Distributed Source Coding: Theory and Applications

Invited talk

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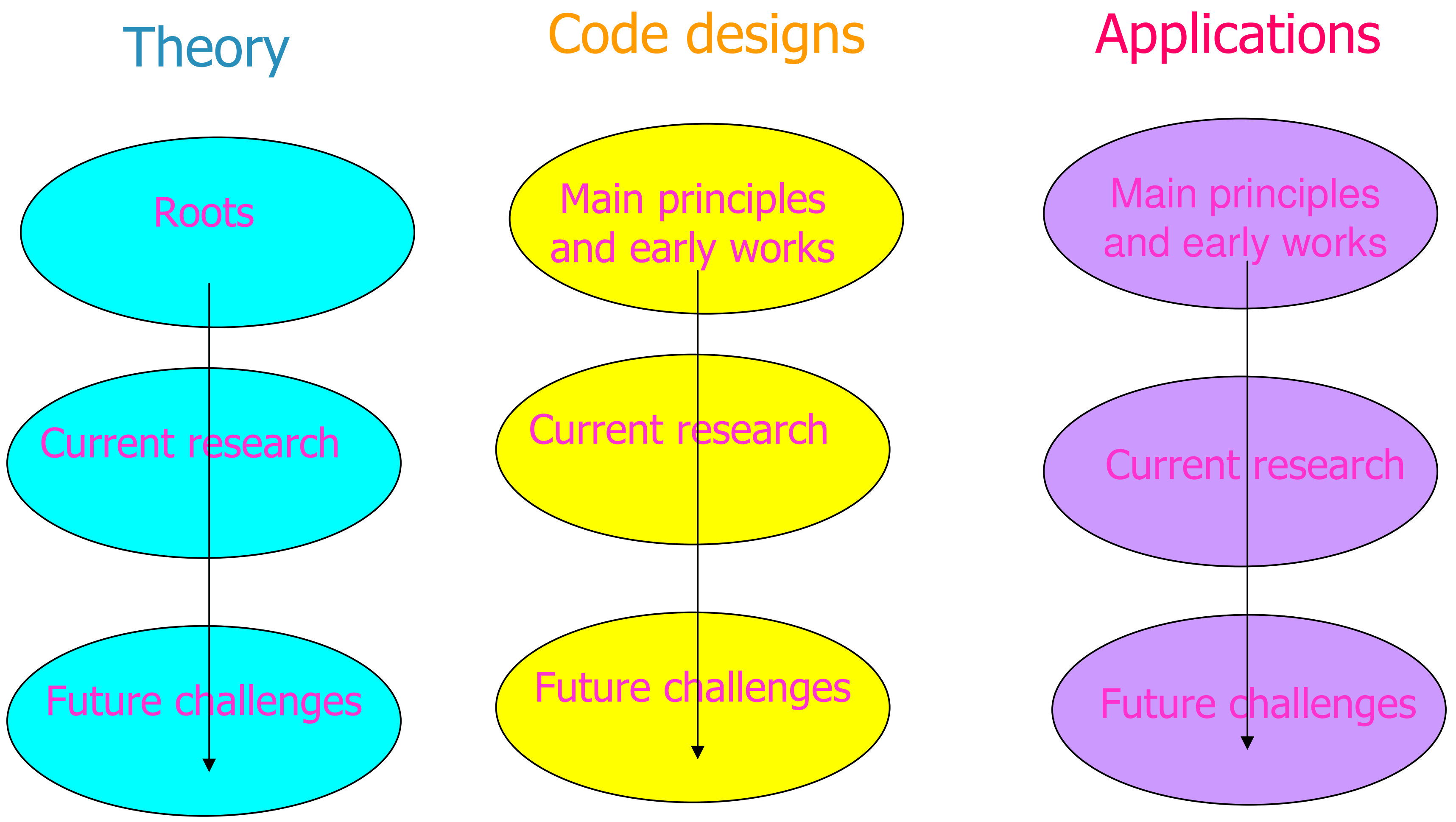
Eusipco-2010, Aalborg Denmark, August 2010

Talk Roadmap

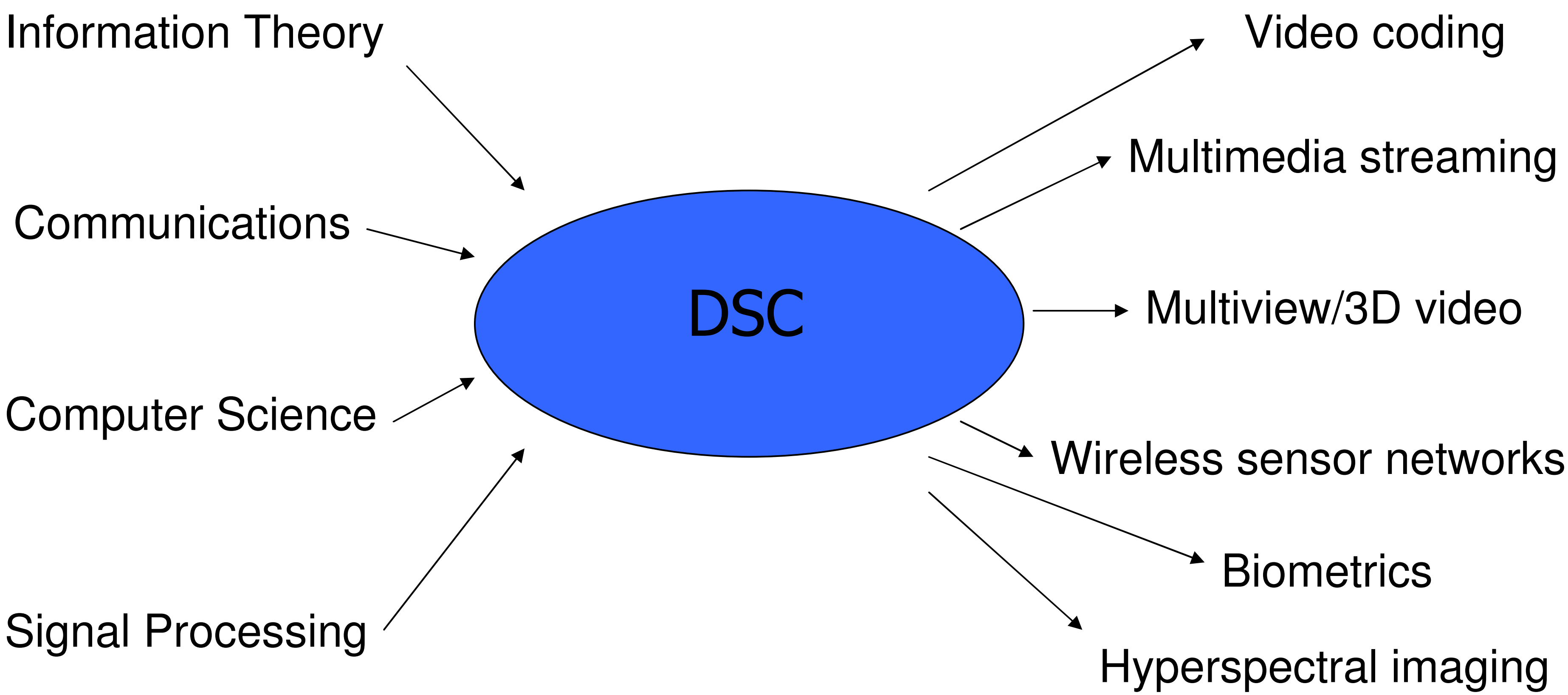


Distributed Source Coding (DSC)

DSC: *Separate compression and joint decompression of multiple correlated sources*

1973. Slepian and Wolf first to consider a DSC problem
1976. Wyner and Ziv – extension to rate/distortion
1999. DISCUS – first practical coding realization with channel codes *(Pradhan and Ramchandran)*
2002. First video coding implementations based on DSC *(Stanford and Berkeley groups)*

DSC Today

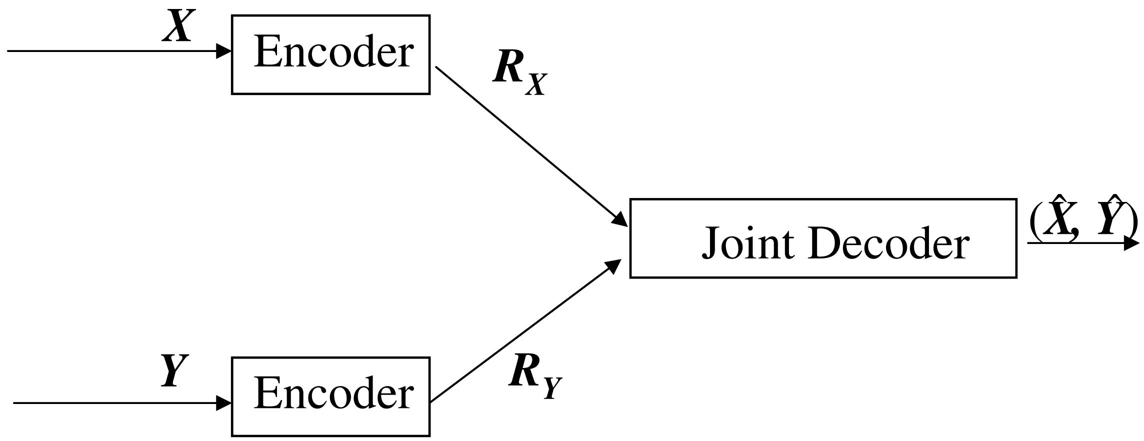


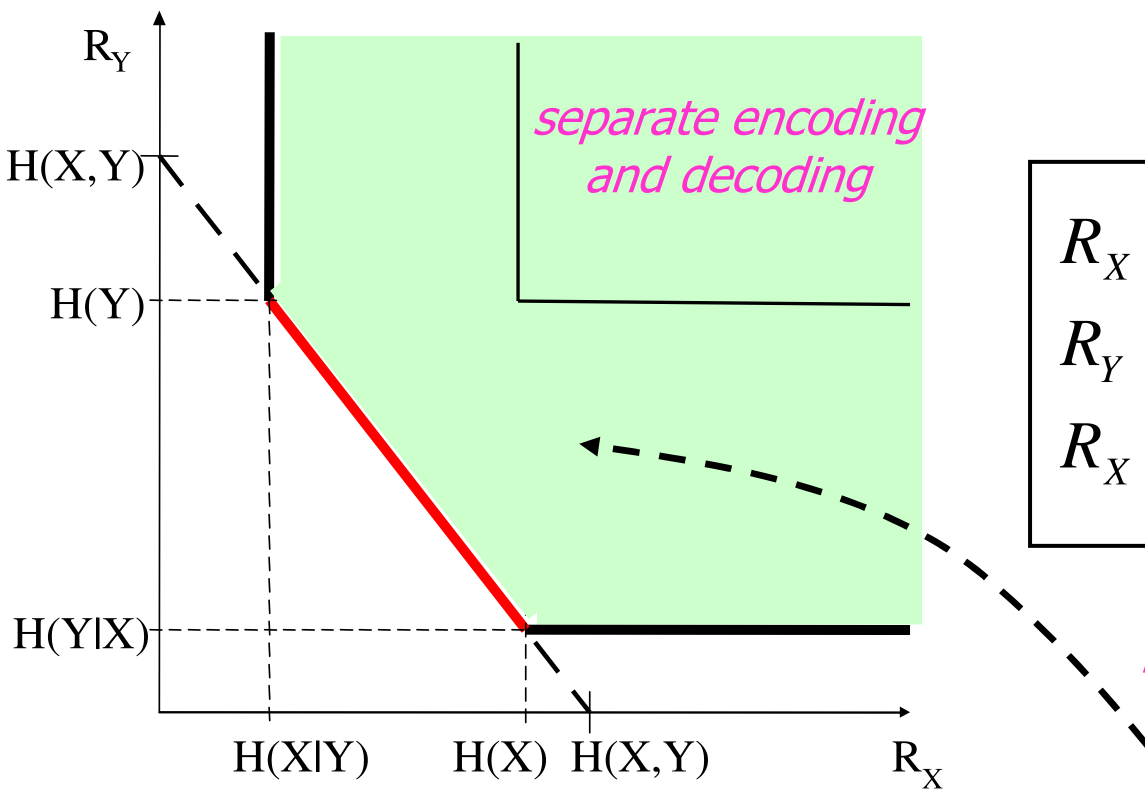
Over 5,200 publications and 1 edited book *(Google Scholar, Aug. 2010)*

