The Future of Image Compression

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Outline

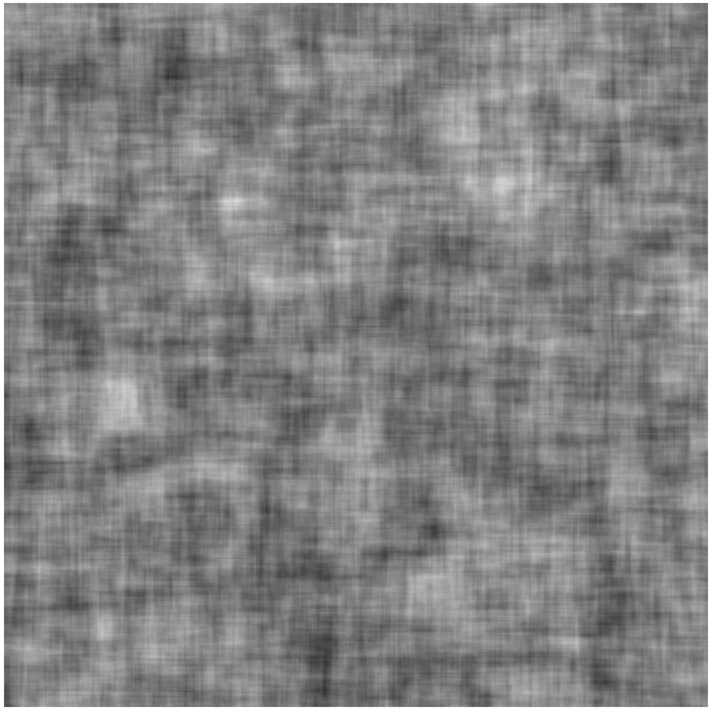
- Where are we?
- Data handling trends
- Improvements? Breakthroughs?
- Conclusions

Efficiency of Modern Methods

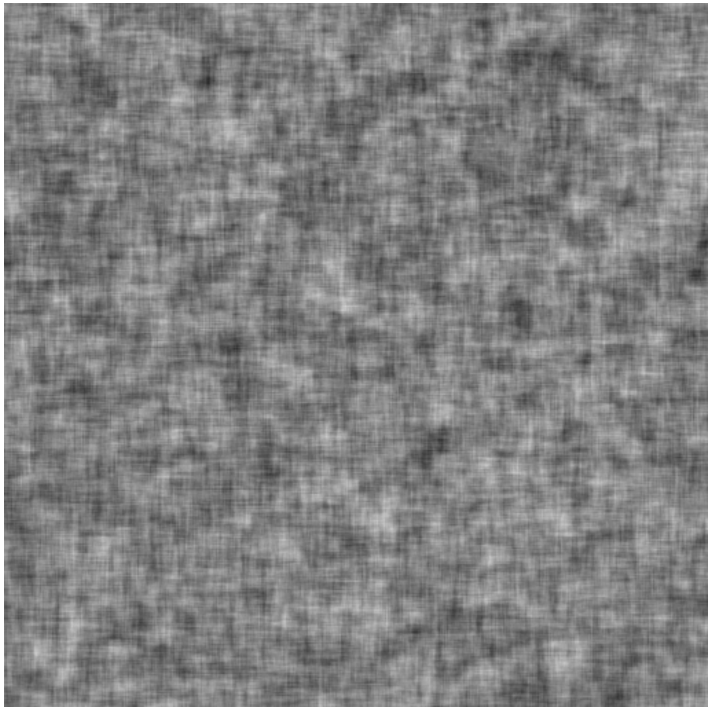
- Methodology
  - Generate Gauss-Markov Images
  - Compare compression results with Rate-Distortion or joint entropy function

Gauss-Markov Images

Variance = 400 Mean = 128



a = 0.95

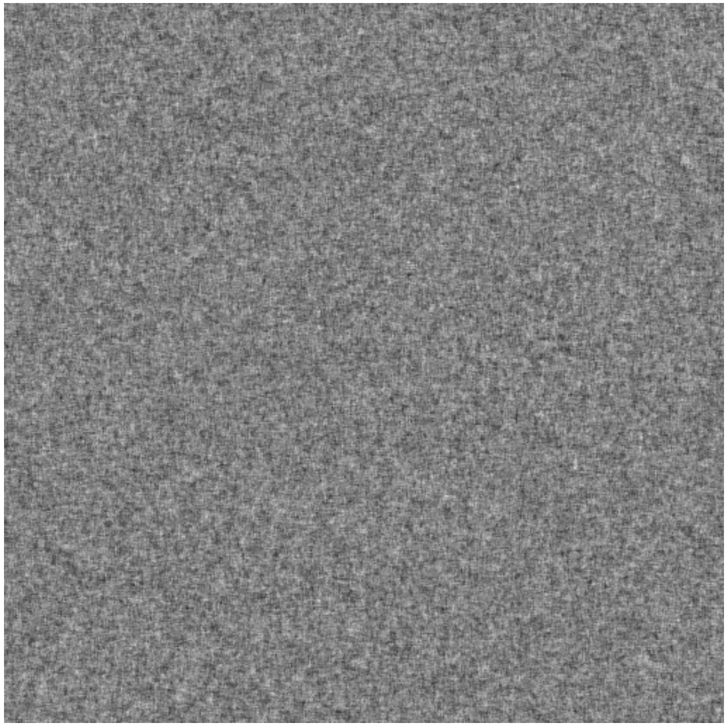


a = 0.90

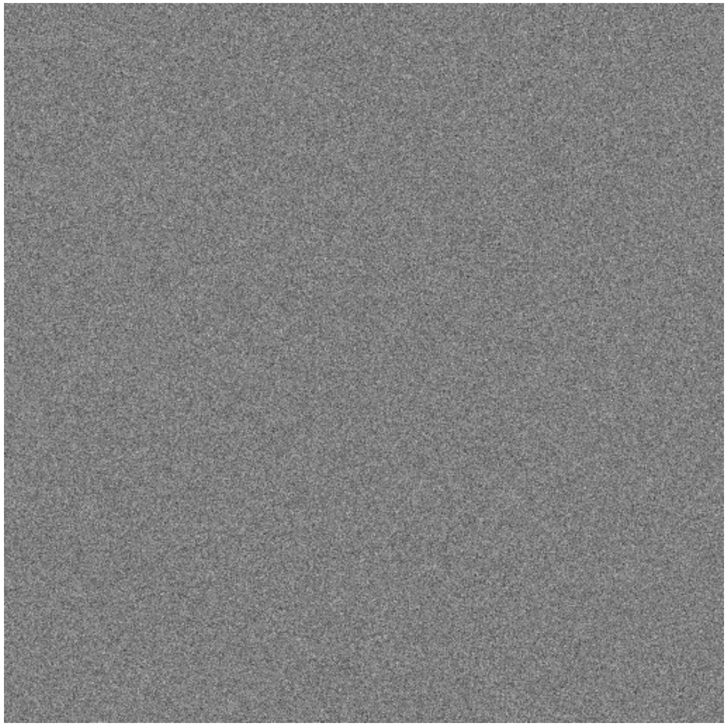
Separable; 8-bit precision;
512x512 lower cut from 640x640

Gauss-Markov Images (cont.)

