Information Embedding: From Theory to Practice

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Outline

- Overview and applications
- Information-theoretic models and analyses
- From theory to practice

Part I:
Overview and Applications

Information Embedding

- **Imperceptibly** embed message into cover data (e.g. images, video, audio, text, computer programs) and **communicate** to receiver
- Private receiver (uses secret key) *vs* Public receiver

Public Receiver	**Private Receiver Public Communication**	**Private Receiver Secret Communication**
in-band captioning database annotation	DRM for multimedia authentication content ID transaction tracking networking	steganography timing channels

Digital Rights Management

- Watermarking is used for copyright protection of Hollywood releases
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- In 2004, watermarking made it possible to trace a bootlegged DVD back to a movie screener for the Motion Picture Academy
- Now he has plenty of time to watch DVDs

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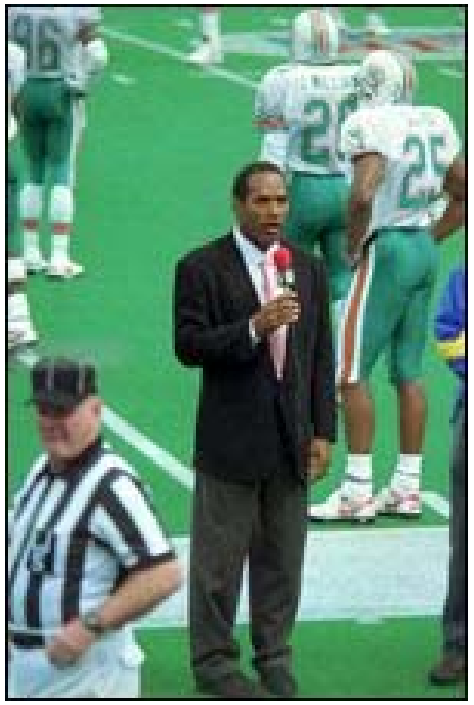
Authentication

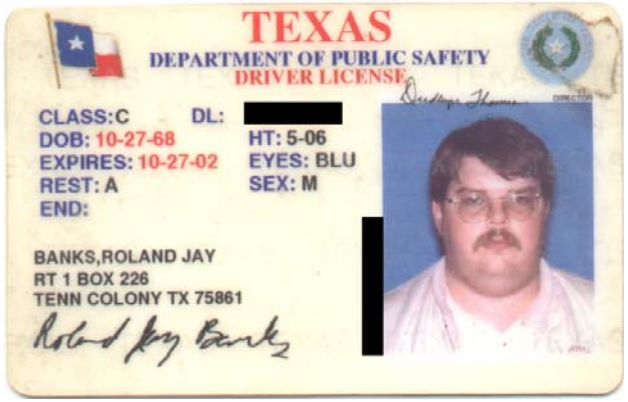
Arrest



O. J. Simpson


Pride in the Past, Progress in
911 EMERGENCY
www.StrangePolice.com

Forgery?



Authentication of driver licenses

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Steganography

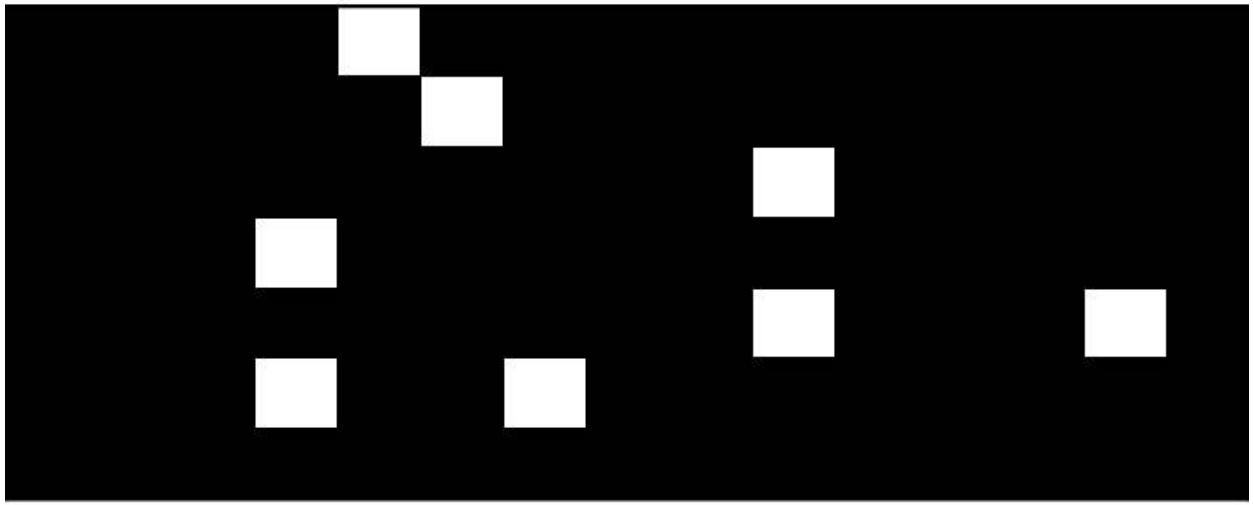
- The ultimate discreet signaling
- Must conceal existence of hidden message
- Applications: spies, military, revolutionaries, terrorists
- Name comes from ancient Greek,

$$\sigma\tau\epsilon\gamma\alpha\nu\omega \;\; \gamma\rho\alpha\phi\omega : \;\; covert\ writing$$