DSC Theory:
Underlying Principles and Information Theoretical Research

Slepian-Wolf (SW) Problem

X and Y are discrete, correlated sources

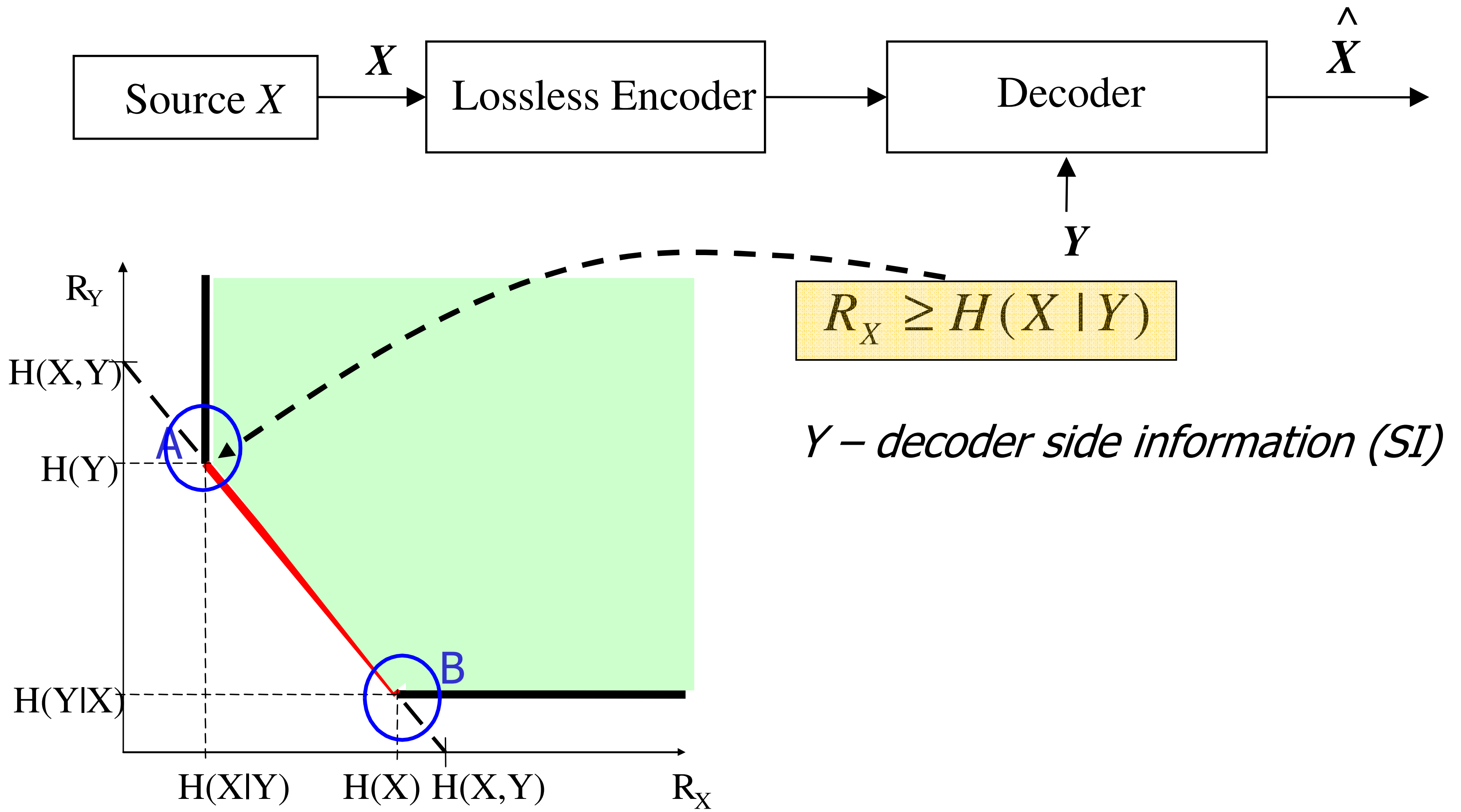




$$R_X \geq H(X \mid Y);$$
$$R_Y \geq H(Y \mid X);$$
$$R_X + R_Y \geq H(X, Y)$$

Achievable rate region

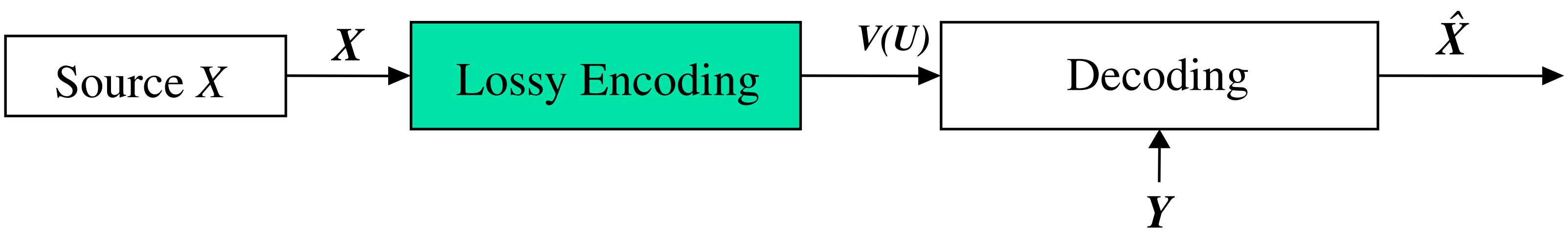
Source Coding with Decoder Side Information (Asymmetric SW)



Y – decoder side information (SI)

Wyner-Ziv (WZ) Problem

- Lossy source coding of X with decoder side information Y
- Extension of asymmetric SW setup to rate-distortion theory
- Distortion constraint at the decoder: $E[d(X,\hat{X})] \leq D$

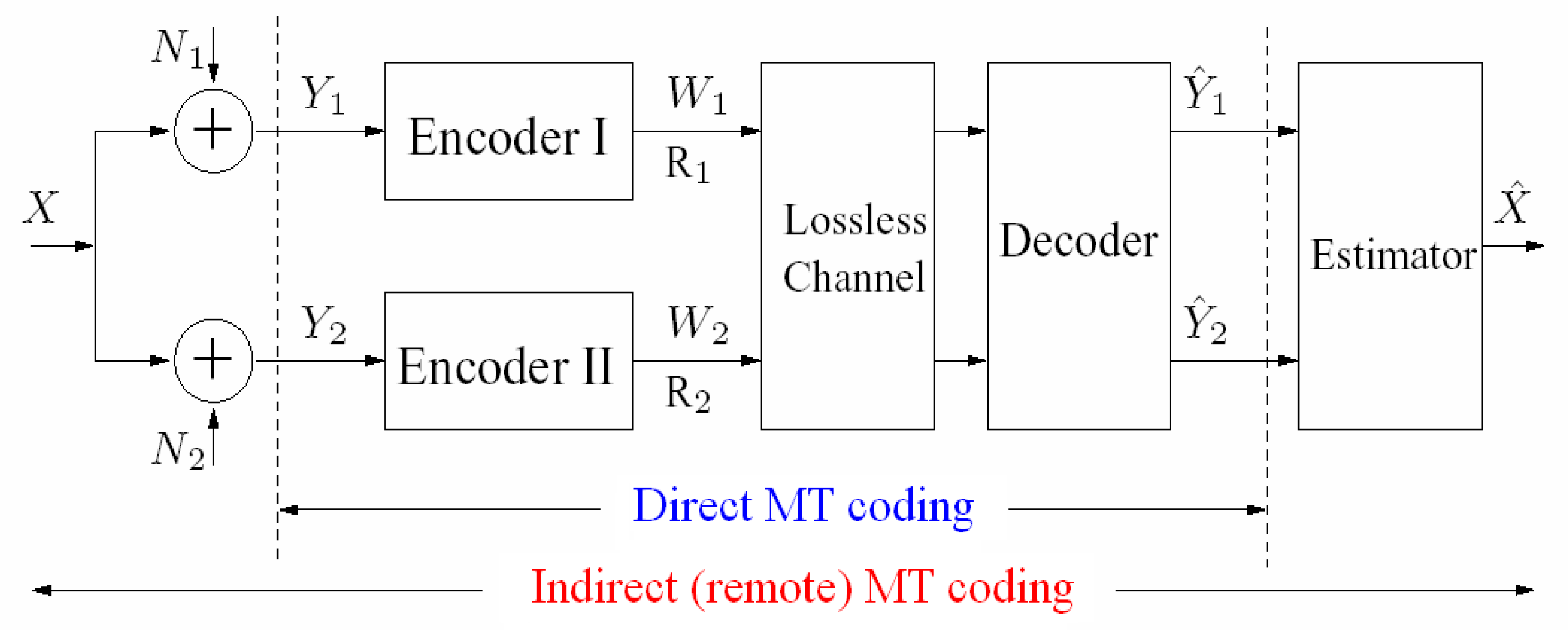


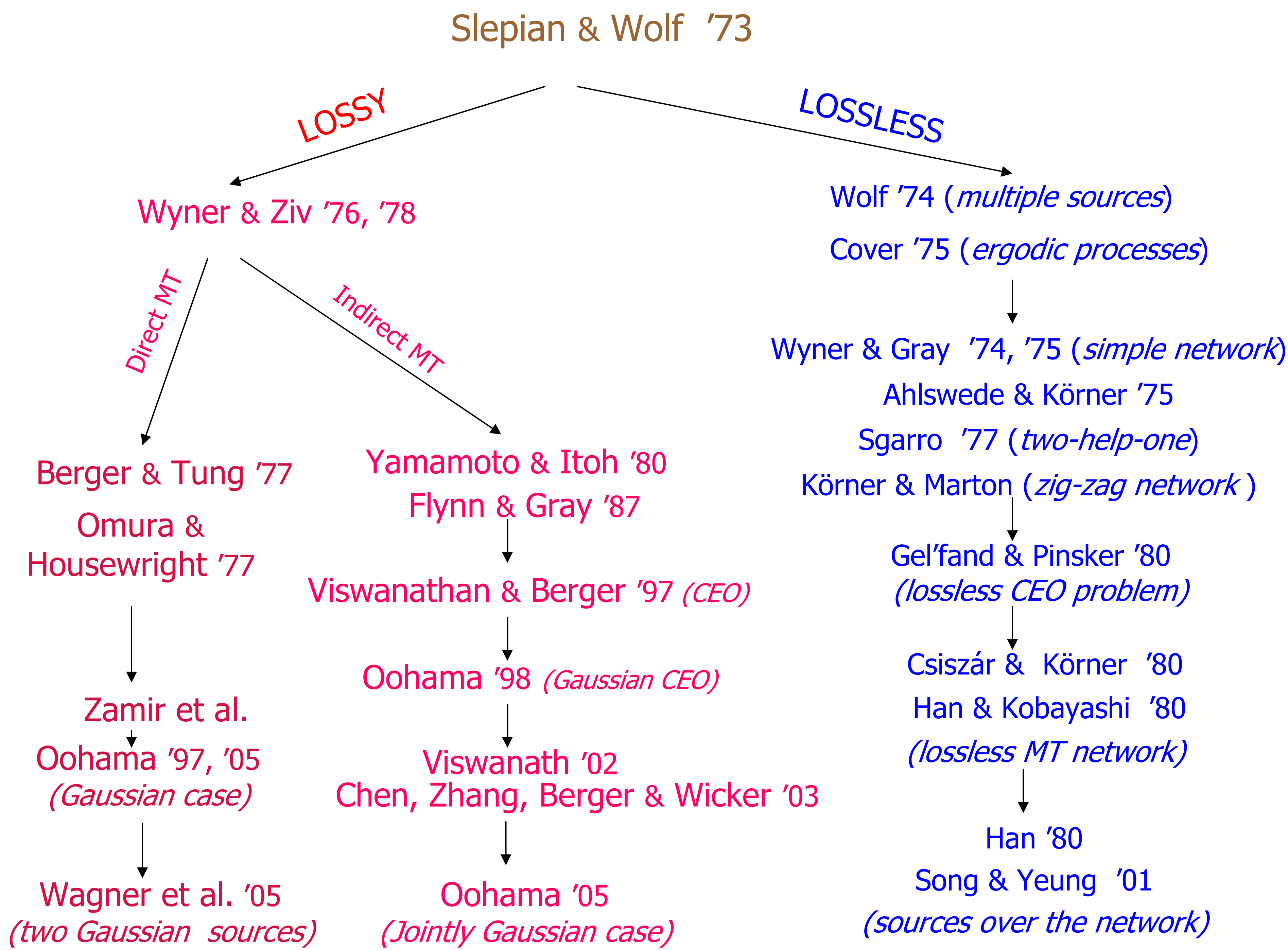
For MSE distortion and jointly Gaussian X and Y, rate-distortion function is the same as for joint encoding and joint decoding

Multiterminal (MT) Source Coding

(Berger & Tung '77, Yamamoto & Itoh '80)

- Non-asymmetric WZ setup
- Extension of the SW setup to rate-distortion theory
- Two types: direct and indirect/remote MT source coding




Slepian & Wolf '73
LOSSY
LOSSLESS
Wyner & Ziv '76, '78
Direct MT
Indirect MT
Berger & Tung '77
Omura & Housewright '77
Zamir et al.
Oohama '97, '05
(Gaussian case)
Wagner et al. '05
(two Gaussian sources)
Yamamoto & Itoh '80
Flynn & Gray '87
Viswanathan & Berger '97 (CEO)
Oohama '98 (Gaussian CEO)
Viswanath '02
Chen, Zhang, Berger & Wicker '03
Oohama '05
(Jointly Gaussian case)
Wolf '74 (multiple sources)
Cover '75 (ergodic processes)
Wyner & Gray '74, '75 (simple network)
Ahlswede & Körner '75
Sgarro '77 (two-help-one)
Körner & Marton (zig-zag network)
Gel'fand & Pinsker '80
(lossless CEO problem)
Csiszár & Körner '80
Han & Kobayashi '80
(lossless MT network)
Han '80
Song & Yeung '01
(sources over the network)

DSC Theory: A Rapidly Growing Field

- >200* published papers on DSC in *IEEE Trans. Information Theory* in the period 1999-present
  - ~70 papers in 1999-2005 and ~160 papers in 2006-2010
  - **>50** papers have been published since January 2009

- Currently dominating topics: DSC in communication systems (relay channels, use-cooperation, etc), MT source coding, distributed source-channel coding, universal DSC, multiple description and DSC, successive refinement