Variance = 400 Mean = 128



a = 0.50



a = 0.0

Separable; 8-bit precision;
512x512 lower cut from 640x640

Theoretical Bounds

Rate-Distortion Function (Gaussian, squared error)

$$R = \frac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} \max\{0, \tfrac{1}{2} \log_2 \frac{\lambda(i)\lambda(j)}{\theta}\}$$

$$D = \frac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} \min\{\theta, \lambda(i)\lambda(j)\}$$

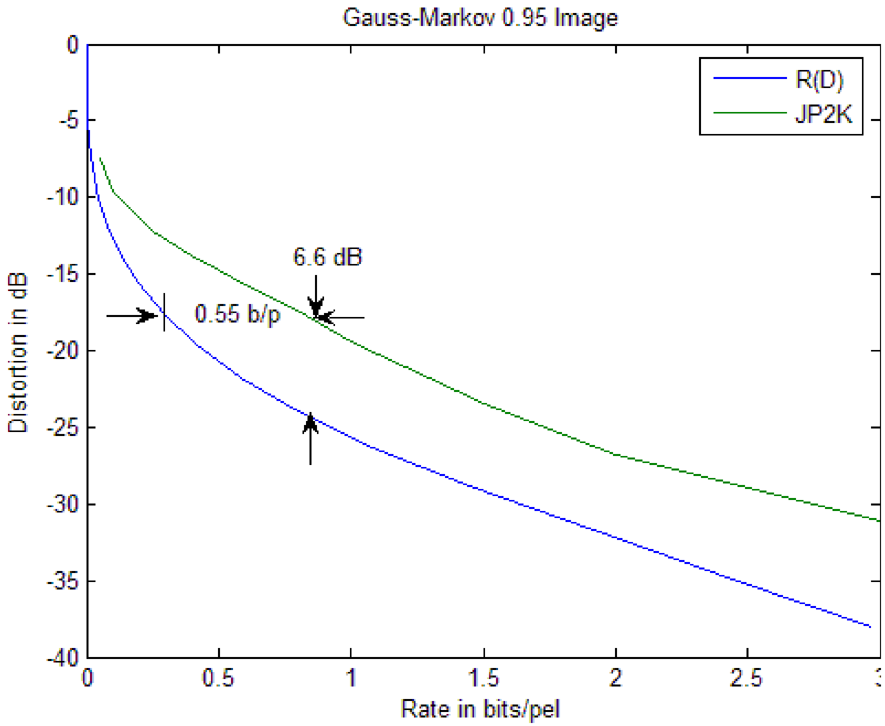
Approximate Gaussian Entropy Function

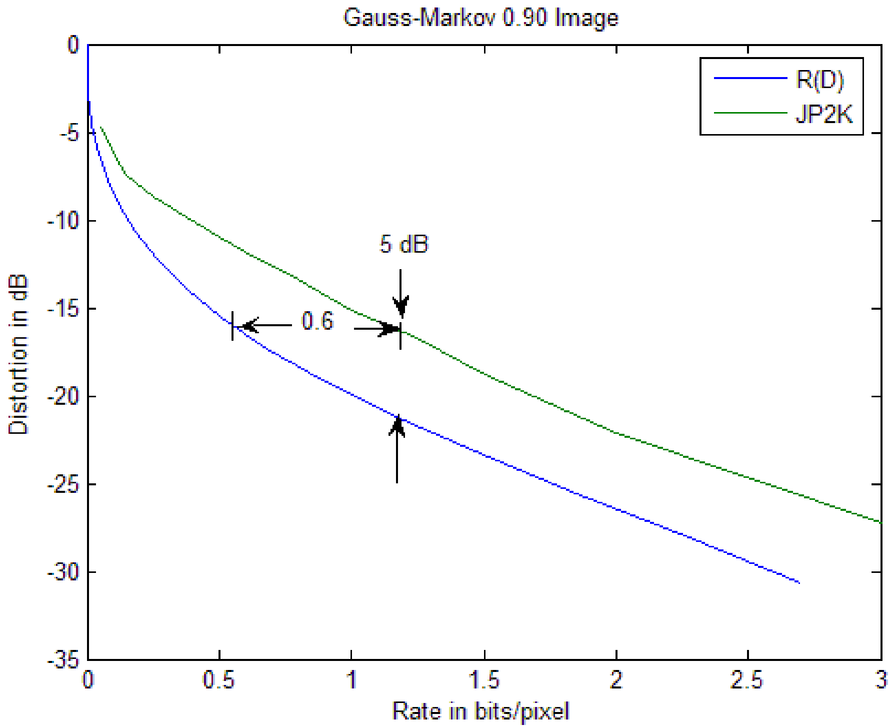
Using $H(X^n) \approx h(X^n) - \log_2 \delta$ $\quad -\log_2 \delta = m$ bits (precision)

$$\frac{1}{N^2} H(X^{N^2}) \approx \frac{1}{2N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} \log_2(\lambda(i)\lambda(j)) + \tfrac{1}{2} \log_2 2\pi e \sigma_X^2 + \frac{m}{N^2}$$

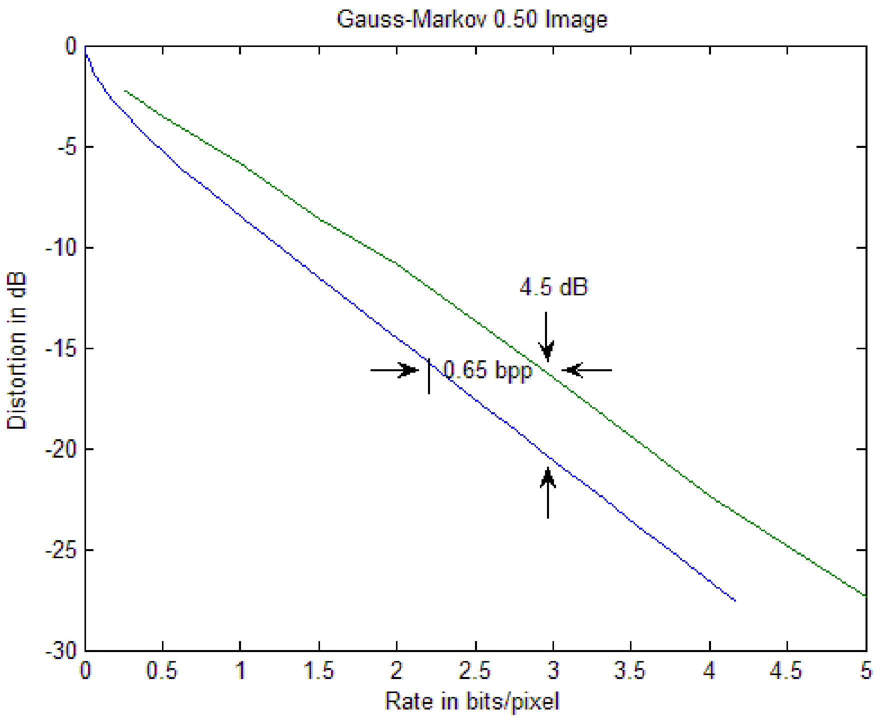
(Eigenvalues normalized for unit variance)

