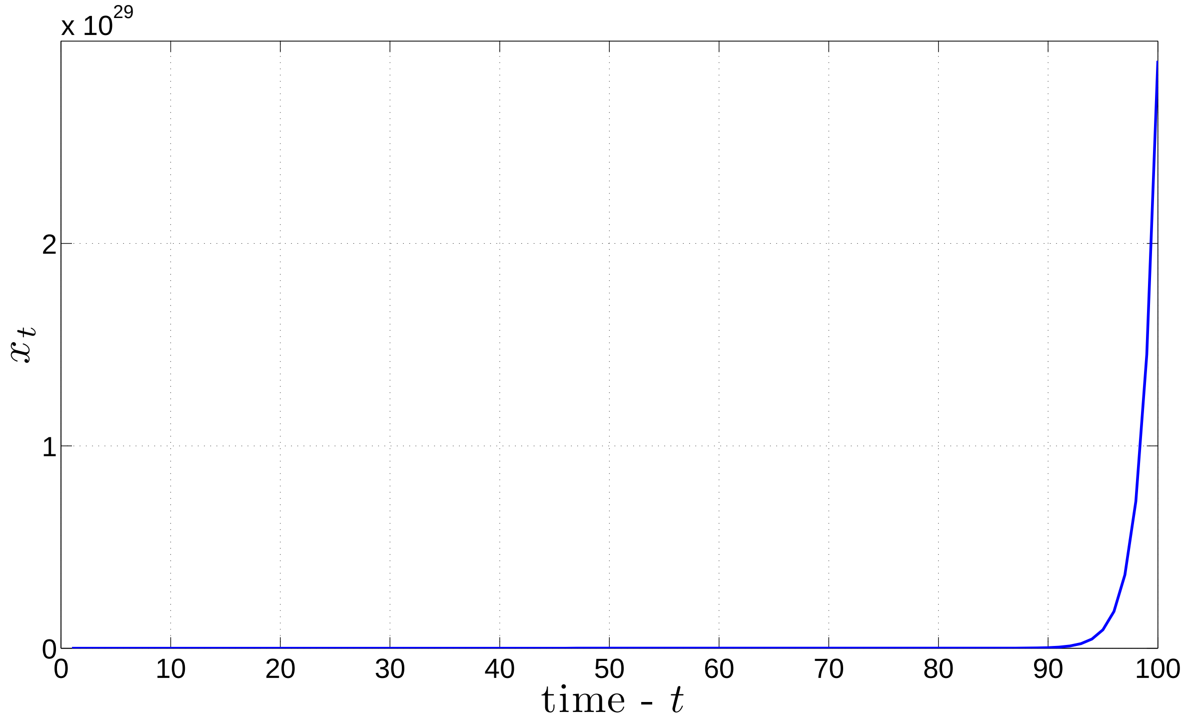



Figure 1: Open loop response.