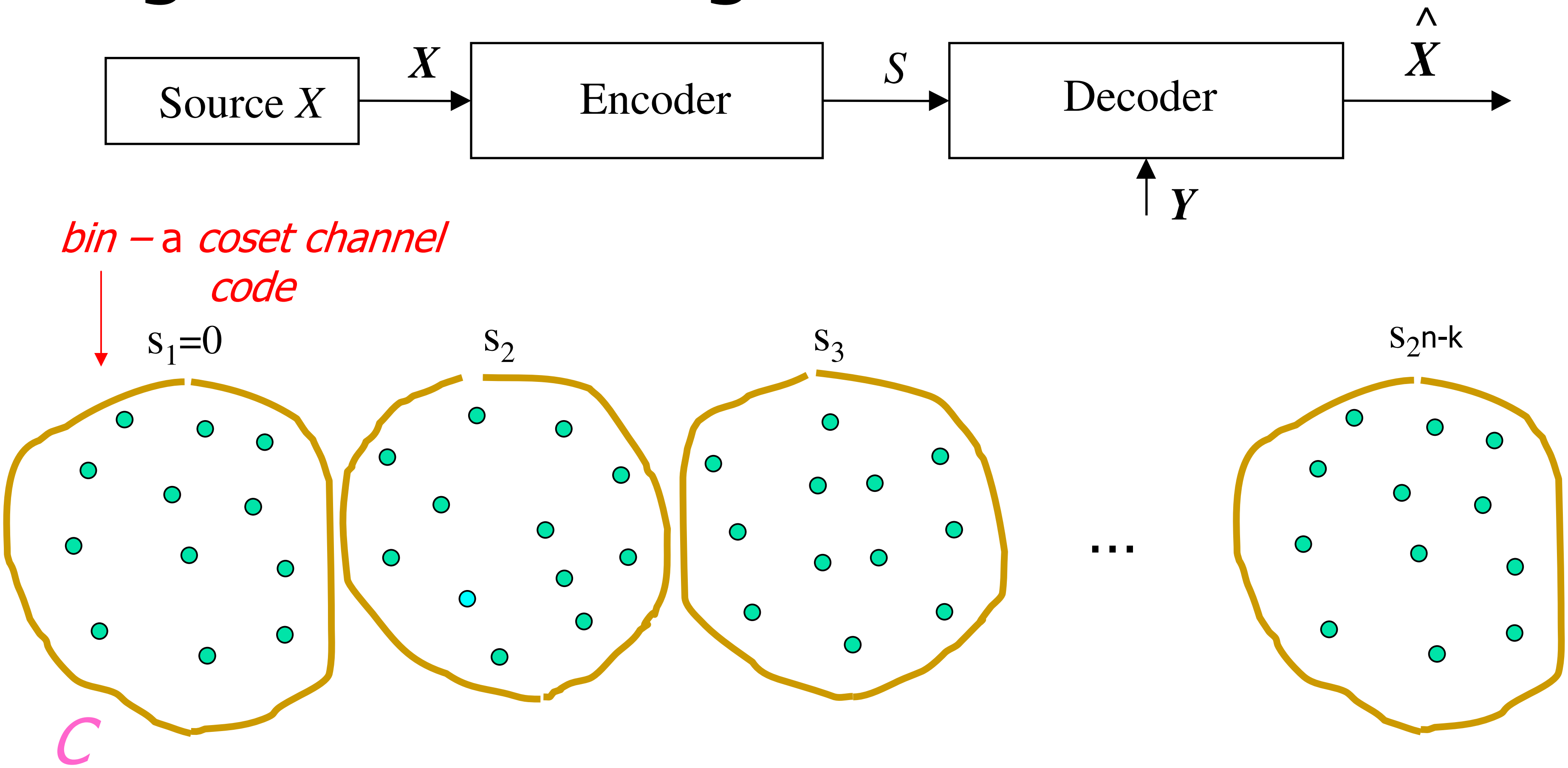
**IEEExplore, August 2010*

Main Challenges

- Addressing noisy cases (noisy non-Gaussian channels, noisy SI, real-world systems, etc.)
- Time-varying statistics
- Reconstructing a function of the sources
- Looking at different network topologies
- Compressive sampling and DSC

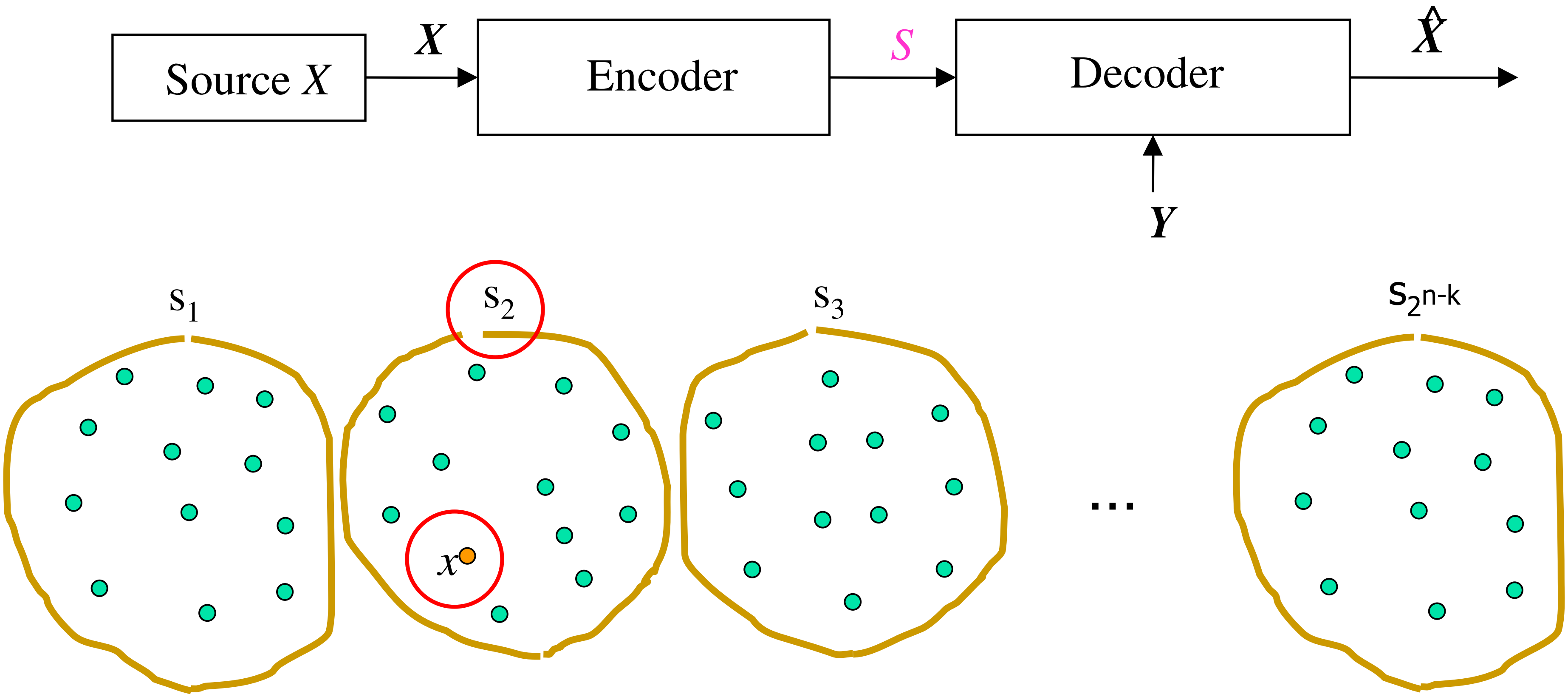
DSC: Code Design

Channel Codes for Compression: Algebraic Binning *(Wyner '74, Zamir et al. '02)*



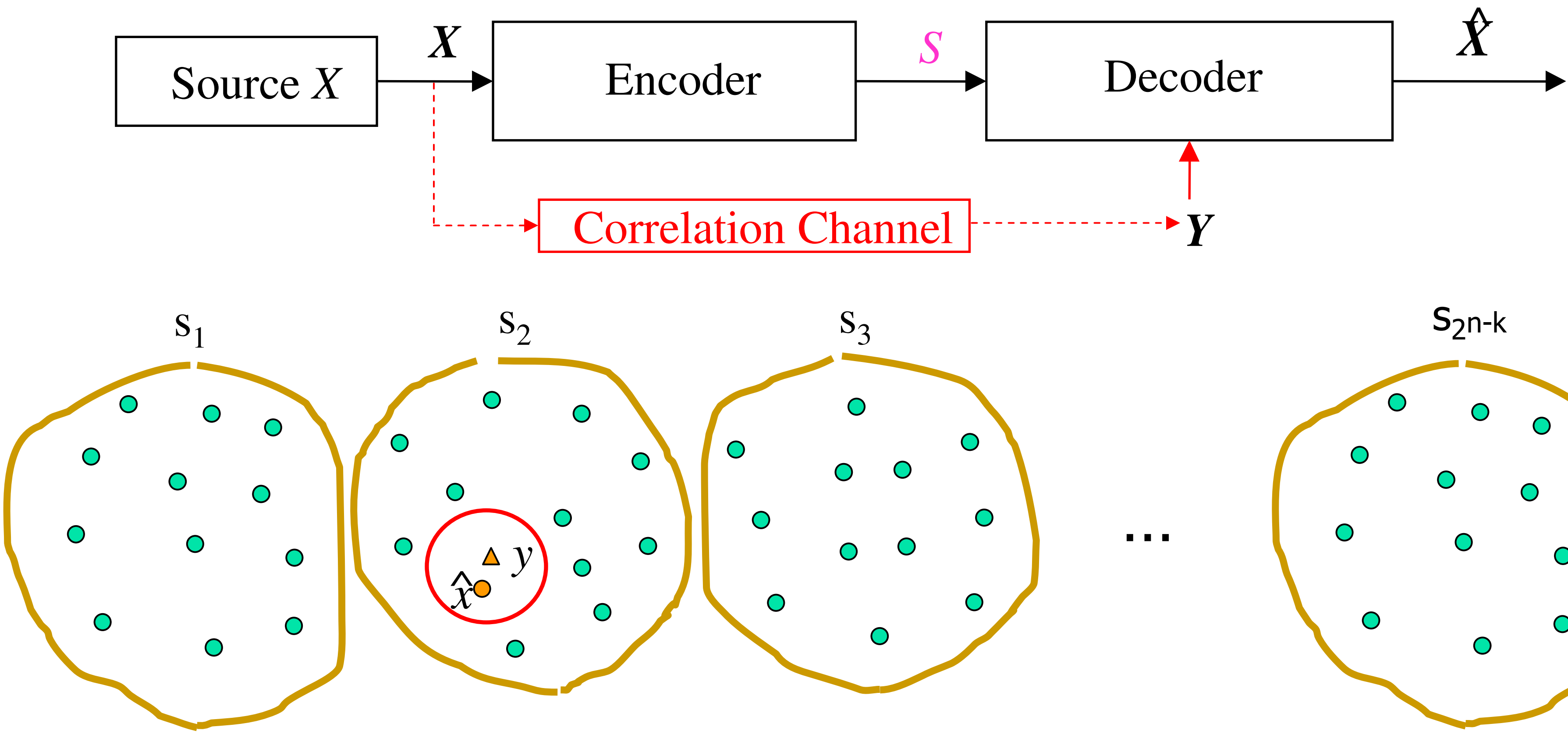
- Distribute all possible realizations of *X* (of length *n*) into bins
- Each bin is a *coset* of an (*n*,*k*) linear channel code *C*, with parity-check matrix *H* of size (*n*,*n*-*k*) indexed by a *syndrome s*

Encoding



- Encoding: For an input x, form a syndrome $s=xH^T$
- Send the resulting syndrome (s_2) to the decoder

Decoding



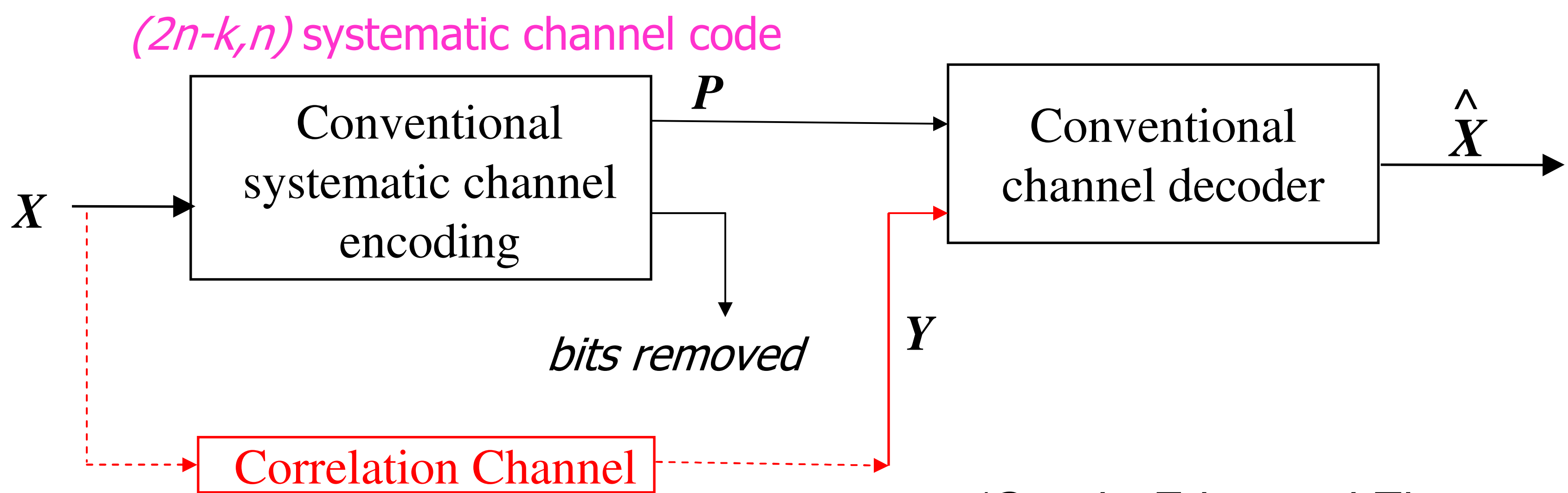
- Interpret *y* as a *noisy version* (output of virtual communication channel called *correlation channel*) of *x*
- Find a codeword of the coset indexed by *s* closest to *y* by performing conventional channel decoding

General Syndrome Concept

- Applicable to *all linear channel codes* (inc. turbo and LDPC codes)
- Key lies in correlation modeling: if the correlation can be modeled with a simple communication channel, existing channel codes can be used
  - SW code will be good if the employed channel code is good for a "correlation channel"
  - If the channel code approaches capacity for the "correlation channel", then the SW code approaches the SW limit
- Complexity is close to that of conventional channel coding