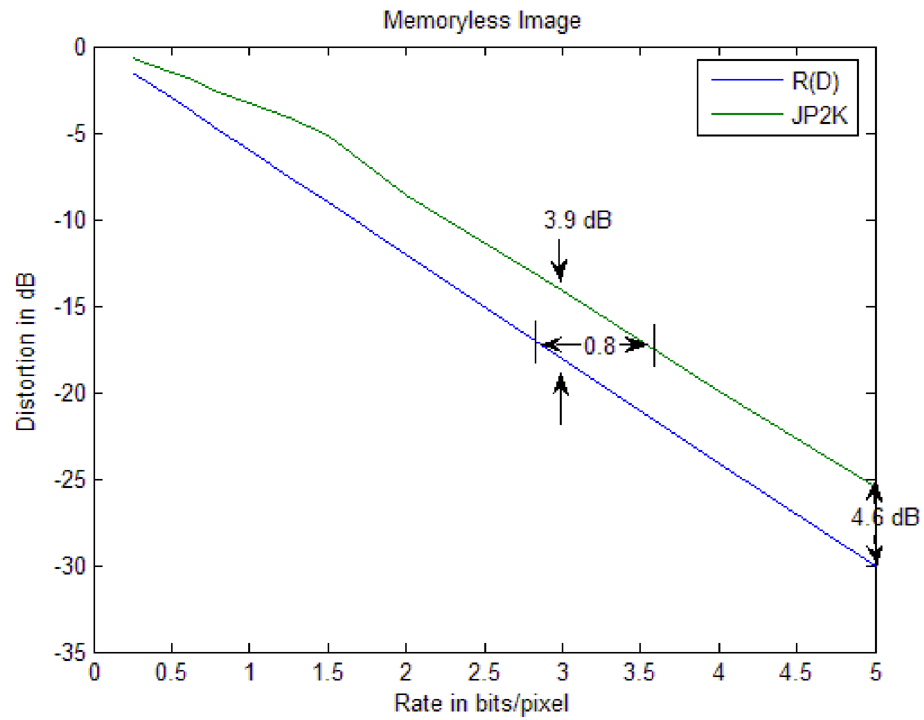
Comparisons





More Comparisons





Lossless Compression

Correlation Parameter	Joint Entropy (b/p)	Differences from Entropy (b/p)		
		SPIHT	CALIC	JP2K
0.95	3.0172	0.9438	0.4188	0.4838
0.90	3.9778	0.6652	0.2312	0.3762
0.50	5.9548	0.2392	0.0872	0.3172
0	6.3691	0.2469	0.1779	0.3639

* CALIC closest to entropy in all cases
* JP2K beats SPIHT above a = 0.5, but worse otherwise

What Have We Learned?

- Much room for improvement for lossy compression :
  - > 0.5 bpp for high quality
  - 4 to 6 dB at useful bit rates
- Small room for improvement for lossless compression - ~0.2 bpp

**Lesson: The best adaptive techniques can take you only so far.

Where to go from here?

- For pure compression, much more potential payoff for lossy methods.
- Clearly advantageous to transform to independent variables and/or segment to stationary entities.
  - closes performance to the latter gaps
- Barring advancements in pure compression, need to pursue
  - better transforms that are adaptive to image features
    - Bandelets, curvelets, etc. ?
  - better segmentation methods

Technology Advances

- Dramatic increases in processor speeds seem to be ending
  - Parallelization by multi-core processor chips is the trend
  - New parallel forms of algorithms for compression likely to emerge
    - Currently JPEG2000 and JPEG have parallel structure --- nothing new here
- More compact, higher power batteries would expand application scenarios for compression
- Miniaturization to quantum limit to be reached in 10 to 15 years
  - Quantum Computers

Future Application Space

- Large images with multiple dimensions
  - Examples:
    - 4 dimensions: fMRI, medical ultrasound view
    - Materials micro-structures with many attributes at given grid point.
- Content-based retrieval from large databases
  - Internet application needs interactivity for consultation and quantitative analysis.
  - Need fast search and retrieval and fast scalable decoding for browsing, retrieval, and transmission
    - Places limits on complexity and memory usage
      - Increase in size always seems to outpace gains in speed
    - Not likely to close existing performance gaps with simpler techniques that utilize less memory.
      - Fruitful or fruitless pursuit?
    - Contribution is to limit degradation the least possible by being clever

Example: Retrieval from Large Multi-D Images

Click on file name in web site and left image appears.

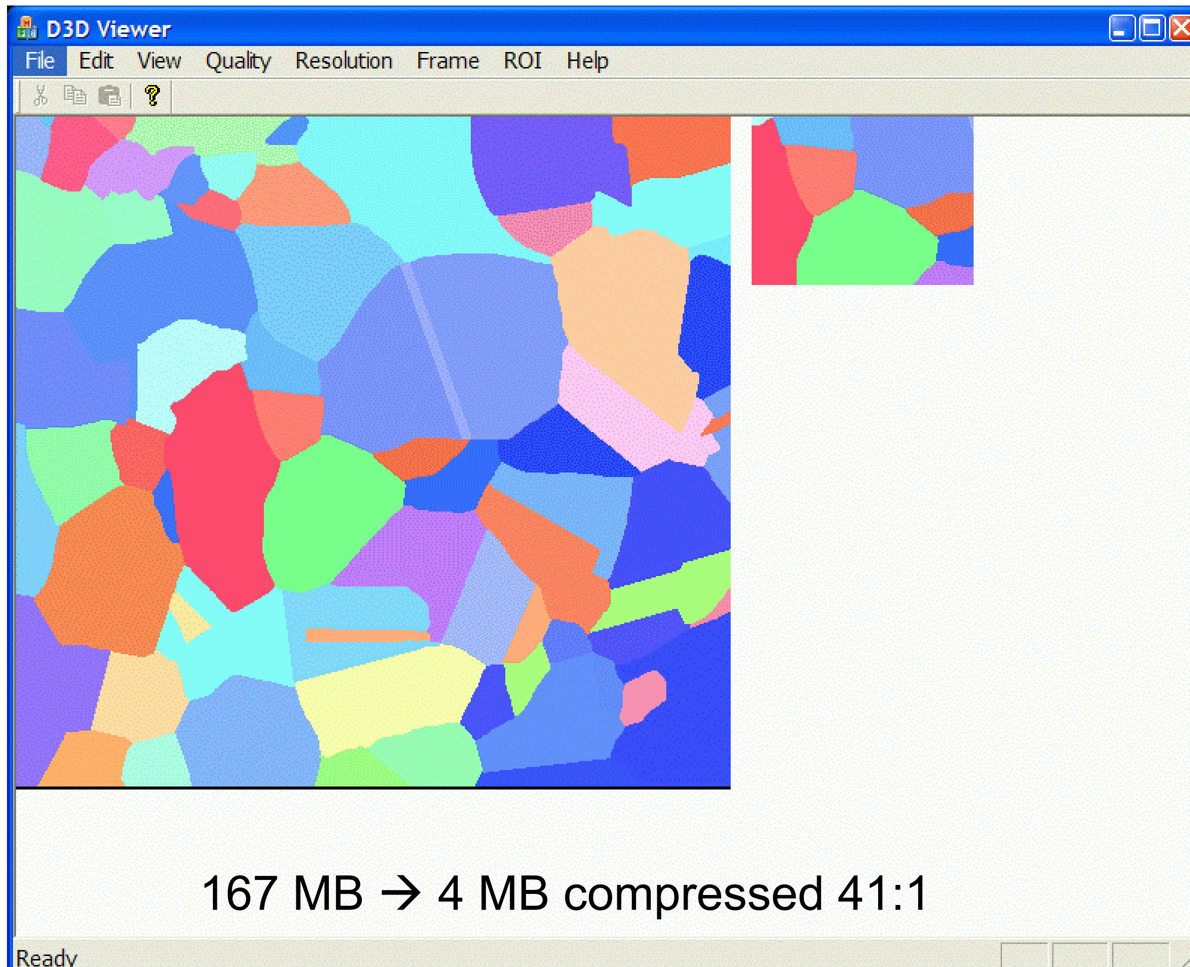
Right image appears using ROI Menu and mouse Selection of region