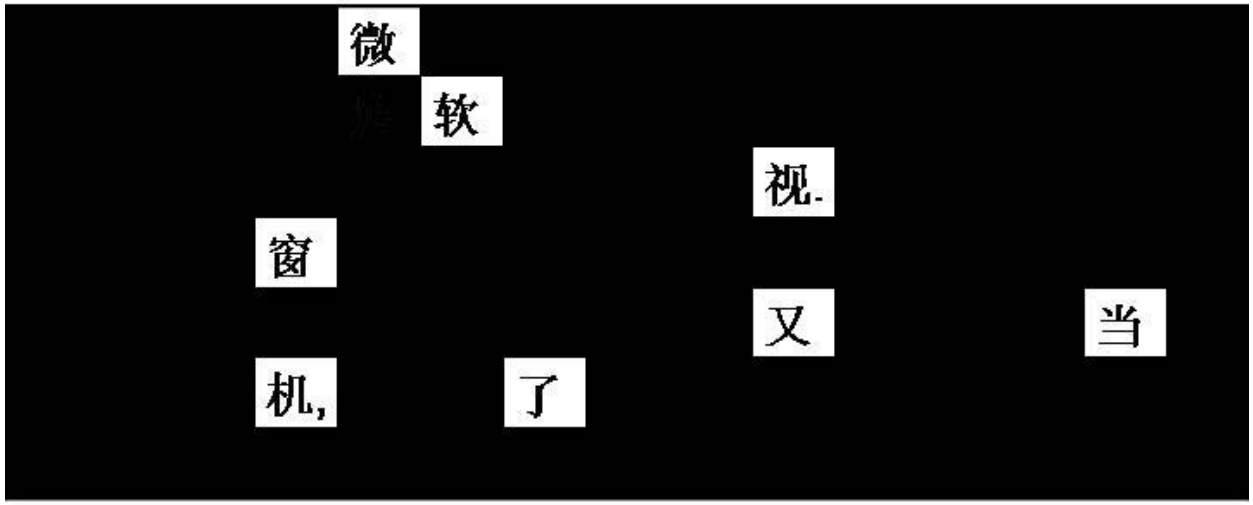
Ancient Chinese Steganography

陛	下	明	鉴:	微	臣	自	受	命	出	师,	一	刻	未	敢
懈	怠.	今	敌	疲	软	于	西,	又	务	于	东,	此	虽	进
趋	之	时	也,	臣	亦	不	敢	轻	视.	臣	本	耕	读	乡
里,	不	闻	窗	外	之	事.	然	陛	下	不	以	臣	卑	鄙,
寄	臣	以	大	事,	尔	来	二	十	又	一	年	矣.	当	此
存	亡	之	机,	唯	盼	了	敌	于	关	外,	以	不	负	陛
下	重	托.												

Secret Mask

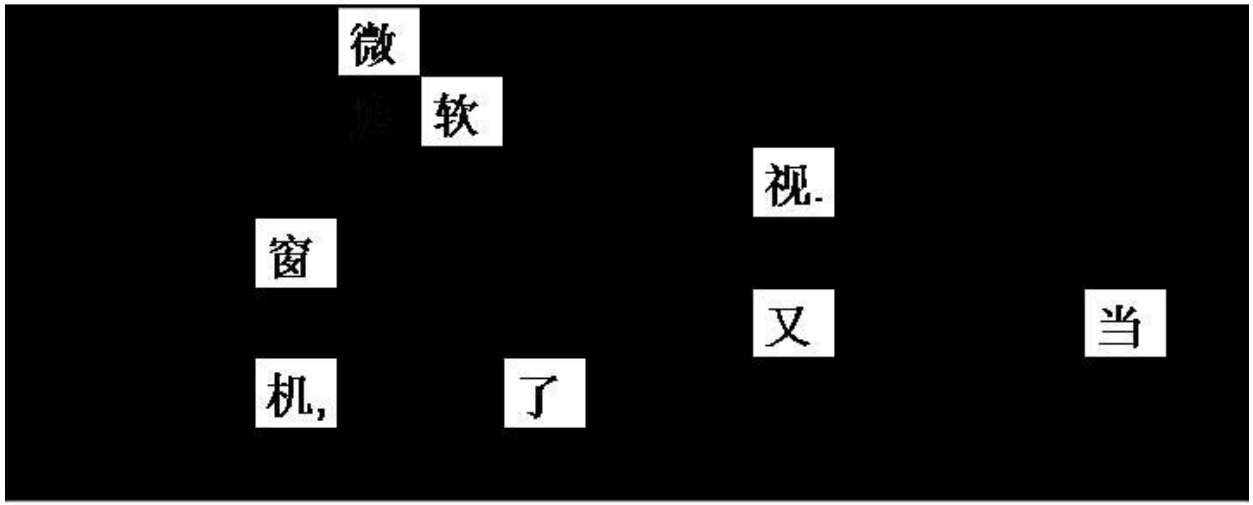


Secret Message



English Translation

Microsoft Windows crashed, again!