Parity-based Binning

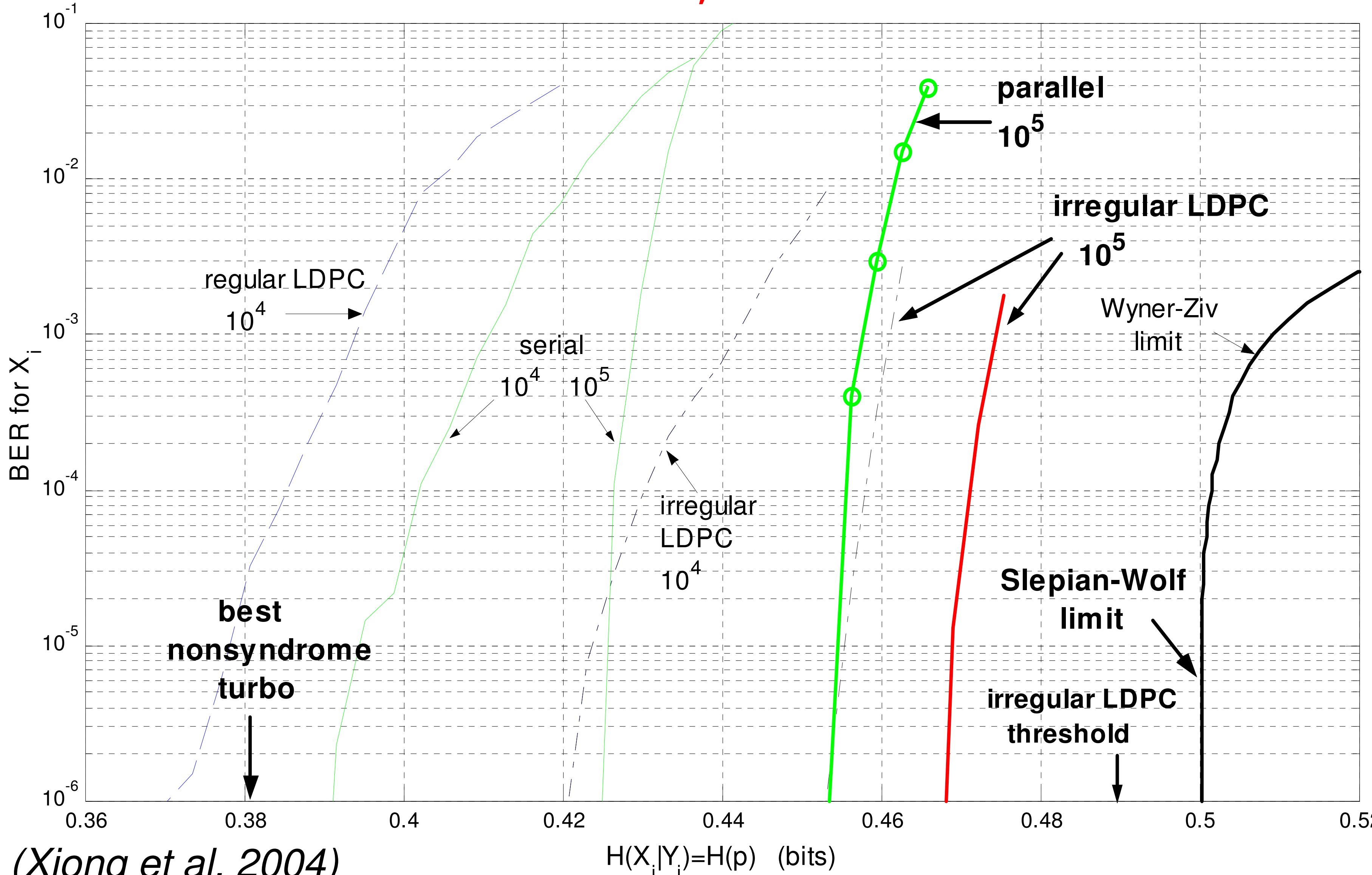
- <u>Syndrome approach</u>: To compress an *n*-bit source, index each bin with a syndrome from a linear channel code *(n,k)*
- <u>Parity-based approach</u>: To compress an *k*-bit source, index each bin with *(n-k)* parity bits *p* of a codeword of a systematic *(n,k)* channel code
- Compression rate: $R_X=(n-k)/k$



(Garcia-Frias and Zhao 2001)

Asymmetric Binning for SW

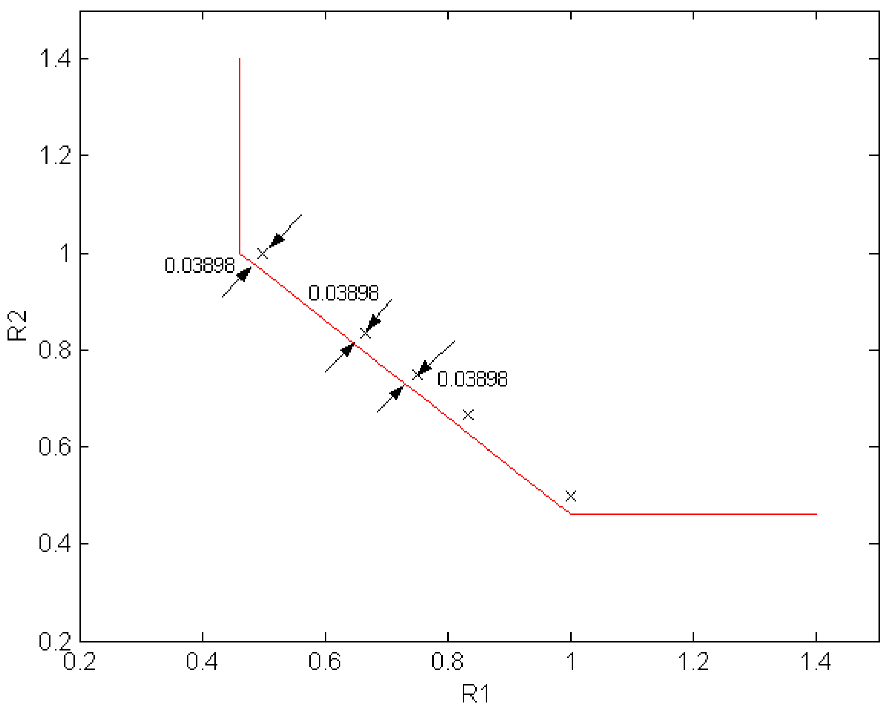
For two sources, code rate = ½



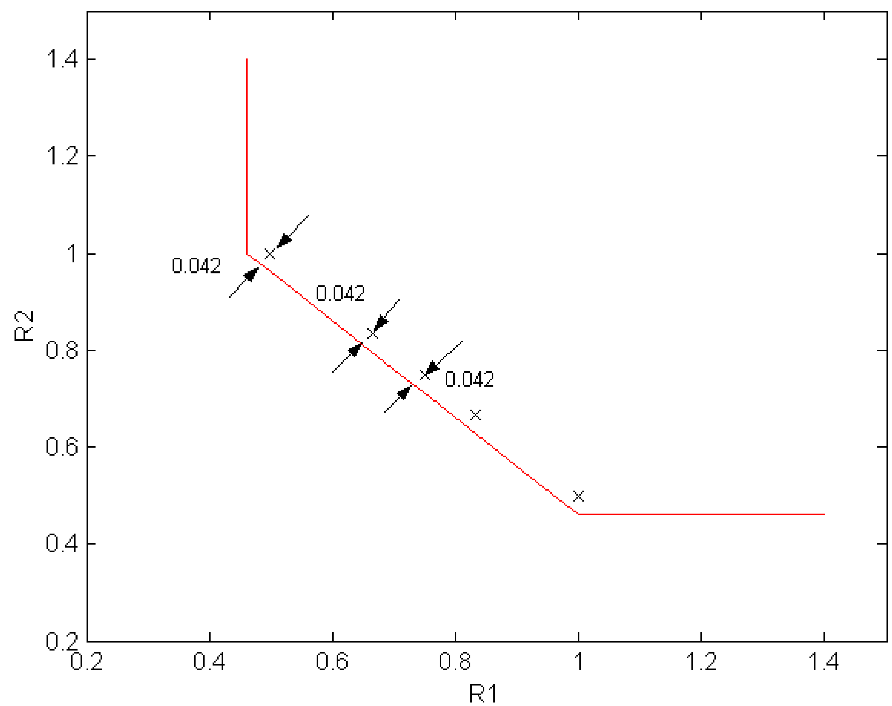
(Xiong et al. 2004)

Non-asymmetric Binning for SW

Codeword length 20,000 bits



LDPC code

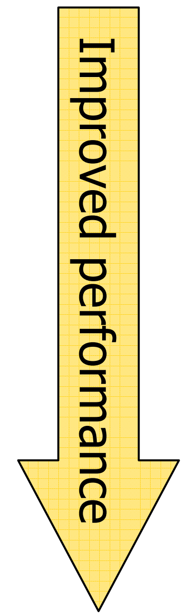


Turbo code

(Stankovic et al. 2006)

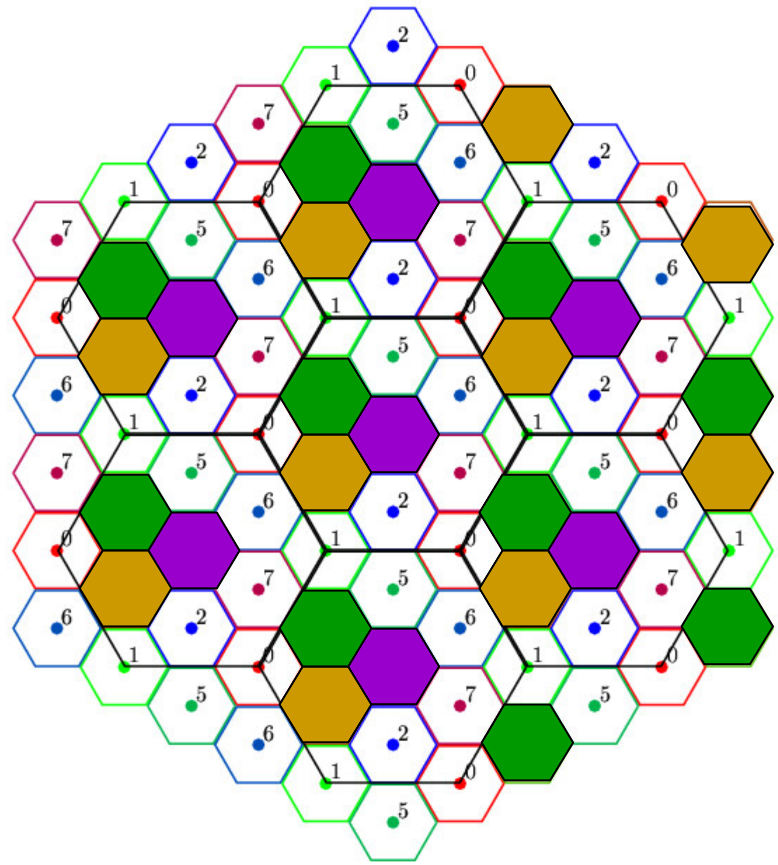
Practical WZ Coding Solutions

- Three types of solutions proposed:
  - Nested quantization
  - Combined quantization and SW coding *(DISCUS, 1999, 2003)*
  - Quantization followed by SW coding (Slepian-Wolf coded quantization - SWCQ)



Nested Lattice Quantization

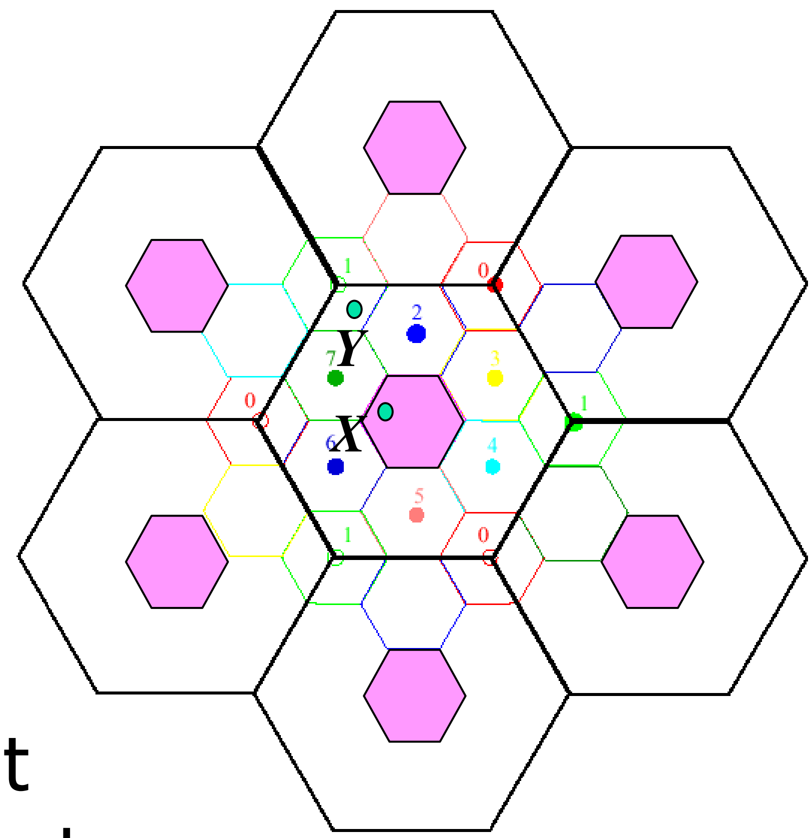
- Nested lattice
  - A (fine) lattice is partitioned into sublattices (coarse lattices)
  - A bin: the union of the original Voronoi regions of points of a sublattice



■ : bin 8
■ : bin 4
■ : bin 3

Nested Lattice Quantization

- Encoding: output index of the bin containing X
  - Quantize X using the fine lattice
  - Output the index V of the coarse lattice containing quantized lattice point
- Decoding: find lattice point of sublattice V that is closest to Y