Any slice can be viewed by dropping Frame menu and entering number

In View menu, can select Full volume and ROI views In 3-D -- see next slide

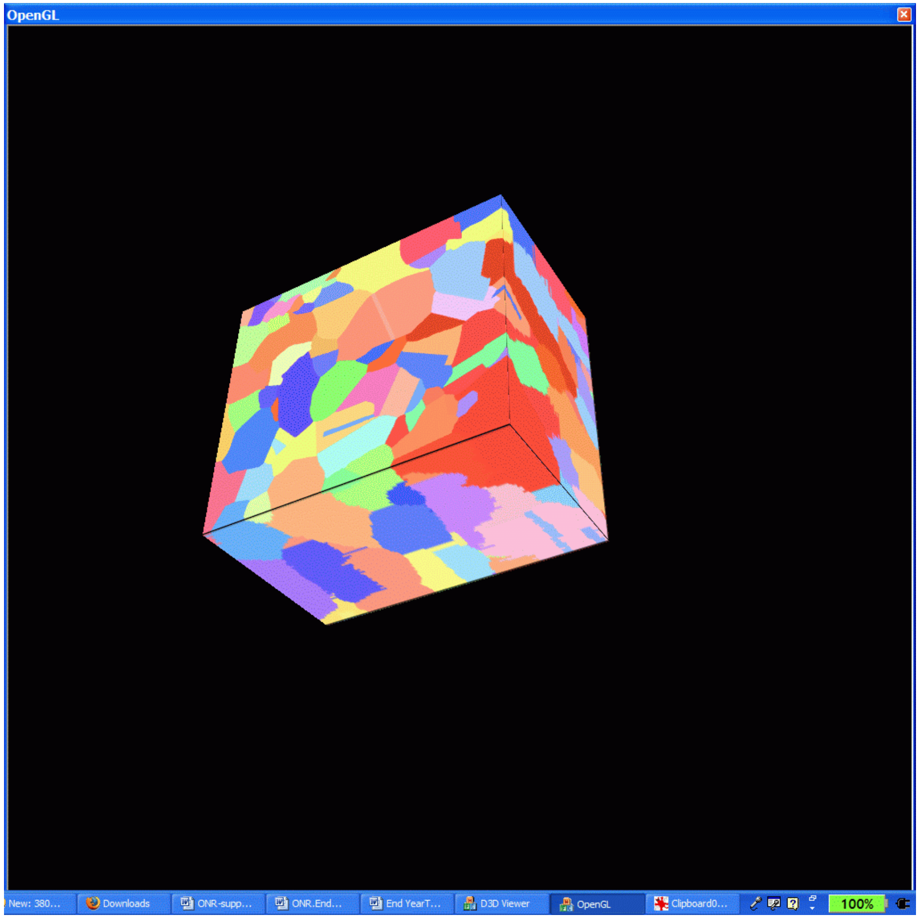
Micro-structure

Communication/Display GUI