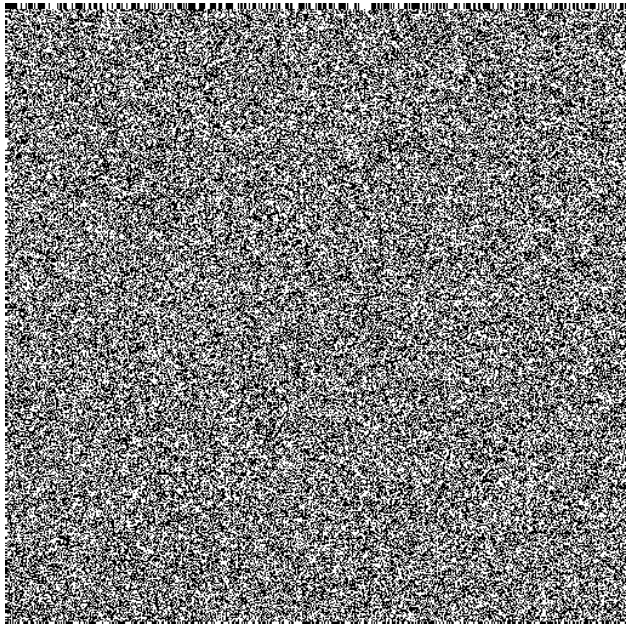
Early Internet Steganography

- **LSB embedding**: a popular image steganography method
- Cover data $\mathbf{s} = \{s_1, s_2, \cdots, s_n\}$
- Each $s_i \in \{0, 1, \cdots, 2^b - 1\}$ (b bits/sample)

$$77 = (01001101)$$

- Replace all n LSB's by hidden binary message
  $\Rightarrow$ rate $R = 1$ bit/sample