Bin index: $V = 8$

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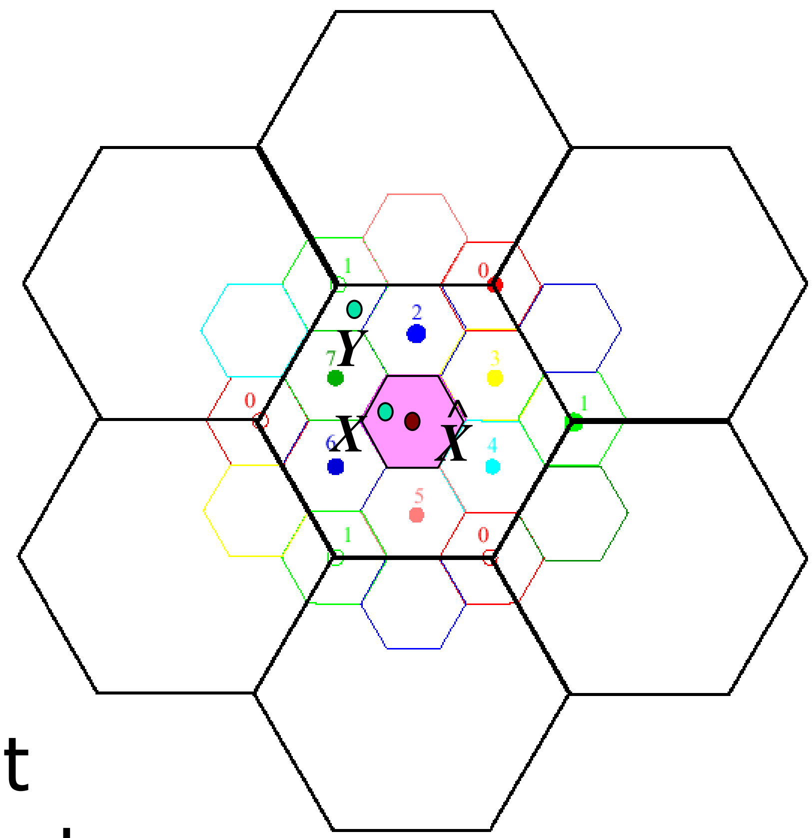
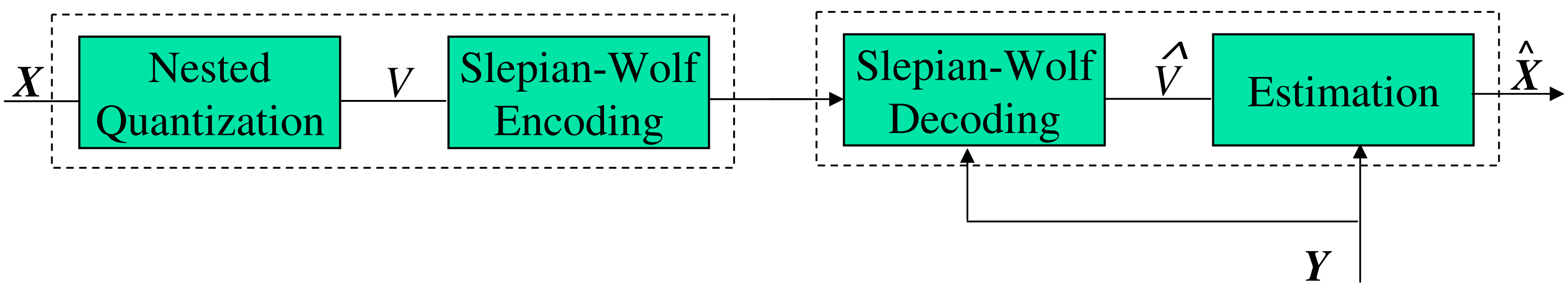


Bin index: $V = 8$

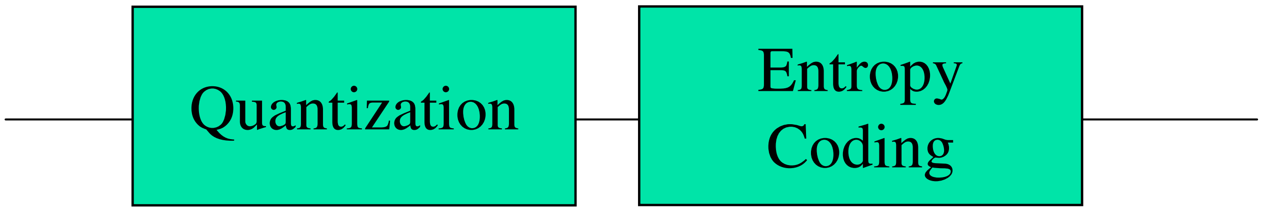
SW Coded Quantization (SWCQ)

- Nested lattice quantization is asymptotically optimal as dimensions go to infinity *(S. Servetto, 2002)*
  - Difficult to implement even in low dimensions
- The bin index V and the SI Y are still highly correlated, i.e., $H(V) > H(V|Y)$
  - Use SW coding to further compress V!

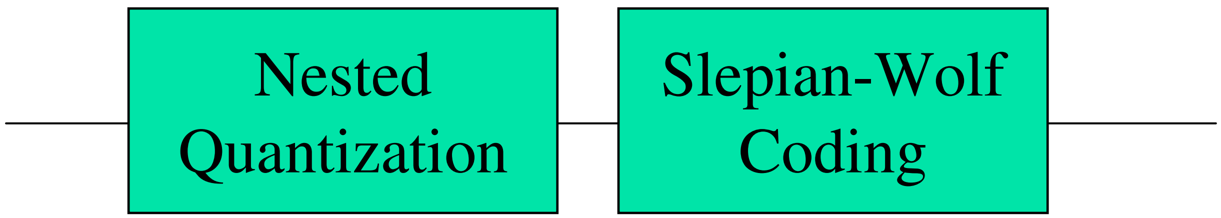


WZC vs. Classic Source Coding

- Classic entropy-constrained quantization (ECQ)



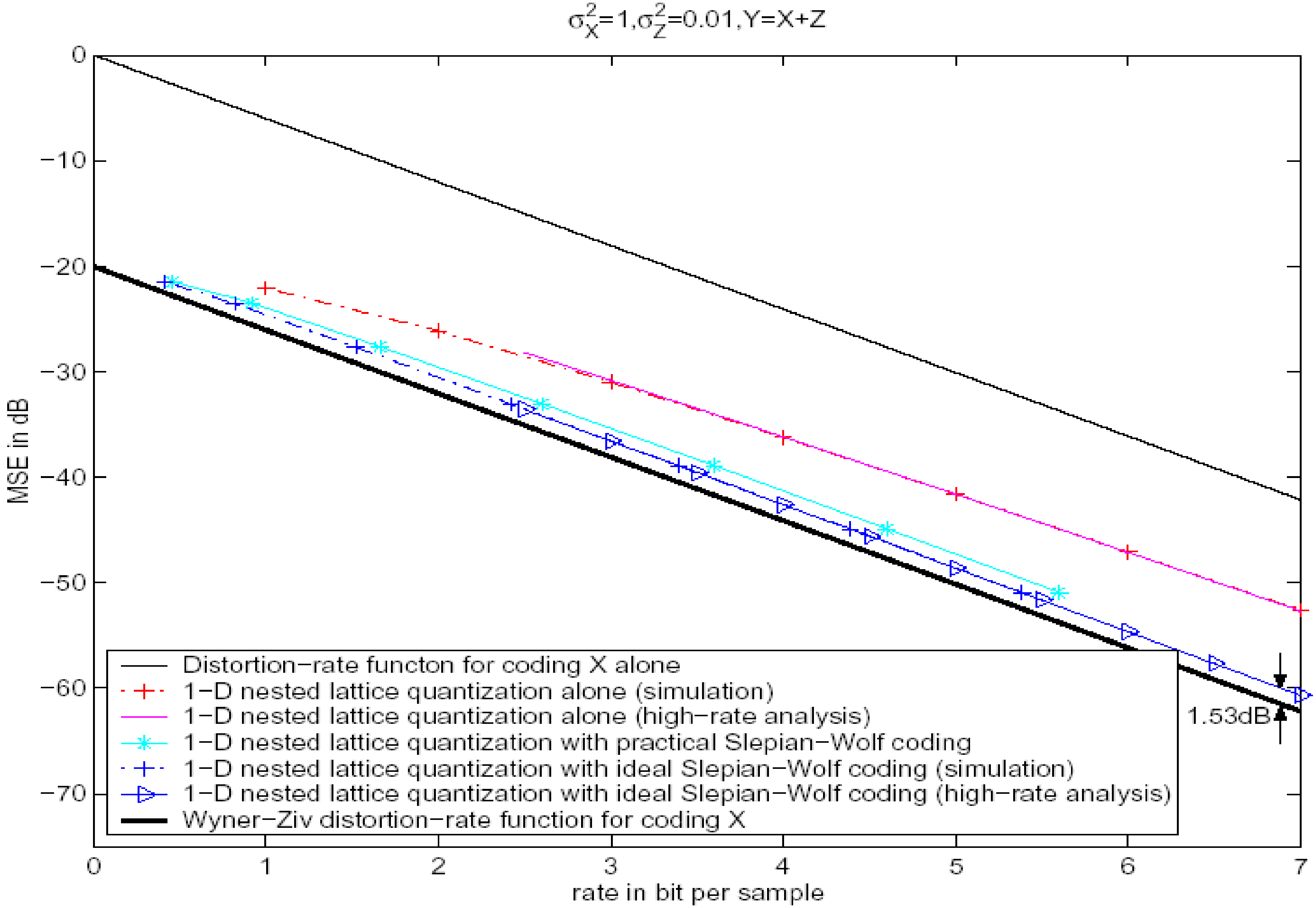
- Wyner-Ziv coding (SWCQ)



  - Nested quantization: quantization with SI
  - Slepian-Wolf coding: entropy coding with SI

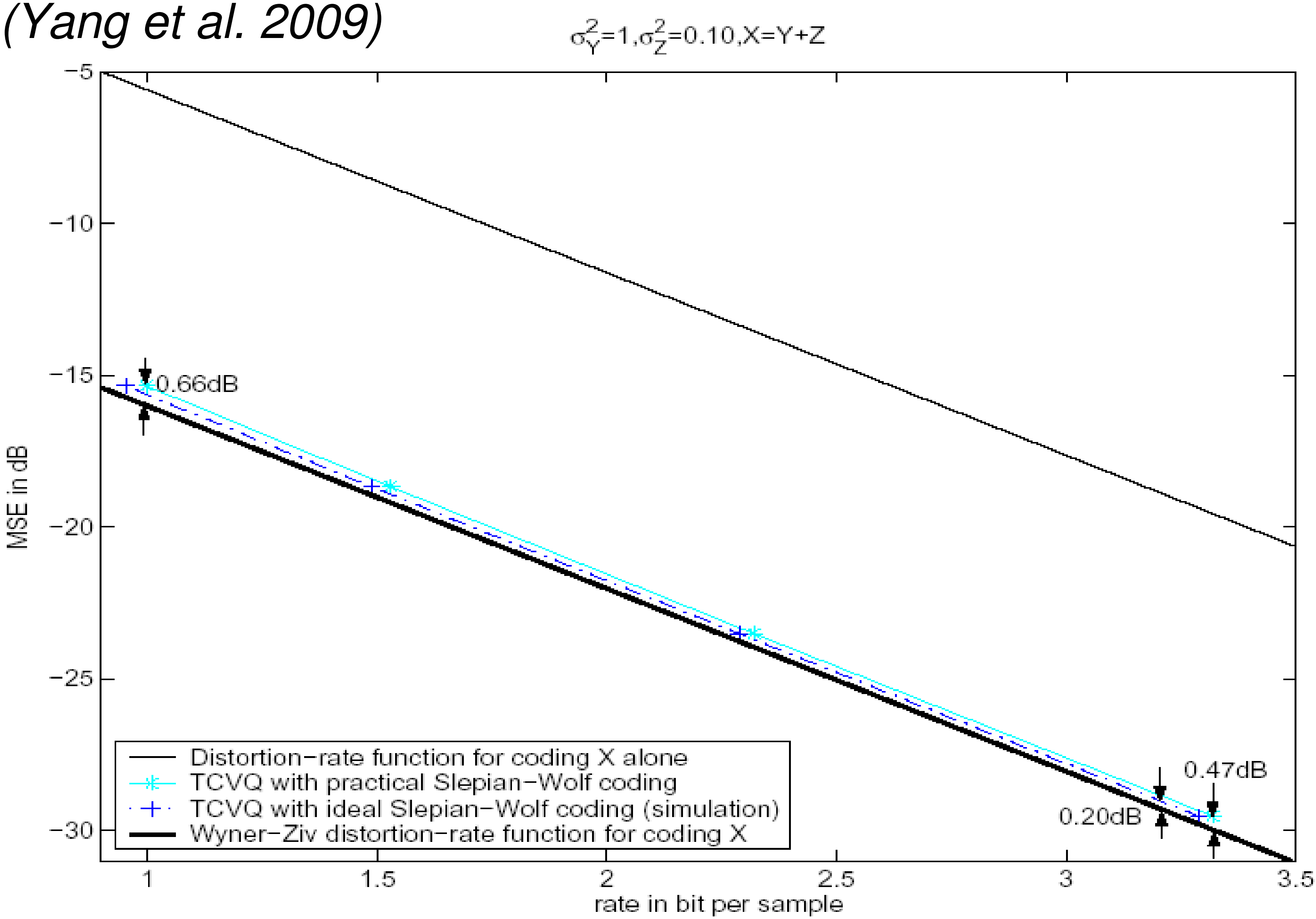
Classic source coding is just a special case of WZ coding
(since the SI can be assumed to be a constant)

Gaussian WZC (NSQ 1-D Lattice)