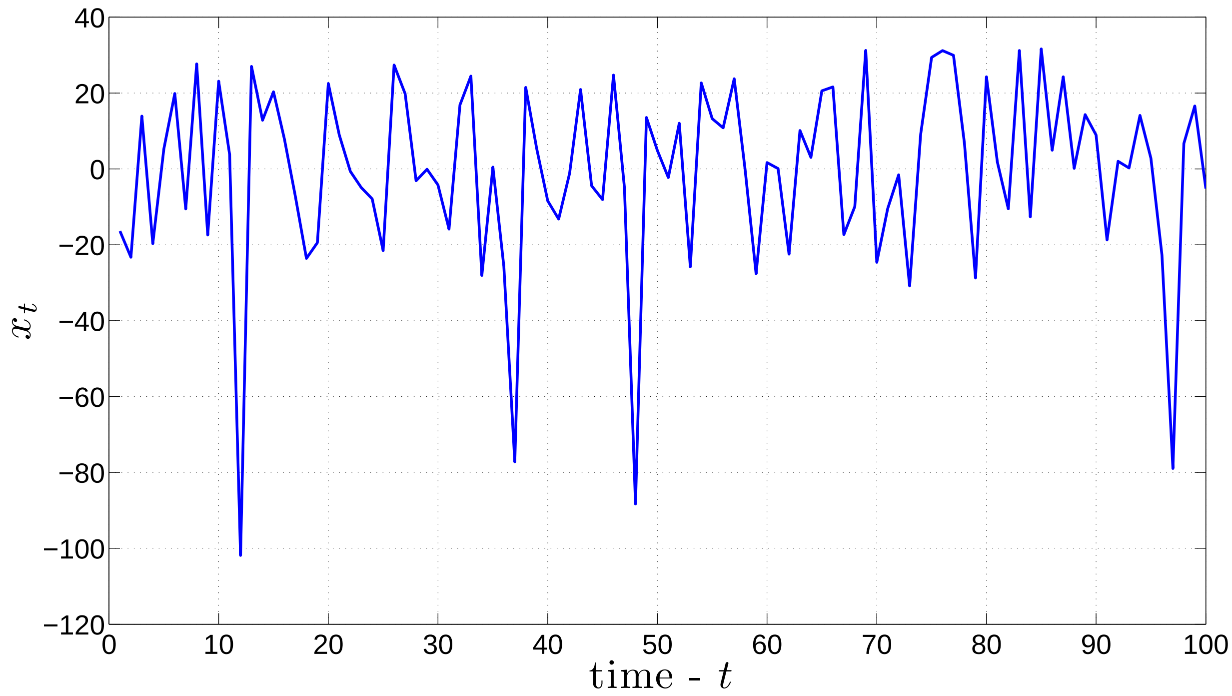



Figure 2: Closed loop response, $k = 5$.

