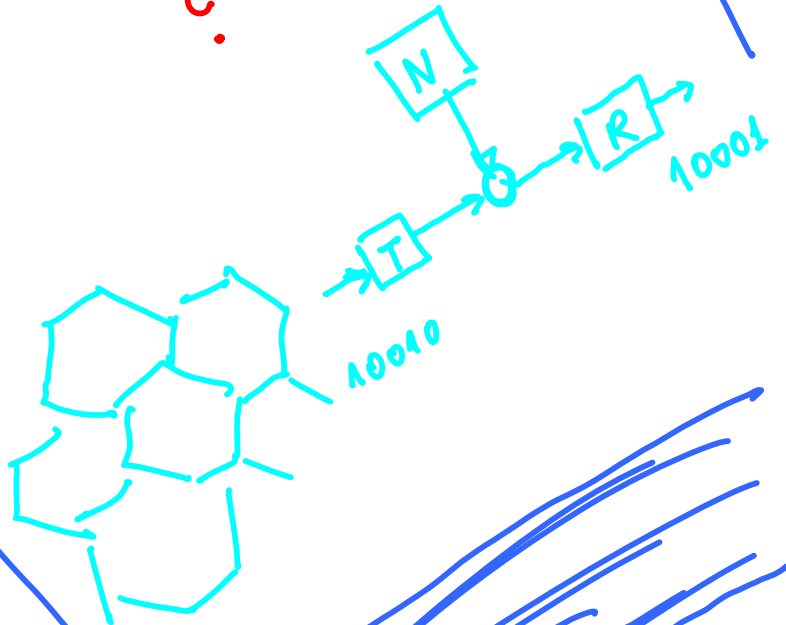


Why to Write a Book  
(about lattice codes)?

?

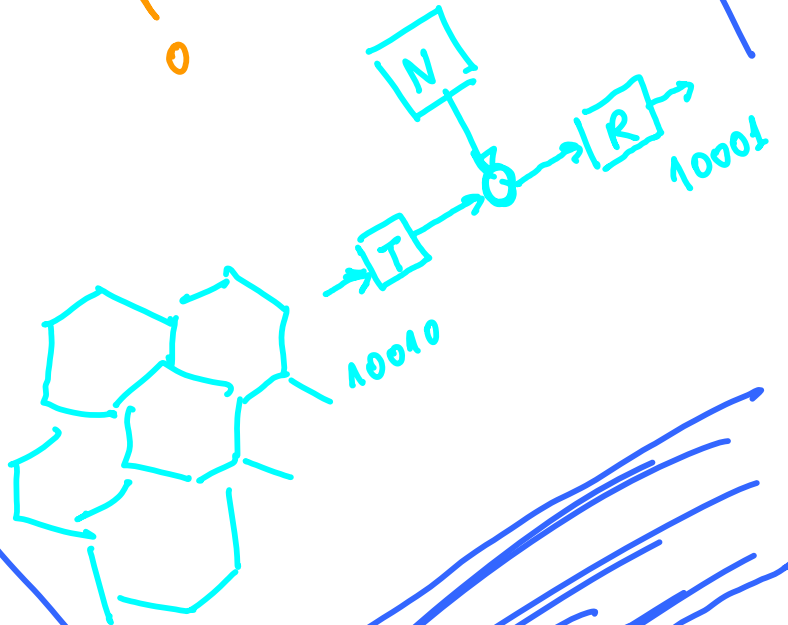
Ram Zamir



NOT  
Why to Write a Book  
(about lattice codes)

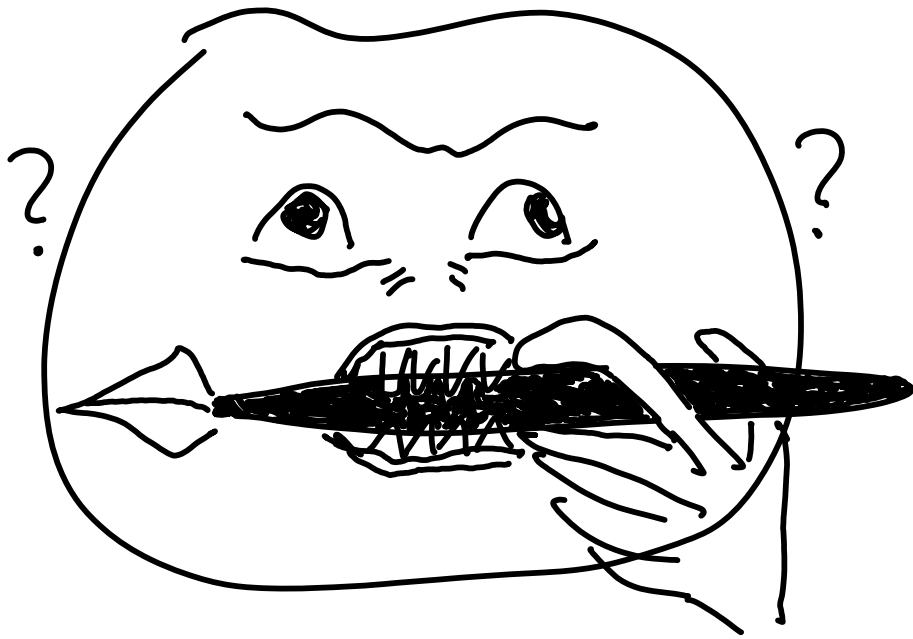


Ram Zamir



# Writer's Misery

"ק'נאט סלפניק זרבה זכמה" [תלמוד, קהא קריטא]  
(= Jealousy among writers increases wisdom)