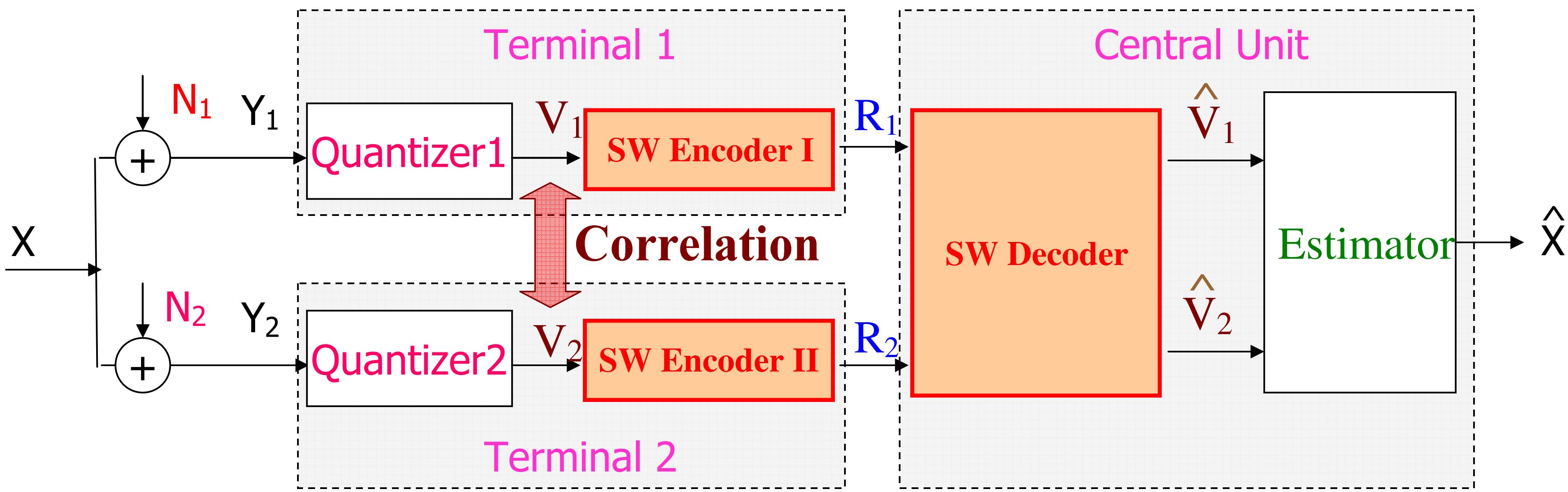


Gaussian WZC (with TCVQ)

(Yang et al. 2009)



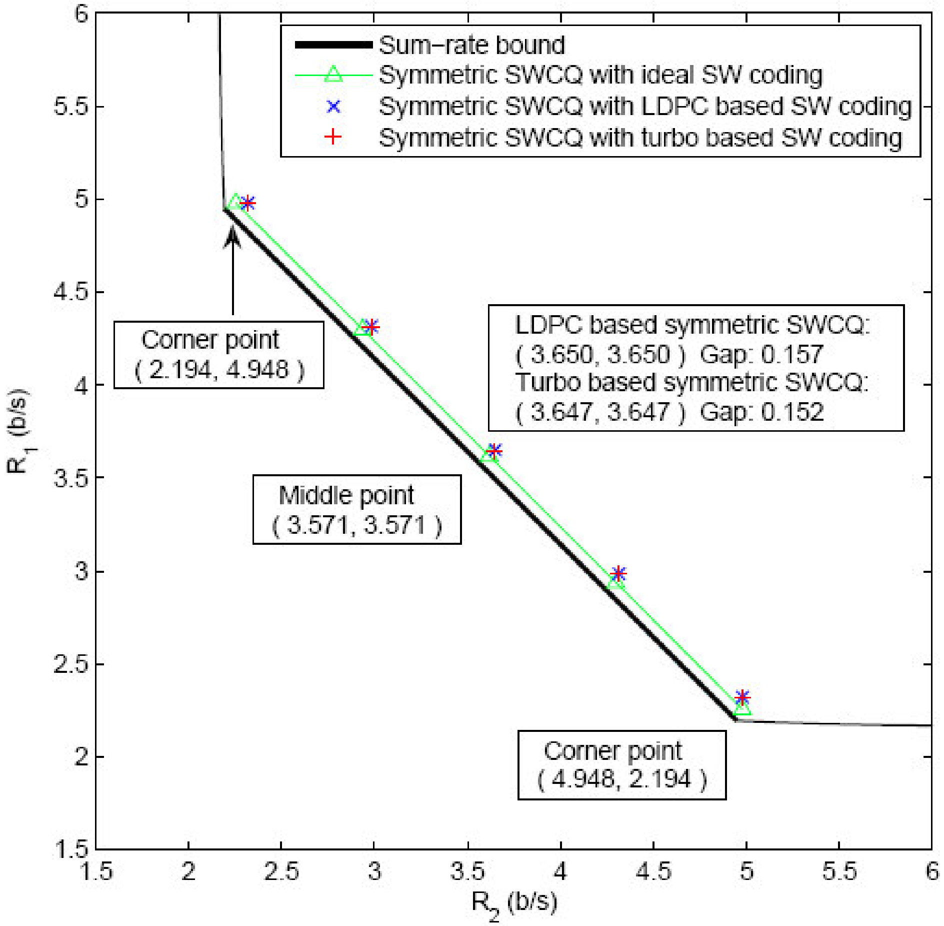
MT Source Code Design

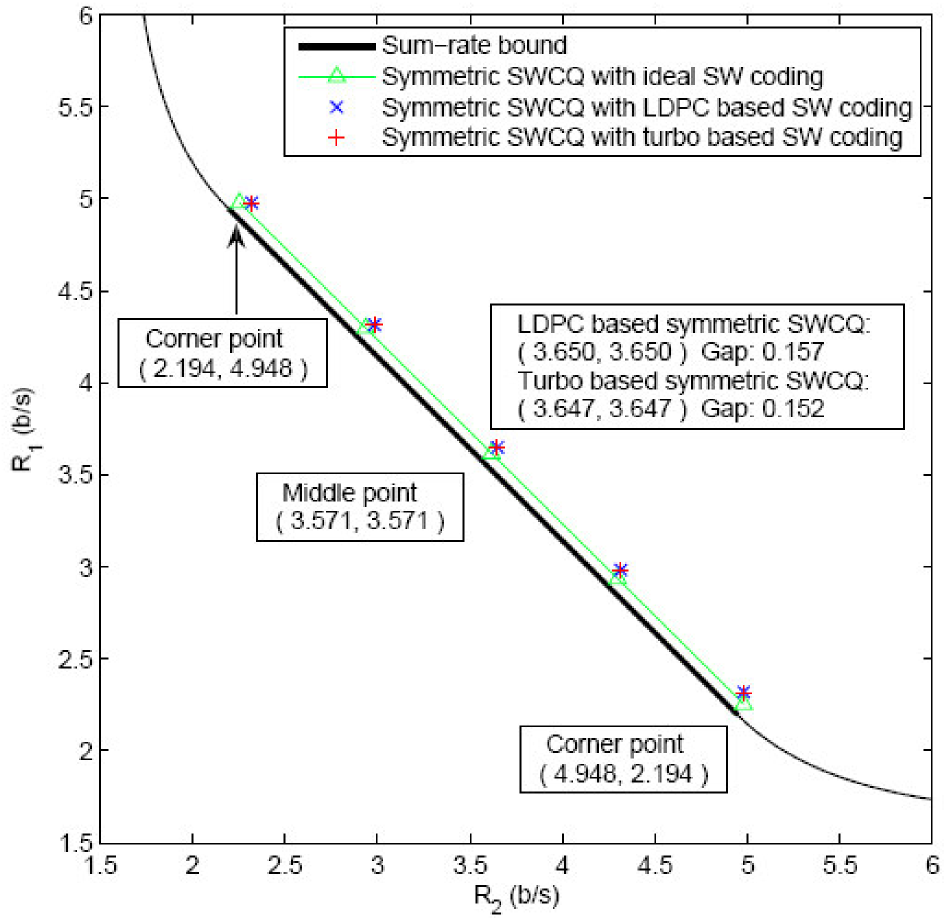


- Conventional quantization + lossless "non-asymmetric" Slepian-Wolf coding of quantization indices V_1 and V_2

(Yang, Stankovic, Xiong, Zhao, IEEE Inform. Theory, March 2008)

Gaussian MT Source Coding (with TCQ)





Direct MT D_1=D_2=-30 dB, ρ=0.99

Indirect MT D=-22.58 dB, σ_{n_1}=σ_{n_2}=1/99

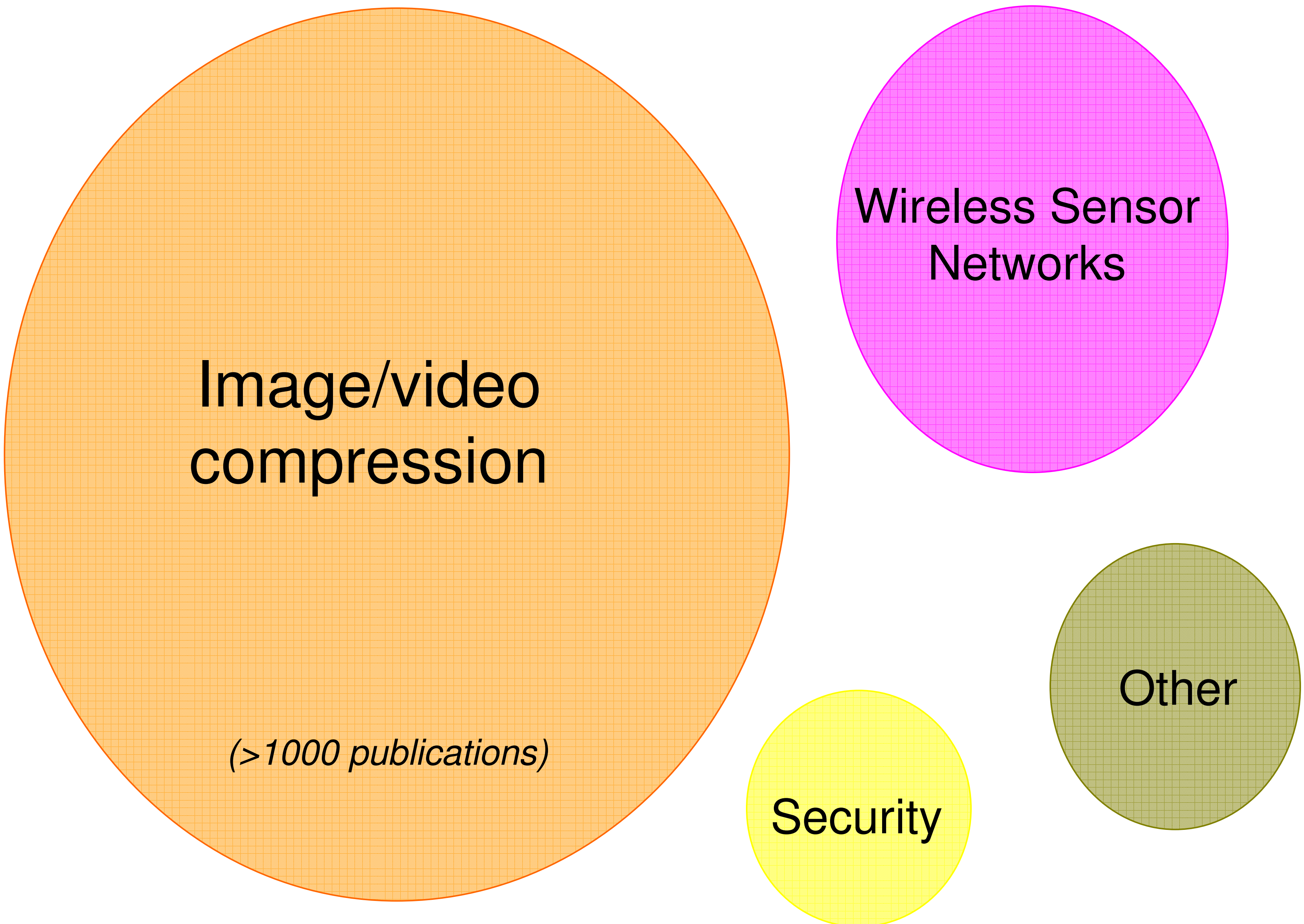
Current Trends

- Rateless/Digital Fountain codes for DSC
- Nonbinary/multilevel channel codes
- Non-channel coding based DSC (Arithmetic coding, Huffman)
- Code designs for compress-forward (relay channels, user cooperation)
- Rate adaptive DSC