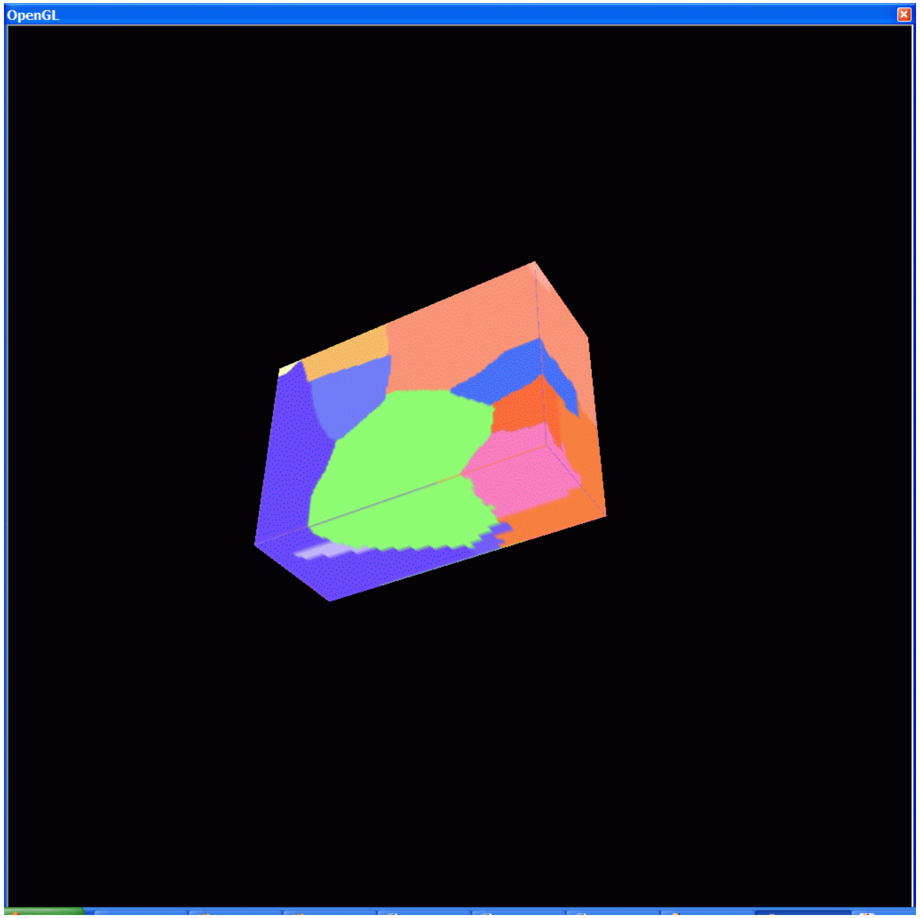


3-D Views

Full volume



ROI



Rotation by mouse manipulation

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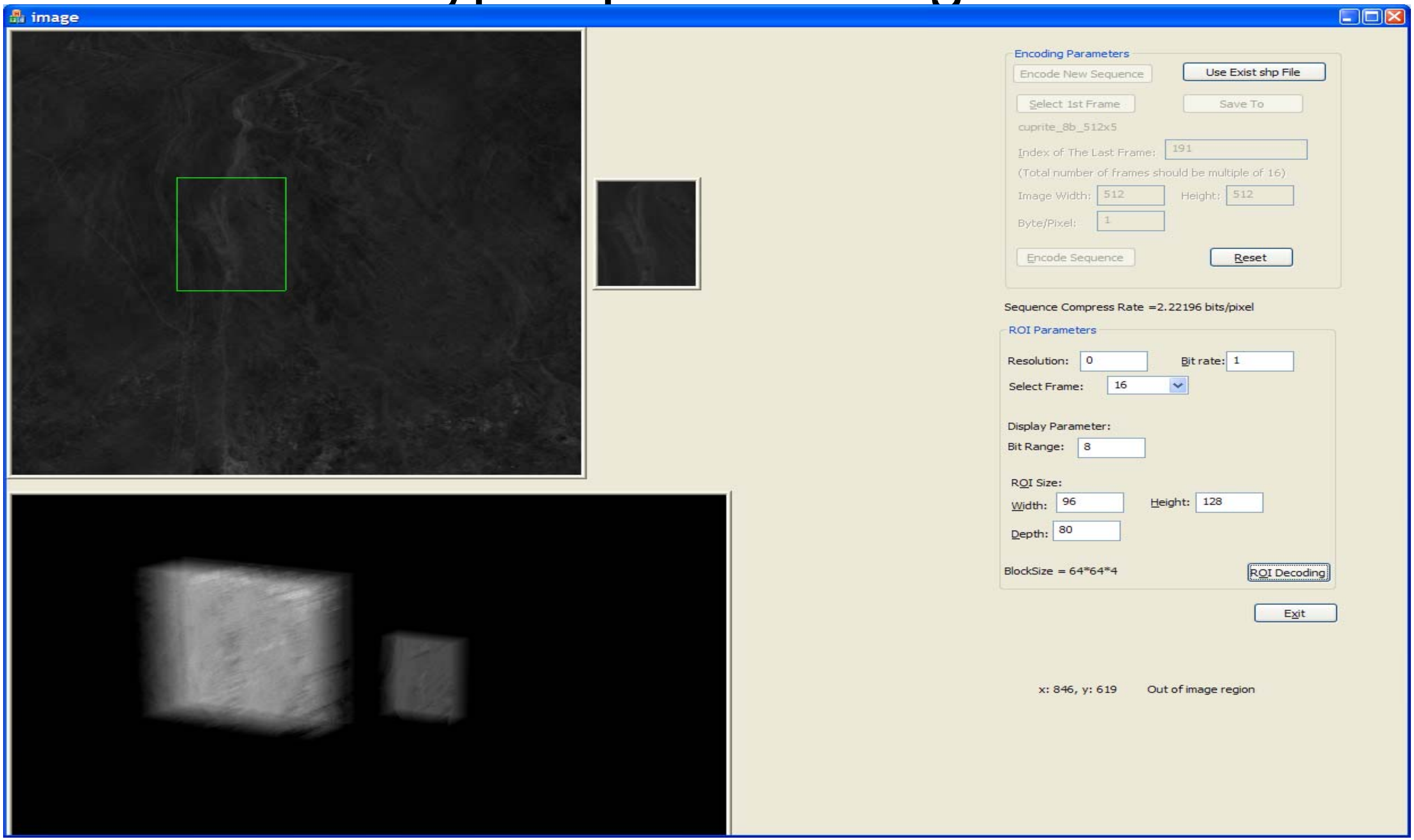
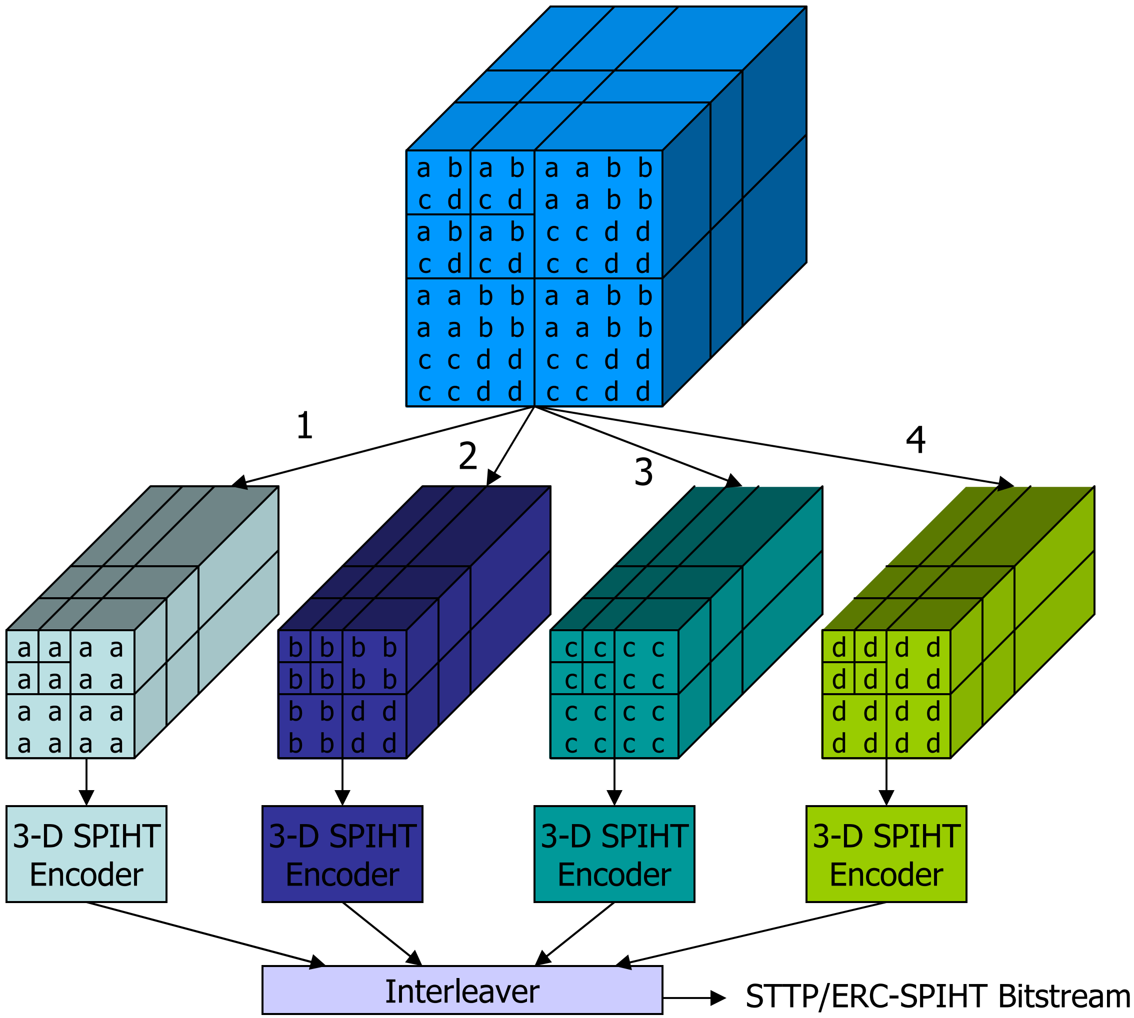
Hyperspectral Images