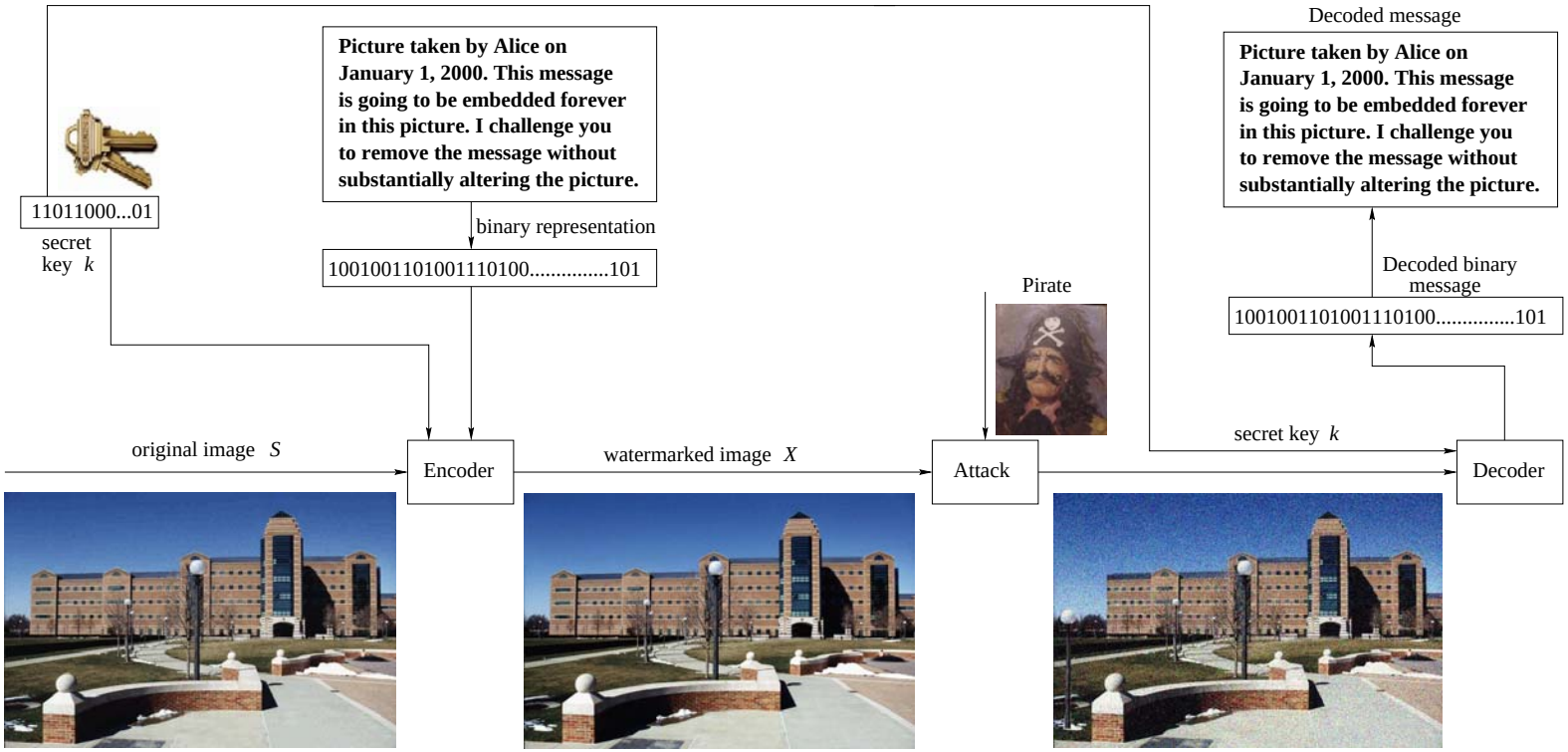
Lena LSB plane



- Invisible but statistically detectable?

Part II: Information-Theoretic Models and Analyses

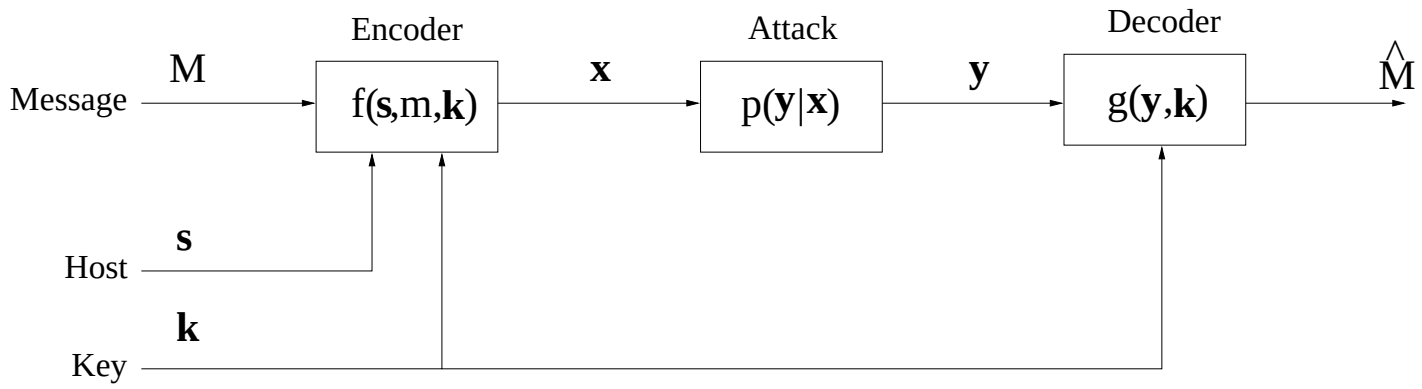
A Generic Problem: Hiding Data in Images



Basic Properties

- **Fidelity** (in terms of signal distortion metric)
  $\leftrightarrow$ discretion level
- **Payload** (number of transmitted bits)
- **Robustness/Security** (against adversary)
- **Detectability** (by steganalyzers/eavesdroppers)

Basic Communication Model



- Encoding function $\mathbf{x} = f(\mathbf{s}, m, \mathbf{k})$
- **Attack channel** $p(\mathbf{y}|\mathbf{x})$ (stochastic)
- **Distortion** constraints on f and $p(\mathbf{y}|\mathbf{x})$
- Decoding function $\hat{m} = g(\mathbf{y}, \mathbf{k})$