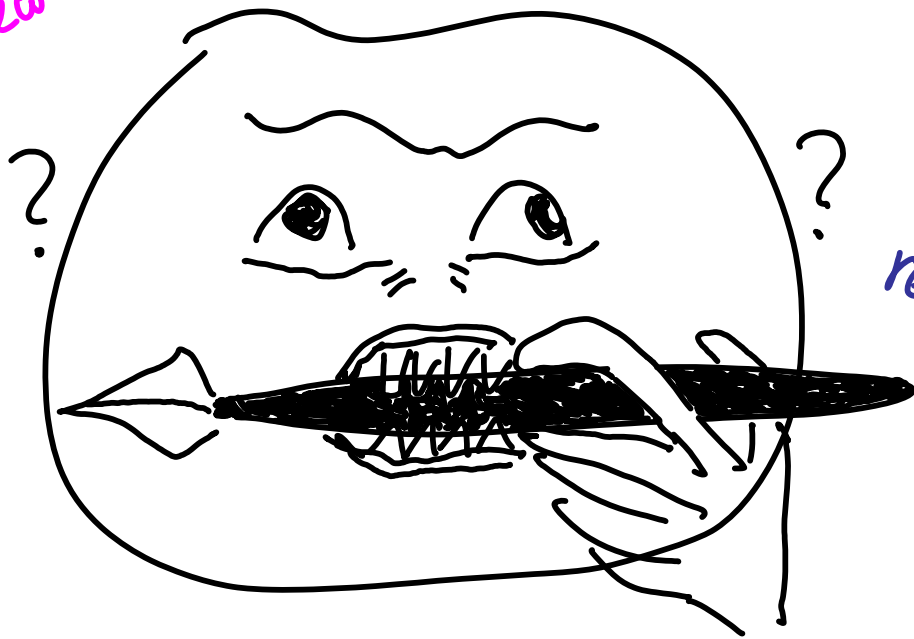
# Writer's Misery

Where to start?

Alone or with...?

Old or new material?

Question of style:  
Formal or  
friendly?



Textbook  
or  
research  
monograph?

Whose notation to use?

How many figures?

What do I (really) want to say?

Where / When  
to finish? ...

Competition...?

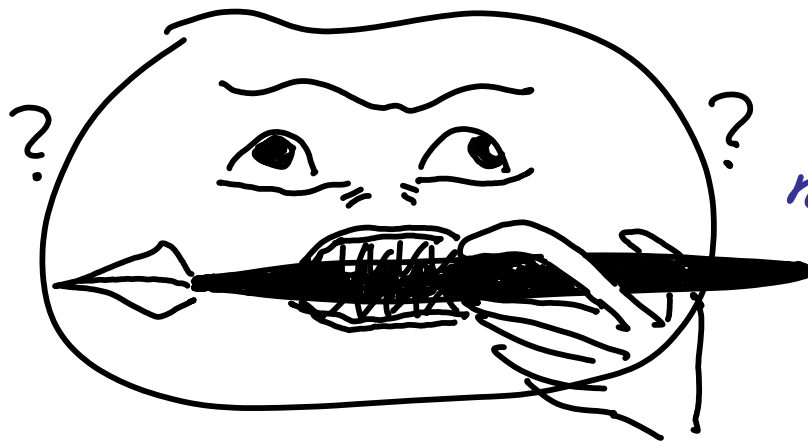
# Writer's Misery

Where to start?

Alone or with...?

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Formal or friendly?



Textbook or research monograph?

Whose notation to use?

How many figures?

What do I want to say?

Where / When to finish?...

Competition...?

Why did I start all this??...

# Complexity Theory & Statistics

\* writing complexity =  $1+2+\dots+n = \underline{O(n^2)}$   
where  $n = 422$  pages ...

\* 4 + 1 years (writing: March 2009 ÷ Oct. 2013)  
editing + printing: one more year)

\* 16 drafts (4 years, 1 every 3 months)

\* 5 deadline extensions with publisher

\* 13 chapters + 1 Appendix,

(originally 10 + 4 chapter splits - 1 cancelled)