Codec

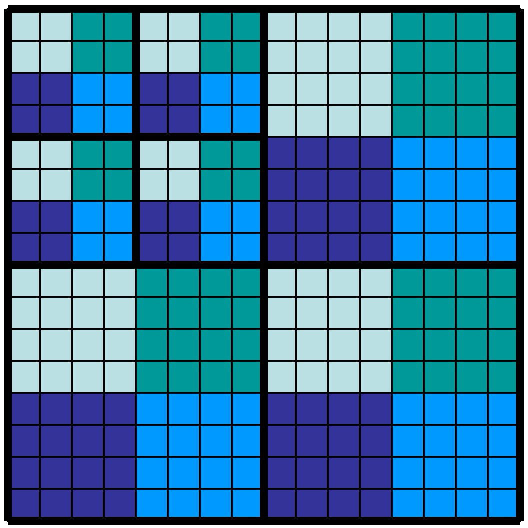
Multiple Description Coding



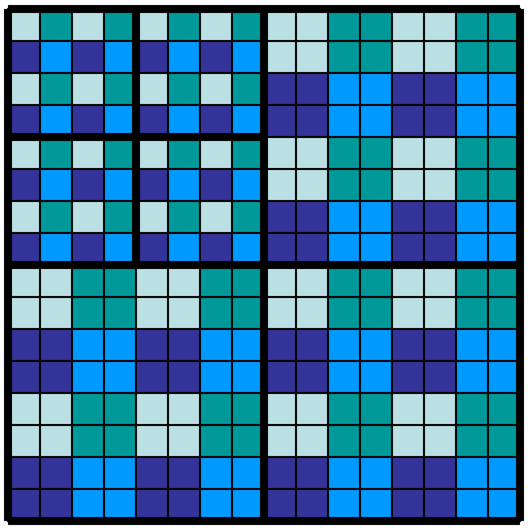
- *S* sub-bitstreams are interleaved in appropriate size units (e.g. bits, bytes, packets, etc.)
- Embedded nature is maintained
- We can stop decoding at any compressed file size
- May transmit sub-bitstreams separately over MIMO channel

Grouping Methods

* 16x16 image with 2 level decomposition, and *S*=4



Contiguous Grouping

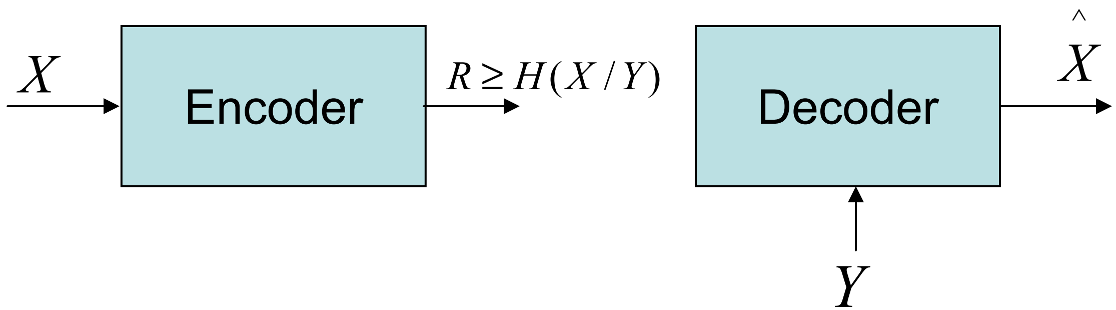


Dispersive Grouping

- Extensible to larger dimensions
- Compatible with parallel architectures
- Follows natural order of coding for tree-based methods: on-the-fly transmission
- Fits well into W-Z or S-W paradigm

Distributed Source Coding

Source Coding with Side Information: Slepian-Wolf 1973, Wyner-Ziv 1976



- X and Y correlated sources
- Y known only at decoder

S-W: Encode X with H(X/Y) bits, Y with H(Y) bits, can achieve $\hat{X} = X$

No loss of performance over when Y is known at encoder also, if statistics X given Y are known.

W-Z: *Lossy coding performance same whether Y is known at both ends or only at decoder, if statistics of X and Y are jointly Gaussian.*