System Issues

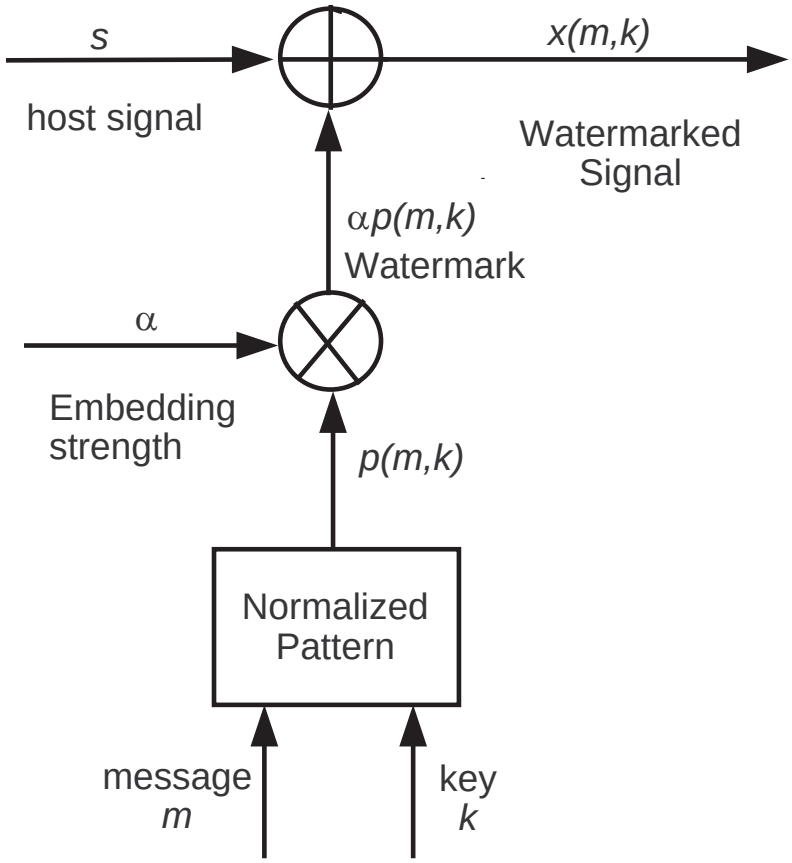
(only partially covered by basic communication model)

- Does receiver know host signal? ($\mathbf{k}$ correlated with $\mathbf{s}$)
  (*blind* vs *nonblind* decoding)
- Communication protocol
- Security level
- Private or public cryptographic system?

Attack Models

- No attack
- "Signal processing" attacks
- Cryptanalysis
- System-level attacks
  (e.g., mosaicing, ambiguity, chosen-plaintext)

The 1990's: Spread-Spectrum Codes



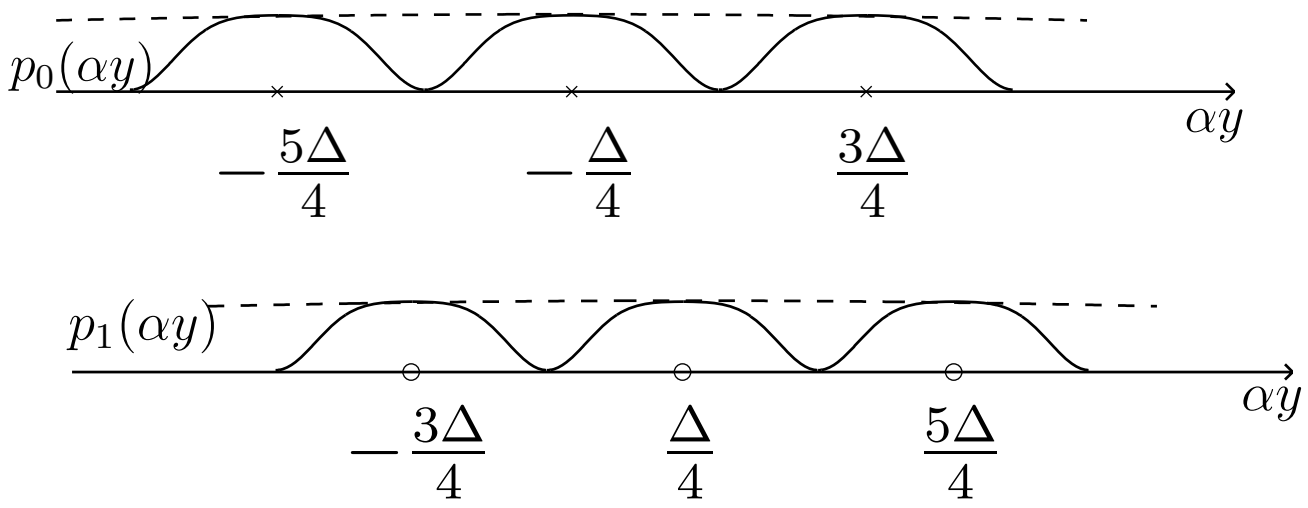
- OK if host **S** is known to receiver
- Weak performance otherwise (**S** is treated as noise)

The 21st Century: Binning Codes

- Fundamental information-theoretic technique
  (Slepian-Wolf 1975; Gel'fand-Pinsker 1980; Costa 1983)
- Host **S** is a **known interference** to encoder
- Can't cancel **S** due to fidelity constraints
- But can "optimally adapt" to **S**
- Natural framework for blind data hiding