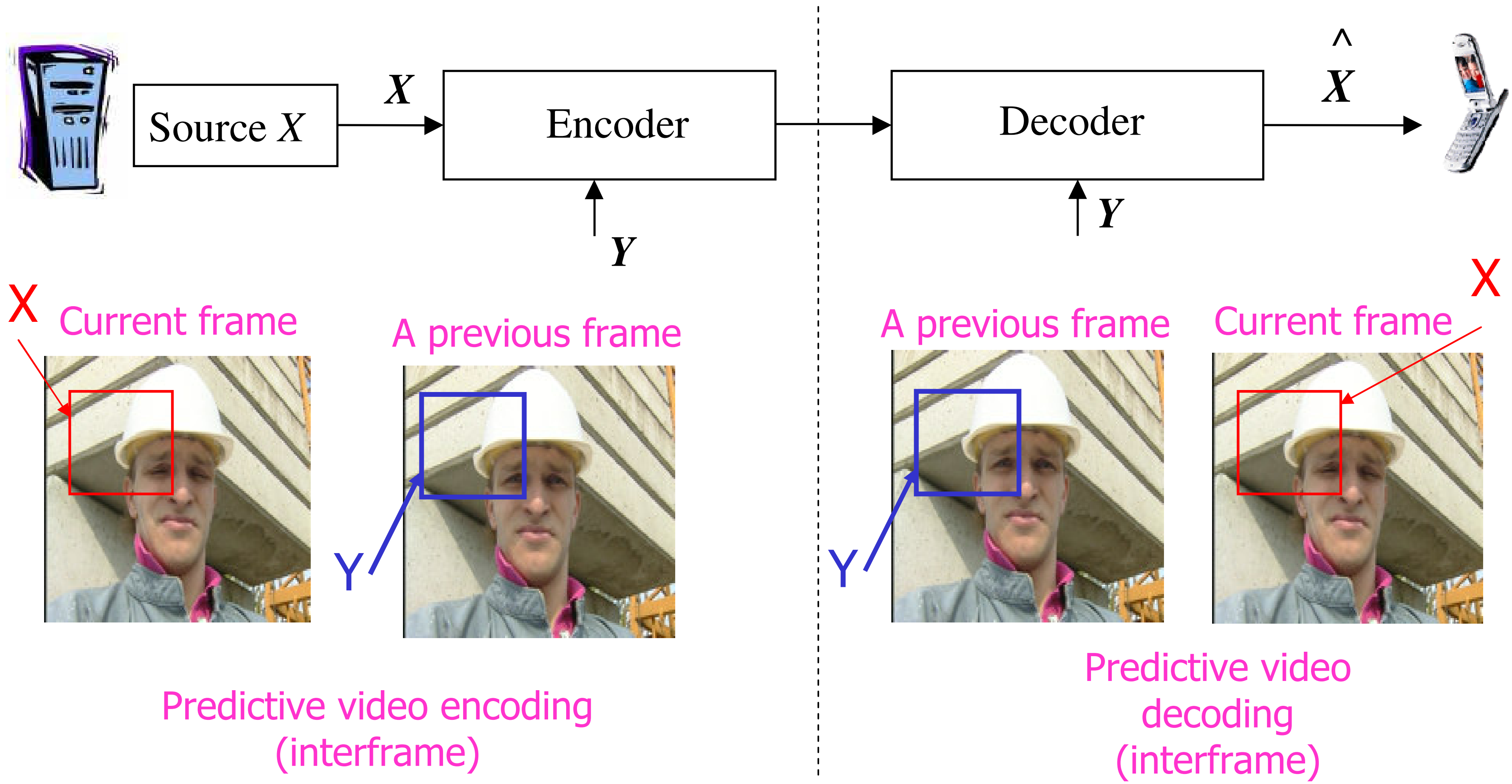
Main Challenges

- Time-varying, non-uniform statistics
- *Low complexity, short code-length codes*
- Rate compatible codes
- Real-time decoding
- Joint source-channel coding
- User-cooperation
- Compressing compressively sampled data

DSC: Key Applications


Image/video compression
(>1000 publications)
Wireless Sensor Networks
Other
Security

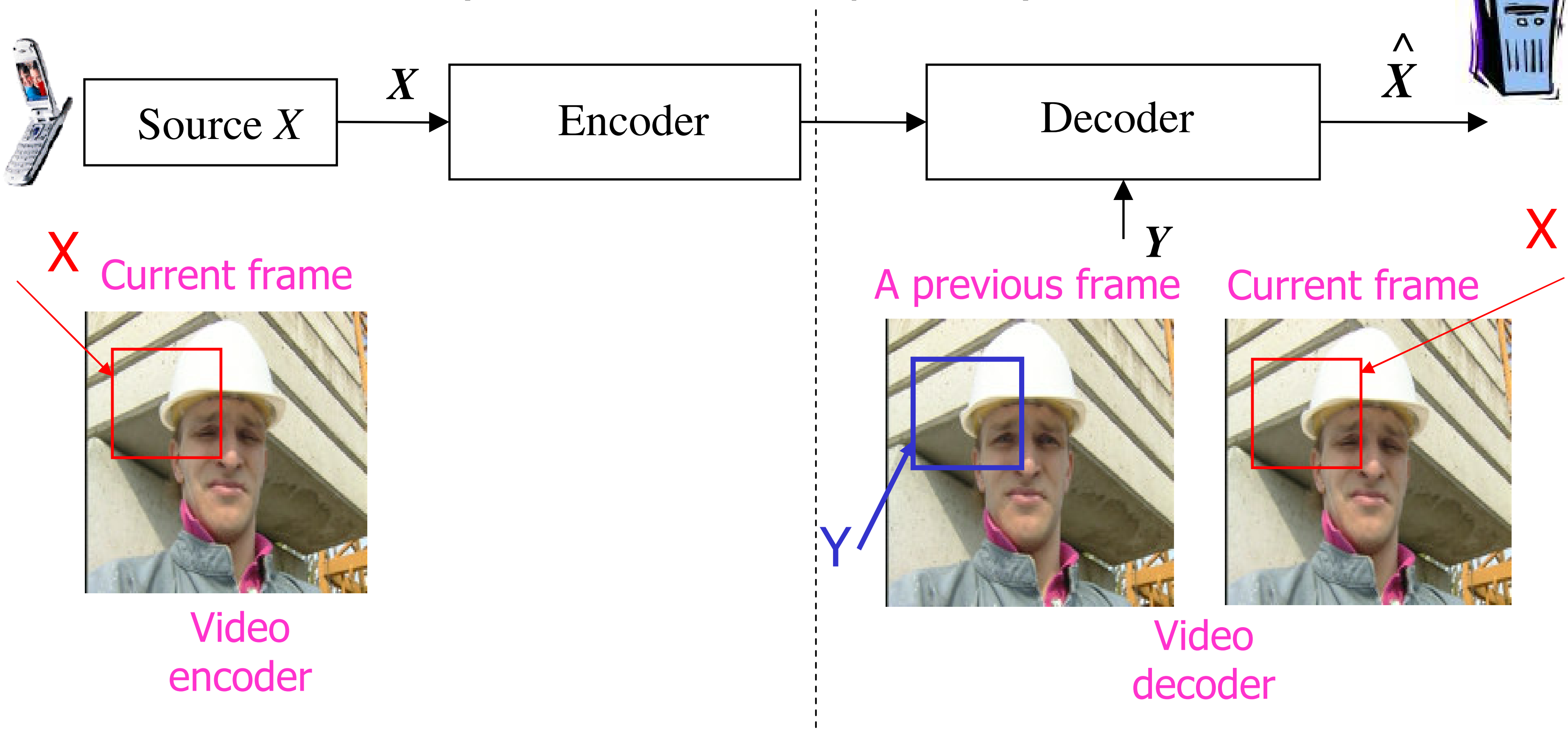
Conventional Video Coding



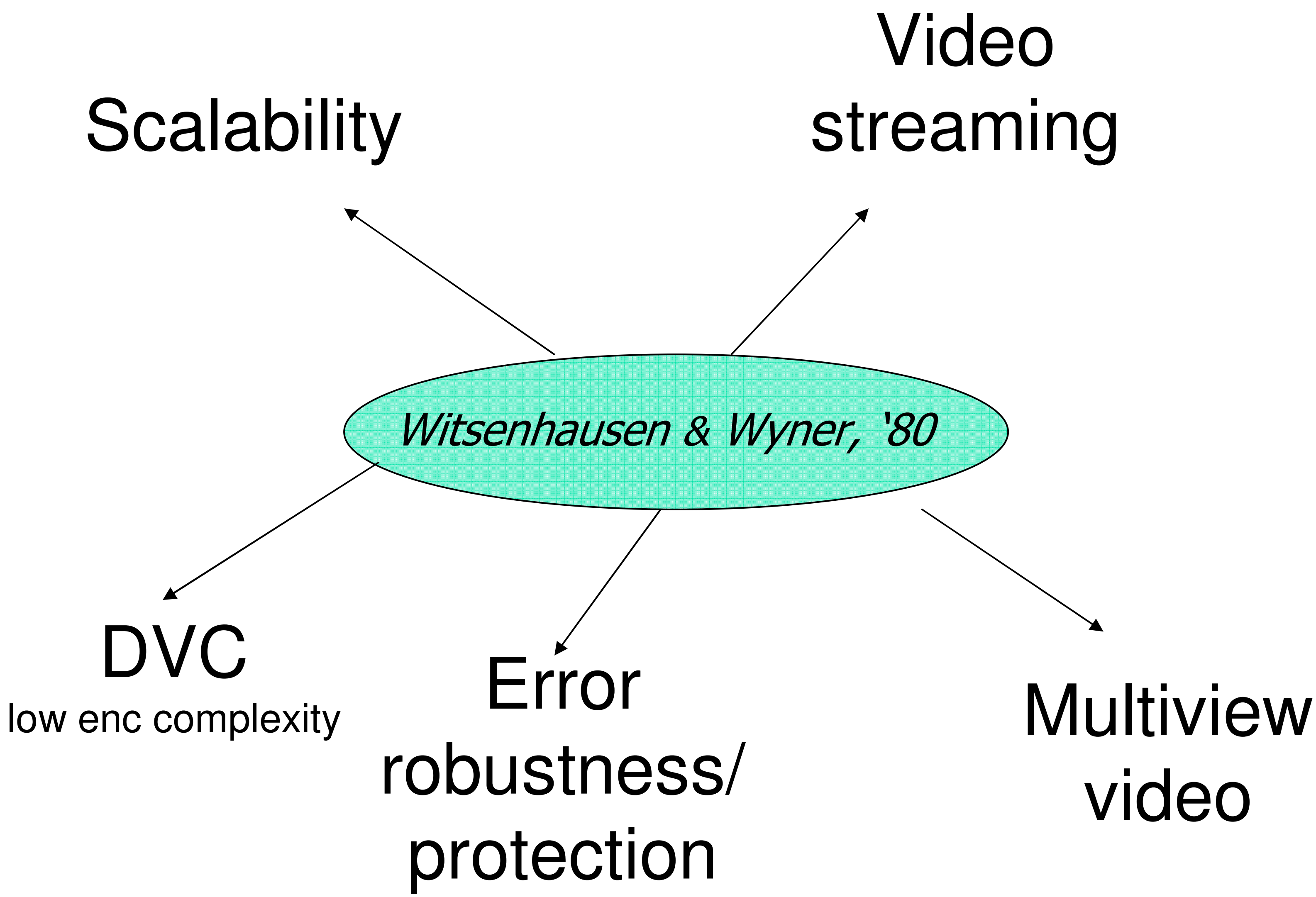
- High-complexity encoding (TV station, strong server)
- Low-complexity decoding (TV, computer, cell-phone)

Distributed Video Coding (DVC)

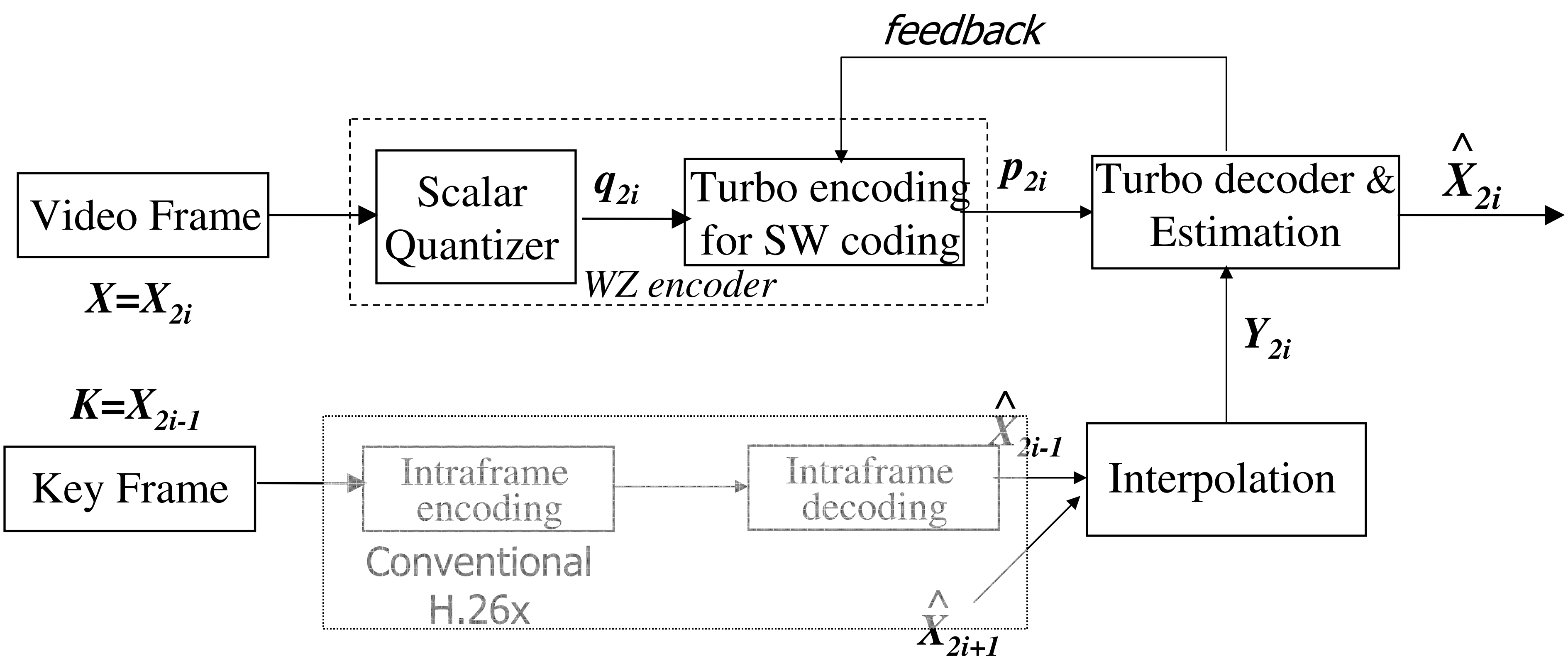
(Witsenhausen & Wyner, '80)