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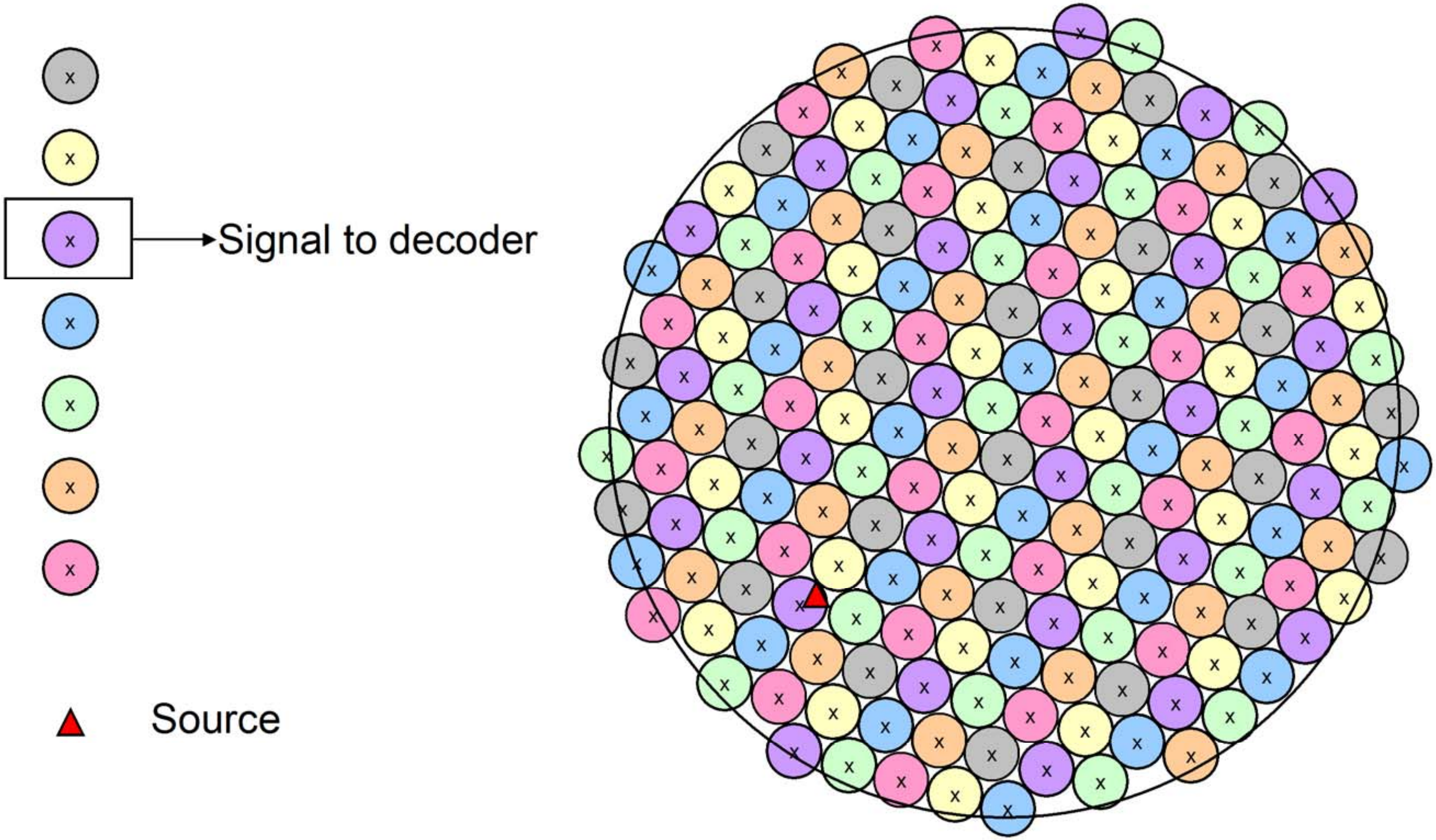
Promising Realization

- Encoder of X sends index of coset (syndrome bits of channel code)
- Decoder uses Y and coset index to estimate X.