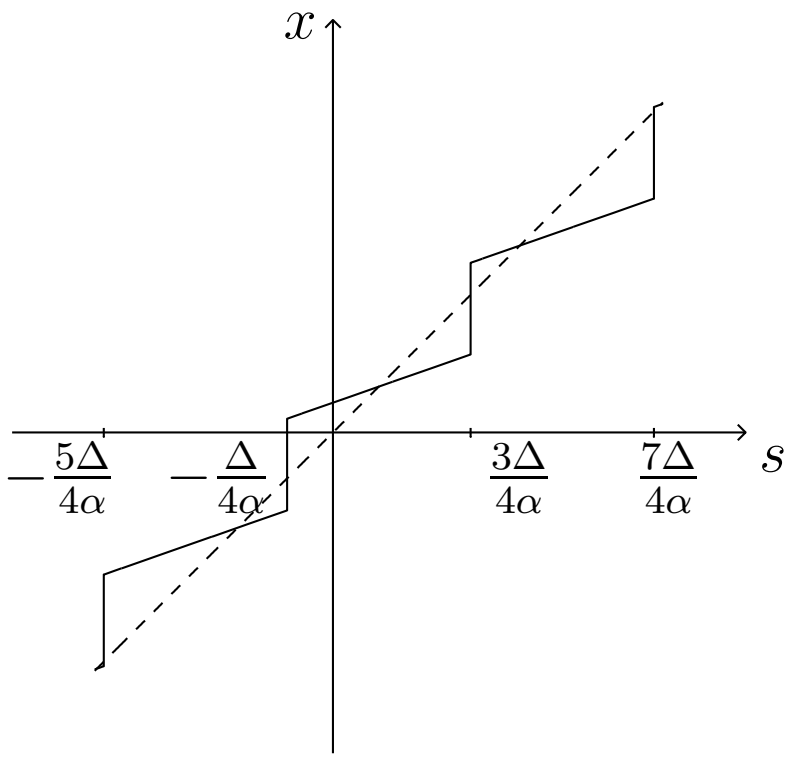
Binning $\leftrightarrow$ pdf shaping

- Embed 1 bit in signal feature $\mathbf{s}$
- Decoder performs statistical test: $Y \sim p_0$ vs $Y \sim p_1$
- Can shape p_0 and p_1 to concentrate information and maximize reliability of test