- The encoder does not need to know SI *Y*
- Low-complexity encoding (cell-phone, web-cam)
- High-complexity decoding (computer server)
- Low-complexity network: cell-server (converts to H264) -cell


Video streaming
Scalability
Witsenhausen & Wyner, '80
DVC
low enc complexity
Error robustness/ protection
Multiview video

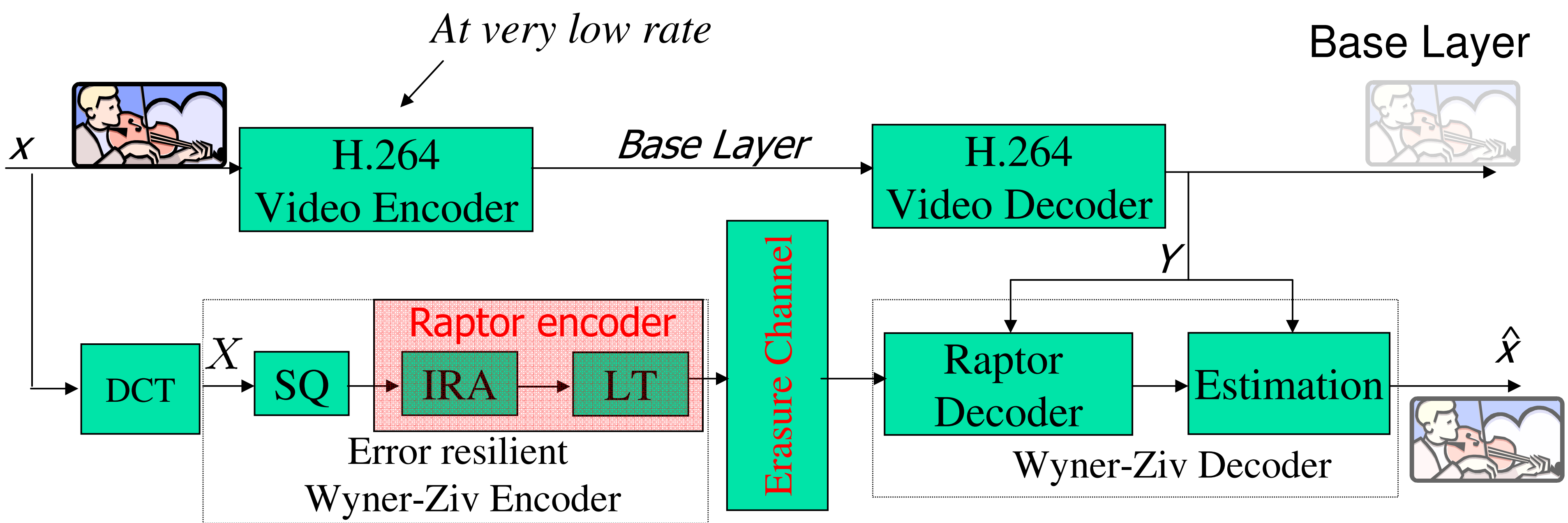
Pixel-domain DVC



(Aaron, Zhang, Girod, 2002)
(Aaron, Rane, Zhang, Girod, 2003)

Robust Scalable DVC

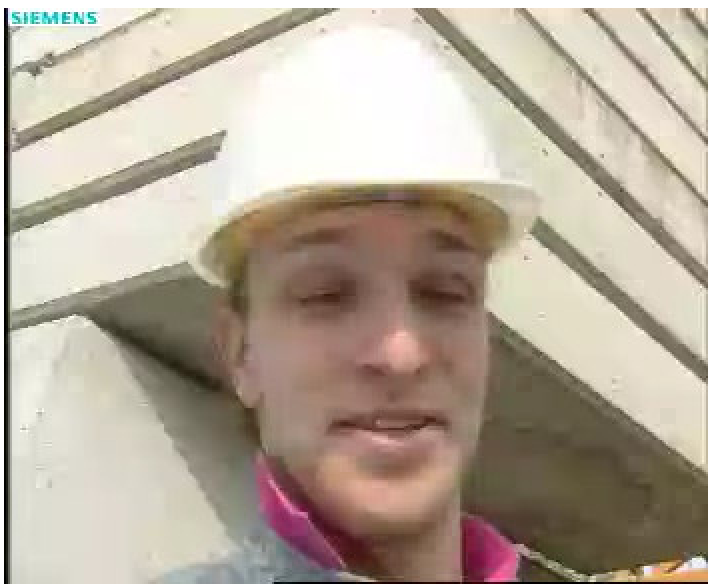
(Xu, Stankovic, Xiong, 2007)



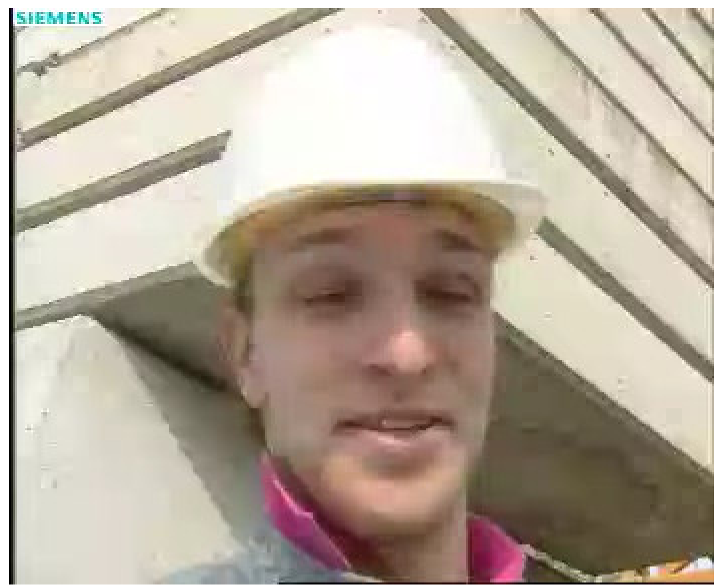
Simulation Example

(Xu, Stankovic, Xiong, 2007)

Transmission rate 256 Kbps
5% macroblock loss rate in the base layer
10% packet loss rate for WZ coding layer



H.264



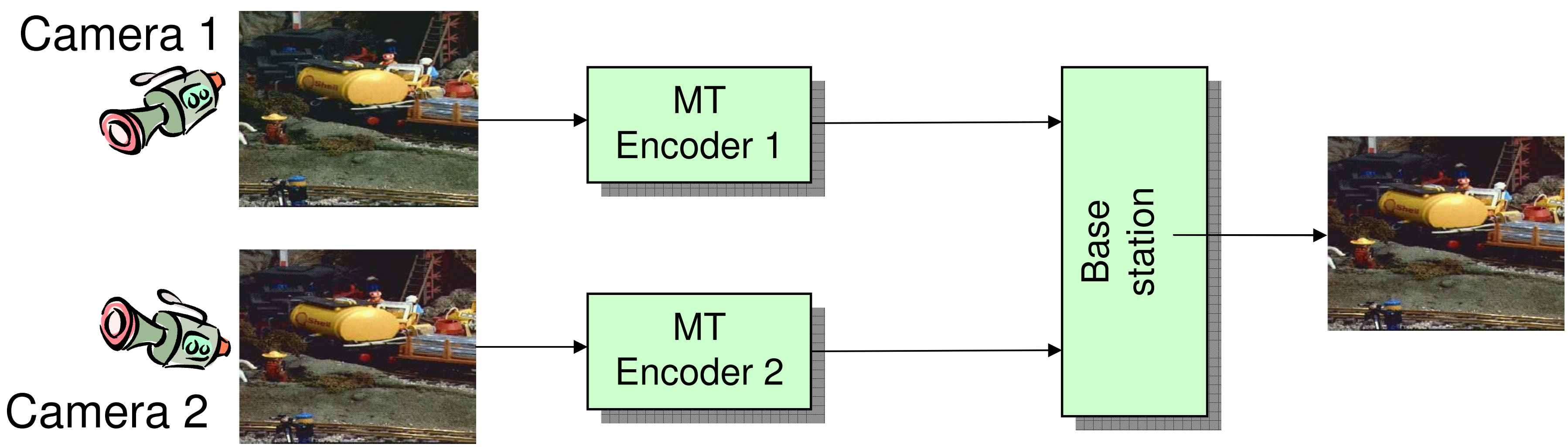
Scalable DVC system

DVC: Latest Developments

- Performance improvement: Advanced side information generation (e.g., bidirectional motion estimation + spatial smoothing)
  - DISCOVER DVC codec close to H.264/AVC no motion
- Improved error resilience
- No need for feedback channel
- Efficient rate control
- Improved reconstruction

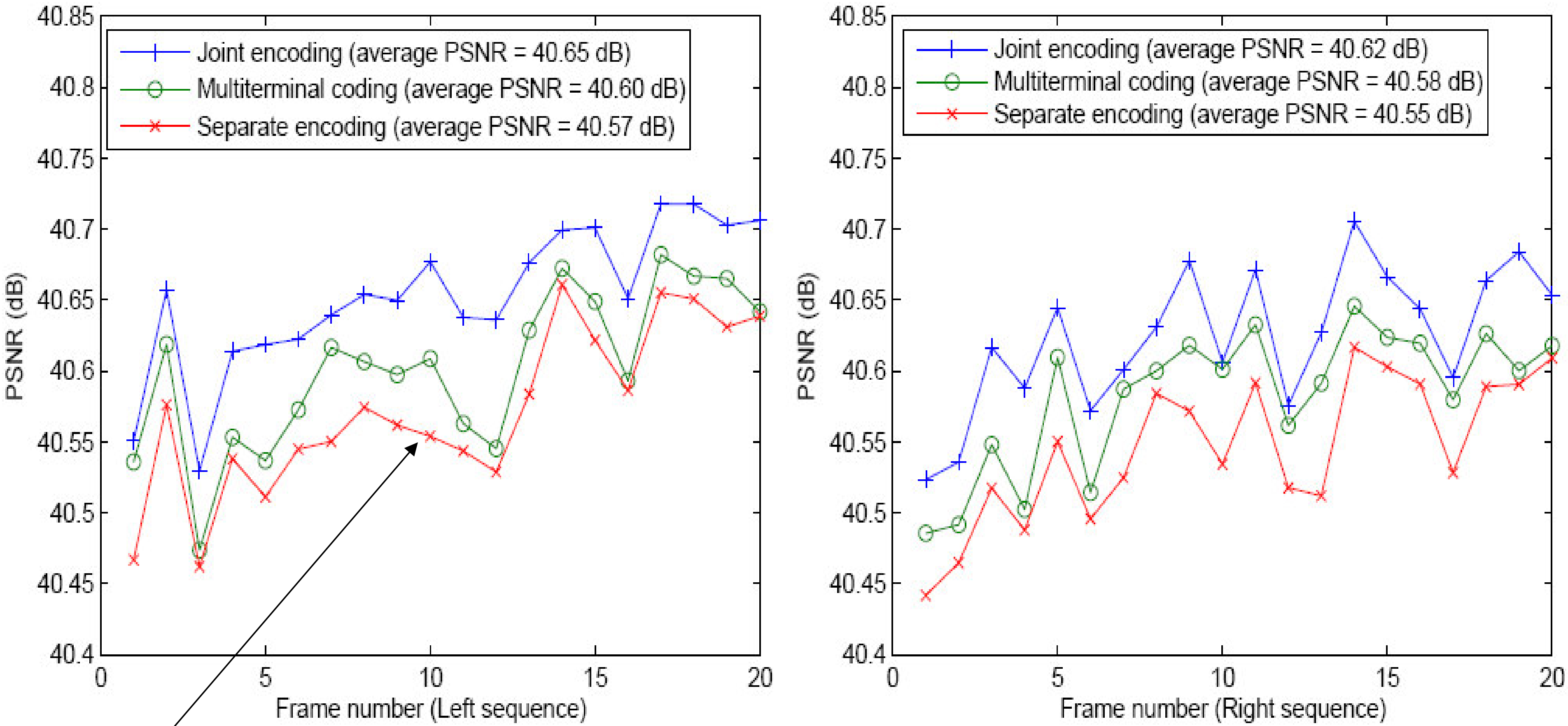
Stereo Video Coding

- The same view encoded independently with two cameras
- High correlation among the views can be exploited with MT source coding



Stereo Video Coding

(Yang, Stankovic, Xiong, Zhao, IEEE TIP'09)



H.264/AVC

Tunnel Stereo Video Sequence

Distributed/Stereo Video Applications

- A new attractive video compression paradigm
  - Video surveillance
  - Low complexity networks
  - Visual sensor networks
  - Multiview/3D video coding

Correlation Tracking

- Correlation between real-world images/source hugely varies in time
- Compression codec requires a good correlation estimation all the time
- Essential to learn correlation and adapt on-the-fly the decoding process
- Idea: particle-based Belief Propagation (BP) for joint tracking and decoding

Simulation Example

Without correlation tracking

With correlation tracking

Other Applications

- Hyperspectral image compression *(Cheung et al. 2006, Abrardo et al. 2010)*
- Wireless hearing aids *(Roy & Vetterli 2009)*
- Biometrics *(Mitsubishi Labs, Draper et al.)*
- Image encryption *(Berkeley group)*
- Cognitive radio spectrum sensing *(Cheng & Stankovics 2009)*

Conclusion

- Over the years DSC research has mainly shifted from IT to signal/image processing and communications
- It has given invaluable insights to coding theory as well as image/video compression

Conclusion: Applications

- Unfortunately, DSC has not yet found a commercial application
- DVC lags behind H.264/AVC performance-wise
- Large code-length and probabilistic nature of DSC are obstacles to WSN applications

Conclusion: Applications

- Rather than a driving technology DSC could become a supporting mechanism
  - to increase image resolution
  - encode colour
  - provide scalable protection
  - encode headers
  - increase security

Final Remark

- Many open problems in theory and practice
- Novel ideas are essential to break the wall

It is not just that DSC is so elegant that we can't let it go…