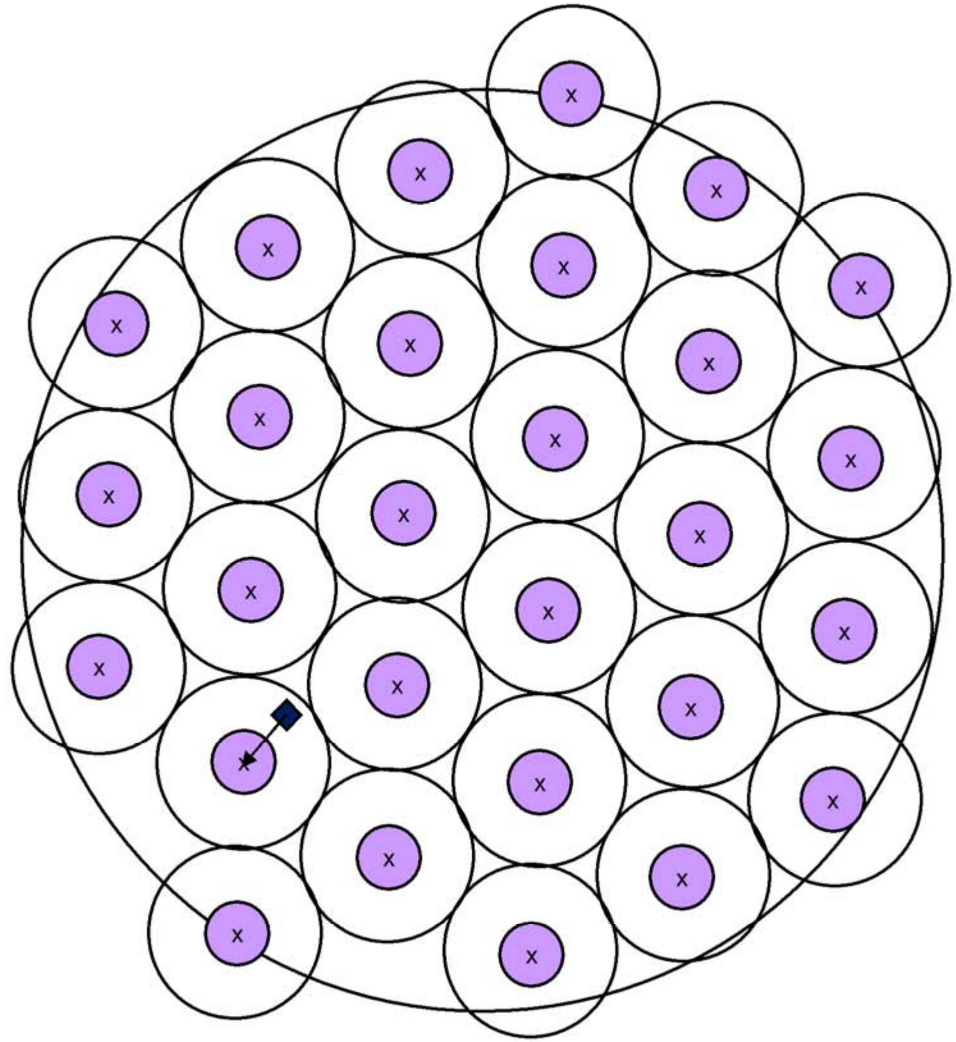
Example: geometric illustration



Assume signal and noise are Gaussian, iid

Figure courtesy of K. Ramchandran

Example: geometric illustration



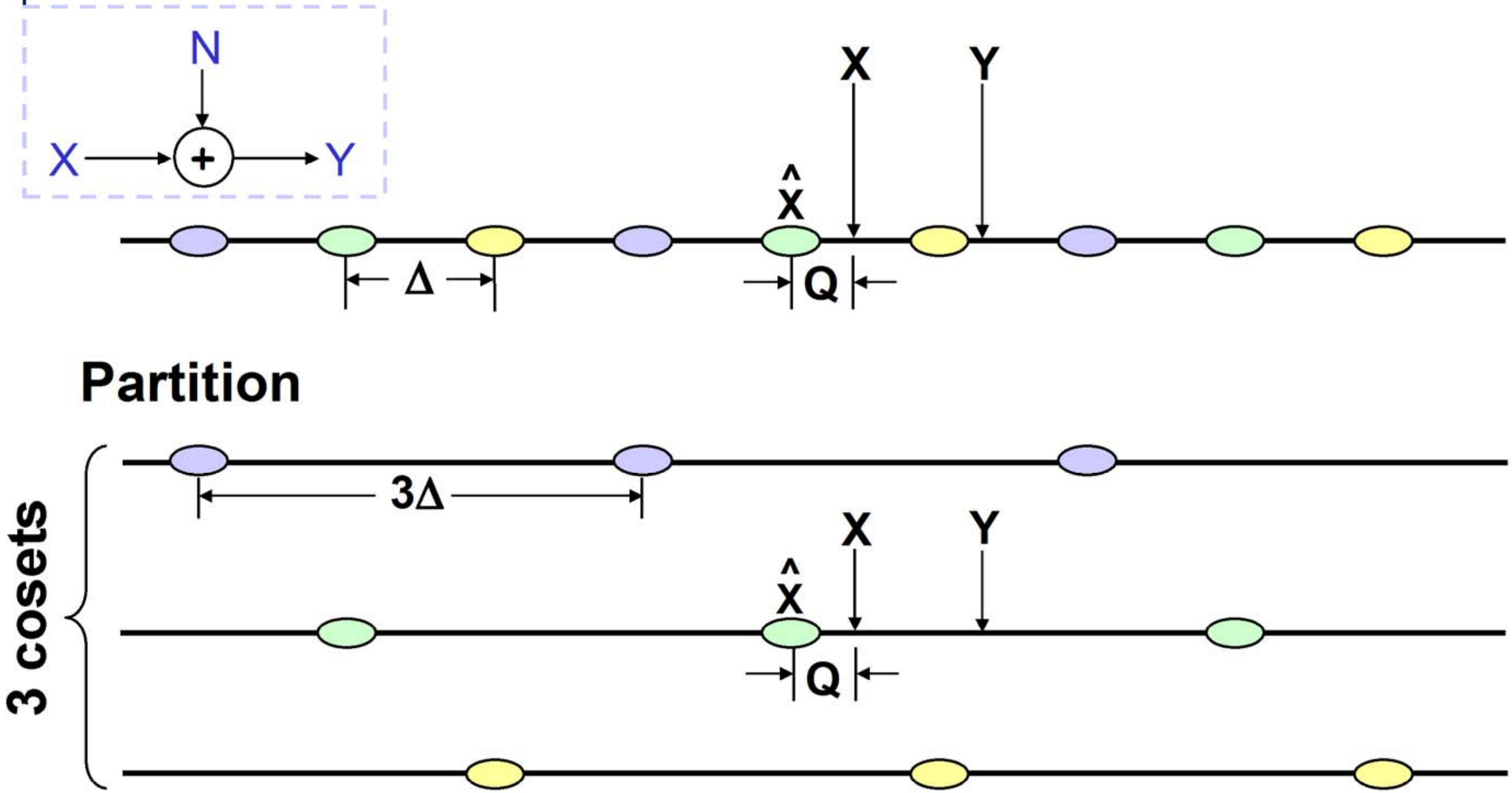
Source

Side information

Assume signal and noise are Gaussian, iid

Figure courtesy of K. Ramchandran

Example: scalar Wyner-Ziv



- Encoder: send the index of the coset ($\log_2 3$ bits)
- Decoder: decode X based on Y and signaled coset

Figure courtesy of K. Ramchandran

DSC Image Compression Scenarios

- Low complexity encoding for image transmission
- Sensor networks
  - Multiview coding
- Multiple description coding
- Camera alignment
- Cryptogram compression

❖ None likely to bridge identified performance gaps, especially for the usual non-Gaussian lossy coding

Quantum Computing

- Quantum computers can solve some math problems considerably faster than classical computers
- Qbit(.com) – claims 2-10:1 lossless image compression at 1.5 Gbits/sec throughput
  - with qubit processor? US 2004/0086038 App.
- Quantum Information Theory
  - Well developed; parallels Shannon theory
    - Source coding theorem (von Neumann entropy limit)
    - R(D) theorem
    - S-W and W-Z theorems
    - Channel capacity theorem

Quantum Bits and Entanglement

- General state of one qubit (input): α 's complex

$$|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle \;,\; |\alpha_0|^2 = \Pr\{|0\rangle\} \quad |\alpha_1|^2 = \Pr\{|1\rangle\} \;, \quad |\alpha_0|^2 + |\alpha_1|^2 = 1$$

  - said to be *entangled*

  Ex.: photon $|\psi\rangle = (1/\sqrt{2})|0\rangle + (1/\sqrt{2})|1\rangle$ linear polarized at 45°

- Output is measurement: $|0\rangle$ or $|1\rangle$
  - Orthogonal states can be measured
  - Similarly for 2-qubit system- states are *entangled*

$$|\psi\rangle = \alpha_{00}|00\rangle + \alpha_{01}|01\rangle + \alpha_{10}|10\rangle + \alpha_{11}|11\rangle$$

- *n-qubit space – 2^n dimensional Hilbert Space*
- *States can not be copied or cloned.*
- *A measurement changes the state:* basis of secure key distribution
- *States can be communicated*

Entropy Example

Two equiprobable photon states: Shannon entropy = 1 bit

Suppose 0 → $|0\rangle$ H polarization

Suppose 1 → $\psi = \cos\theta|0\rangle + \sin\theta|1\rangle$ Angle θ polarization

Von Neumann Entropy S($|0\rangle$, ψ) = $H_2((1-\cos\theta)/2)$

Binary entropy function $H_2(p) = -p\log_2 p - (1-p)\log_2(1-p)$

Except for $\theta = \pm\pi/2$, S($|0\rangle$,ψ) < 1

But, only $\theta = \pm\pi/2$ is detectable !!

Therefore, von Neumann entropy may have no realizable association to information.

Prospect of Lower Compression Limit

- So far, quantum information theory does not give physically realizable lower entropy limits
- Also, the devices and detectors work only in the laboratory or with limited capability – polarizers,1-qubit gates, and short shift registers
- Short error-correcting codes, secure key distribution
- Physicists are hard at work to make the devices that form specified quantum states
- Physicists have taken the lead at formulating quantum information theory, but our community has been roused (e.g., Devetak & Berger, "Quantum R-D Theory," Trans. IT Jun 2002; Rob Calderbank)
- Further reading
  - M. A. Nielson, I. L. Chang: *Quantum Computation and Quantum Information*
  - N. D. Mermin : *Quantum Computer Science: An Introduction*
  - J. Audretsch, Ed.: *Entangled World: The Fascination of Quantum Information and Computation*
  - Bennett & Shor, "Quantum Information Theory", Trans IT, Oct 1998

Conclusion

- Substantial gaps to compression limits still exist
- Trend toward algorithms to handle large, multi-dimensional images
- Trend to multiple core processors to spur development of new parallel processing paradigms
- Open question whether quantum information theory and quantum computation will save the day

Thank you!