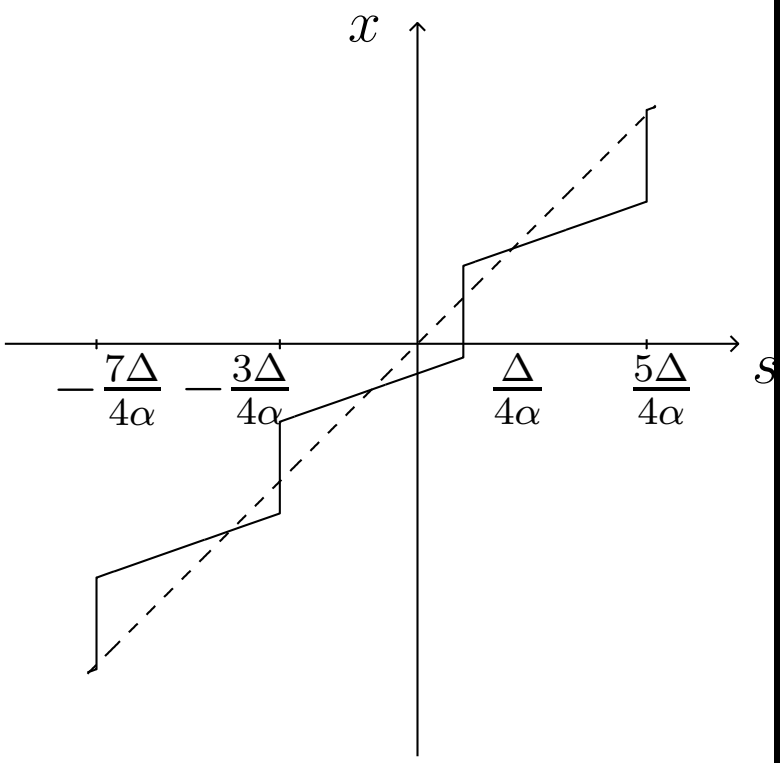


- Can shape p_0 and p_1 using quantization scheme

- Quantization embedding

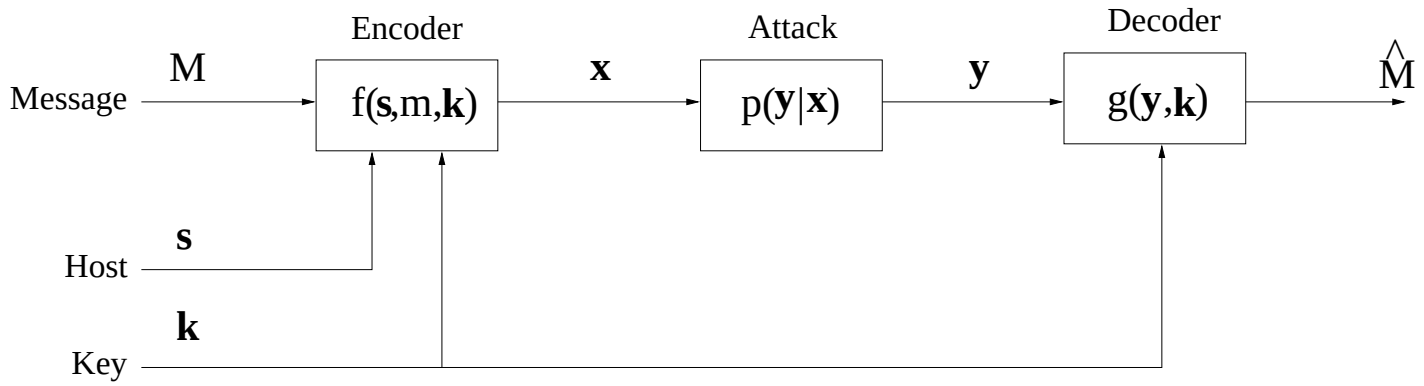


$m = 0$



$m = 1$

Information-Theoretic Limits



- Probability of error $P_{e,N} = Pr[\hat{M} \neq M]$
- Probability mass function $p_S(s)$ (i.i.d. symbols)
- Additive distortion function $d^N(\mathbf{S}, \mathbf{X}) = \frac{1}{N} \sum_{i=1}^{N} d(S_i, X_i)$
- Constraint on encoder: $d^N(\mathbf{S}, \mathbf{X}) \leq D_1$
- Constraint on attacker : $d^N(\mathbf{X}, \mathbf{Y}) \leq D_2$

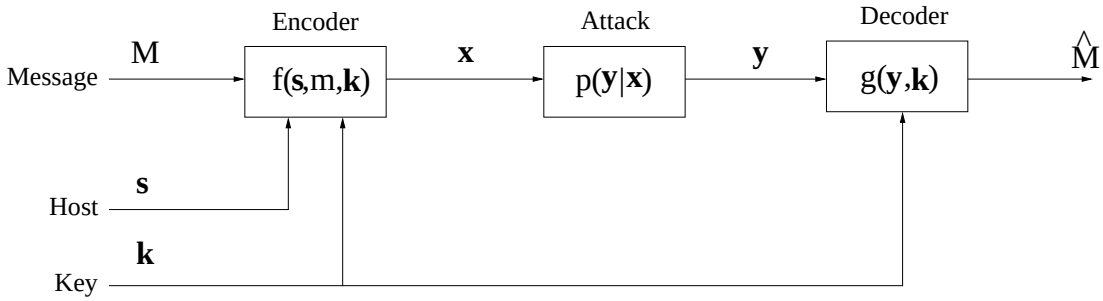
Capacity and Reliability Function

- **Goal**: make $P_{e,N} \to 0$ as $N \to \infty$
- Coding problem with side information (Gel'fand-Pinsker type)
- What is the maximum rate C such that this is possible?

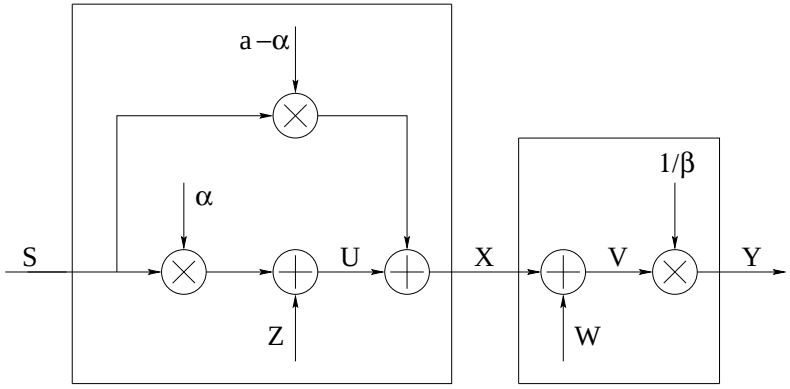
$$C = \max_{Q(x,u|s,k)} \min_{A(y|x)} [I(U;Y,K) - I(U;S,K)]$$

- Mathematical expressions for capacity can be derived and evaluated numerically
- The capacity limit is achievable by random binning