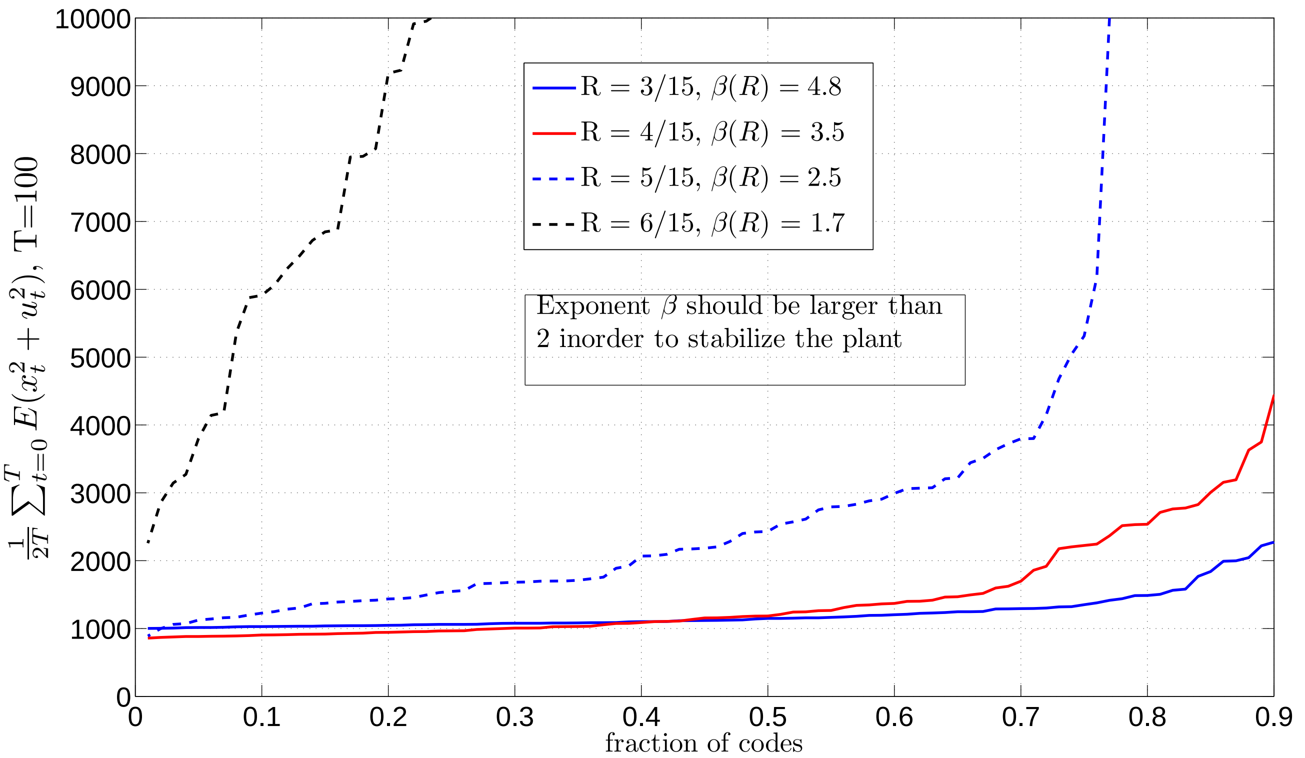



Figure 3: CDF of LQR costs for different realizations of the codes.

# The Vector Case

Necessary and sufficient conditions to guarantee stability for LTI systems with vector state-space is not known. Here is a useful sufficient condition.

- Consider an LTI system with vector state-space, scalar measurement, and *bounded* system and measurement noise.
- Wlog write the state-space system in observer canonical form

$$\begin{cases} x_{i+1} = \begin{bmatrix} -a_1 & 1 & 0 & \dots & 0 \\ -a_2 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ -a_n & 0 & 0 & \dots & 1 \end{bmatrix} x_i + w_i + u_i \\ y_i = \begin{bmatrix} 1 & 0 & 0 & \dots & 0 \end{bmatrix} x_i + v_i \end{cases}$$

Note that the $a_i$ are the coefficients of the characteristic polynomial of the system matrix.

- Let $\lambda > 1$ be the smallest positive number such that the matrix

$$\begin{bmatrix} \frac{|a_1|}{\lambda} & 1 & 0 & \dots & 0 \\ \frac{|a_2|}{\lambda} & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ \frac{|a_n|}{\lambda} & 0 & 0 & \dots & 1 \end{bmatrix}$$

  is stable.

- Then we can stabilize the system (in a mean-square sense) by appropriately quantizing each measurement with $k$ bits and using a tree code, such that
  1. $k > \log \lambda$
  2. $P_e(i, d) < K|\lambda_{max}|^{-2d-\epsilon}$ for all $i$ and $d > \Delta$, where $|\lambda_{max}|$ is the largest eigenvalue of the system matrix (in absolute value).

# A Vector Example

$$\begin{aligned} x_{i+1} &= \begin{bmatrix} 2 & 1 & 0 \\ 0.25 & 0 & 1 \\ -0.5 & 0 & 0 \end{bmatrix} x_i + w_i + u_i \\ y_i &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} x_i + v_i \end{aligned}$$

where $w_i$ and $v_i$ are truncated $N(0,1)$ normals to lie in $[-2.5, 2.5]$.
$\lambda_{max} = 2$.

- We would like to stabilize the plant over an erasure channel with $\epsilon = 0.3$.
- We have $n = 15$ bits per measurement available.
- We need an exponent $< \frac{1}{2}$: an application of the theorem shows that we need a rate $R < 0.43$, hence $k < 7$.