Gaussian Case

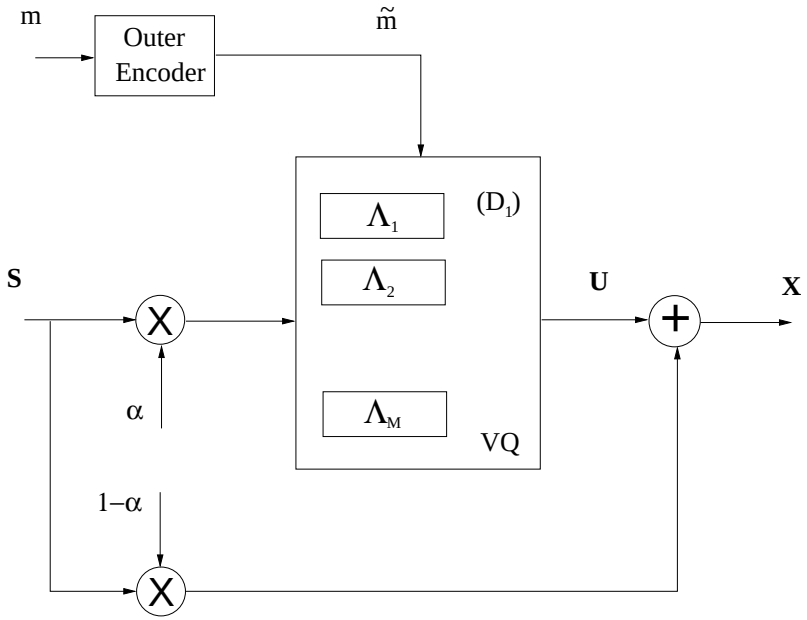


- Host $\mathbf{S}$ is i.i.d. Gaussian, MSE distortion constraints D_1, D_2
- $\sigma_S^2 \gg D_1$ (large interference) $\Rightarrow \quad C \sim \frac{1}{2}\log\left(1+\frac{D_1}{D_2}\right)$
- Perfect interference cancellation!
- C-achieving distributions are Gaussian:

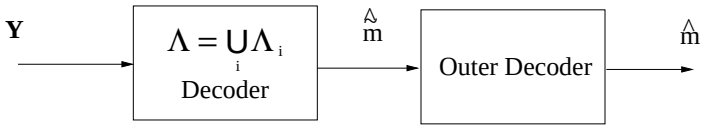


Lattice VQ Based Binning Codes

- Decompose lattice Λ into cosets $\Lambda_1, \Lambda_2, \cdots, \Lambda_M$



Encoder



Decoder

- Capacity-achieving family!
- Outperforms Spread Spectrum codes

Part III:
From Theory to Practice

Hiding Data in Images

Lena

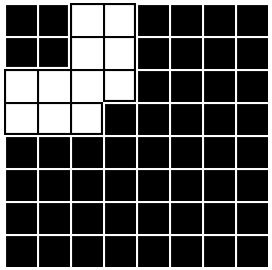
Block-DCT coefficients

- Parallel-Gaussian model for host
- Weighted MSE metric
- $D_2 = 5D_1 \quad \Rightarrow C \approx 0.01$ bpp

Practical IT-Based Codes

(Solanki et al. 2004)

Active Blocks



Selected DCT coefficients

- Order selected DCT coefficients into a sequence
- Interleave information bits, concatenate Reed-Solomon code with quantization code

- Embed 14,336 bits ($R = 0.055$ bpp)
- Withstands erasures and deletions

- Error-free recovery of the information bits

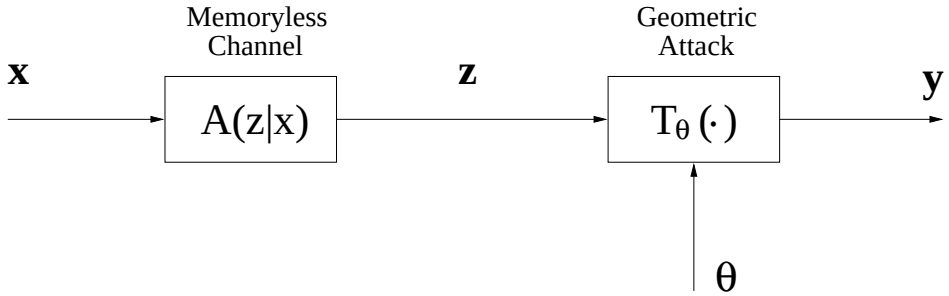
Simple Geometric Attacks

Shifted Lena

Lena

Rotated Lena

- General model: parametric class $\{T_\theta, \theta \in \Theta\}$ of attacks



- No loss in capacity relative to coherent case

Complex Geometric Attacks

Lena Warped Lena

- The "noncoherent penalty" can be severe when θ is time-varying, e.g., warping or random bending
- There exist good binning codes, but constructing practical ones is difficult!

Steganography

- Data hiding with undetectability requirement
- Assume steganalyzer knows f and statistics of $\mathbf{S}$ and tests

$$\begin{cases} \text{hypothesis } H_0 \;:\; \mathbf{X} \sim p_{\mathbf{s}} & \text{no hidden data} \\ \text{hypothesis } H_1 \;:\; \mathbf{X} \sim p_{\mathbf{x}} & \text{hidden data} \end{cases}$$

- *Perfect Secrecy* condition: $p_{\mathbf{x}} = p_{\mathbf{s}}$
- Randomized codes

Conclusion

- Specify communication model, including distortion and robustness levels
- Information Theory
  - provides fundamental performance bounds
  - guides the development of good practical schemes

For more details, see Moulin and Koetter, "Data-Hiding Codes," *Proceedings of the IEEE*, December 2005.