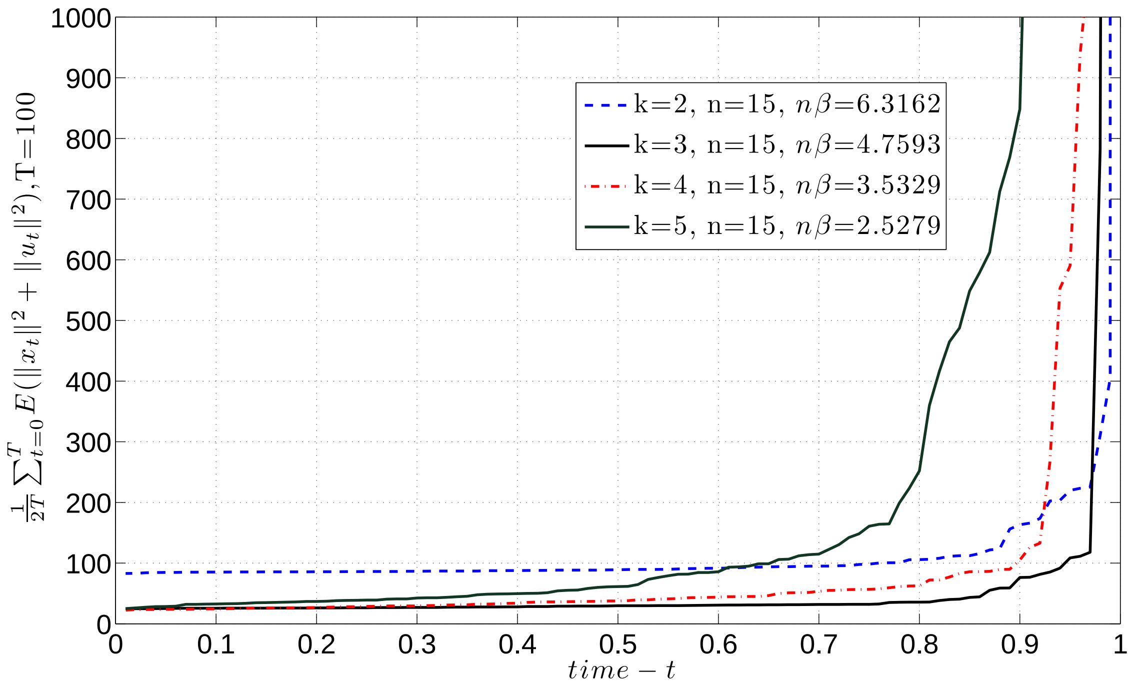



Figure 4: CDF of LQR costs for different realizations of the codes.

## Some Remarks

- We have developed a universal and efficient method for stabilizing plants driven by *bounded* noise over erasure channels
- This is perhaps the most practically interesting case: most systems will probably quantize their measurements to some number of bits, put them in packets and send them across a lossy network (where packets will either be received or dropped)
- Not clear how to deal with unbounded noise (say, Gaussian). Seems to require perfect feedback. Not clear if this is important in practice.
- Stabilizing a plant is the first step. Optimizing performance is the next.
  - this will require studying the trade-offs between control and communication resources
  - shoule we quantize coarsely, but heavily protect the bits, or quantize finely and moderately protect the bits?

## Other Channels

- It would be interesting to develop efficiently-decodable tree codes for other types of channels, especially, the BSC and the AWGNC.
- These appear to be much more challenging, since ML decoding is out of the question.
  - even in the block coding case, the codes that achieve capacity over these channels (such as LDPCs or polar codes) do not do so with an error exponent
  - for example, polar codes approach capacity with a probability-of-error $e^{-\alpha\sqrt{N}}$
- We care about having an error exponent much more than the rate
  - in the block coding case, decoders that achieve an error exponent are those that can correct a fixed fraction of errors
  - Reed-Solomon codes; LDPC and expander codes with bit-flipping and/or LP decoding

## Conclusion

- Traditional information theory lives in Asymptopia—not appropriate for real-time constraints
- Control has long ignored information theory...
- Controlling an unstable plant over a noisy channel is one place where the two must meet
  - the key object is a "tree code" (essentially a causal code), rather than a block code
  - the key criterion is the interplay between the rate and the decay of the probability of error as a function of the delay (anytime capacity)

- For the first time:
  - showed the existence (with high probability) of linear tree codes for a wide class of channels
  - developed an efficiently decodable tree code for erasure channels and demonstrated the efficacy of the method
- This opens up many possibilities for controlling distributed systems over noisy communication links and lossy networks
- It is important to study how best to trade off control and communication resources to optimize system performance
- Developing efficiently-decodable tree codes for other classes of channels is an important and interesting open problem