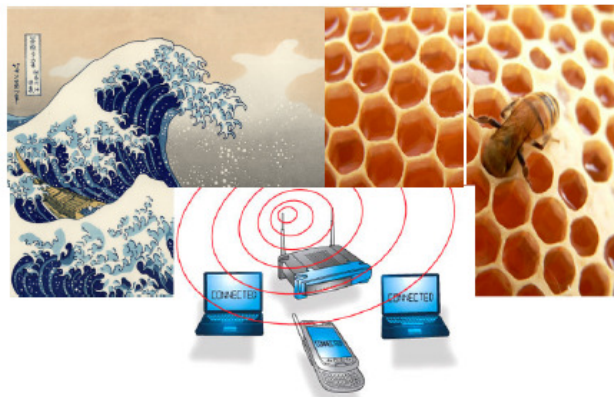
134 figures, — examples

— definitions, — theorems

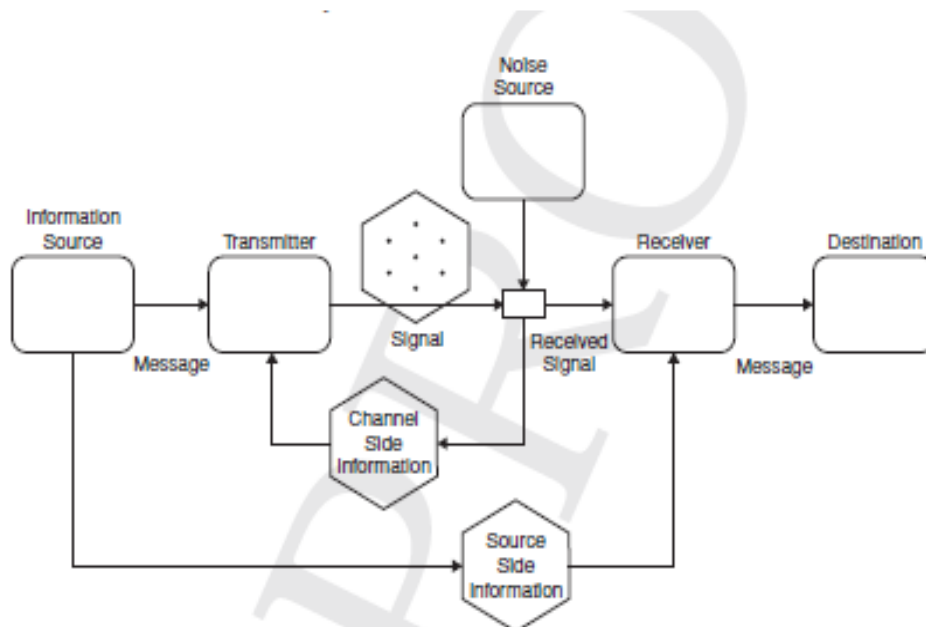
— references, — index terms

# Cover page designs ...

## Lattice Coding for Signals and Networks



Raw Zamir



Many Cons, what about Pros?

⬡ Beauty of lattices

⬡ History

⬡ Circumstances

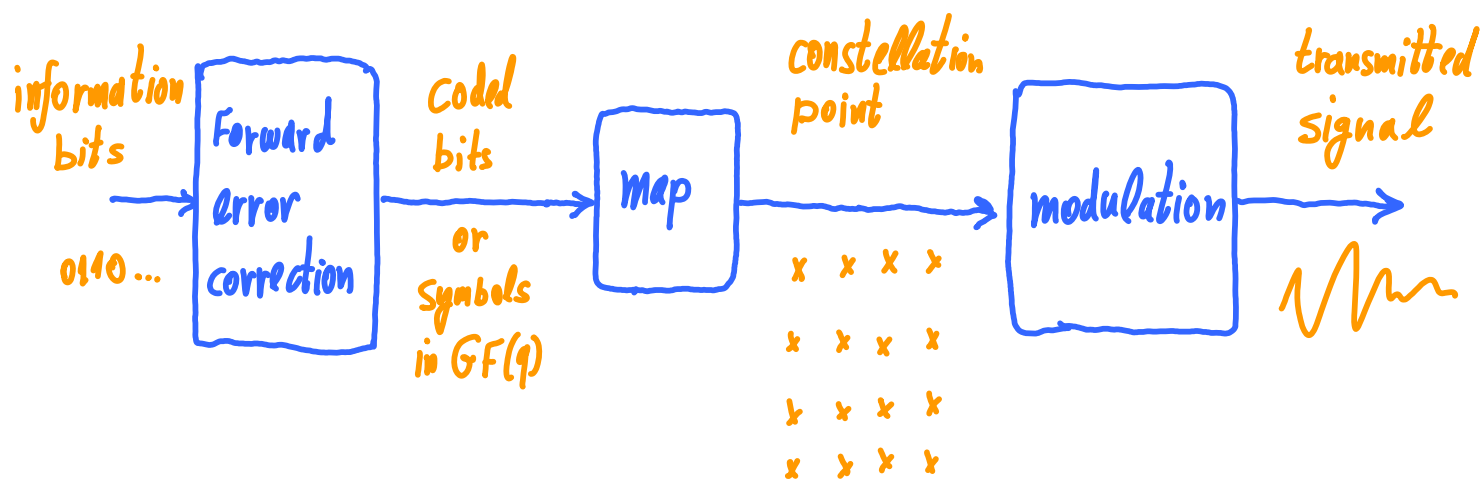
⬡ Teaching (basis for a course)

⬡ Anecdotes, Future ...



# Lattice Codes as an "Alternative Language" for Digital Communication

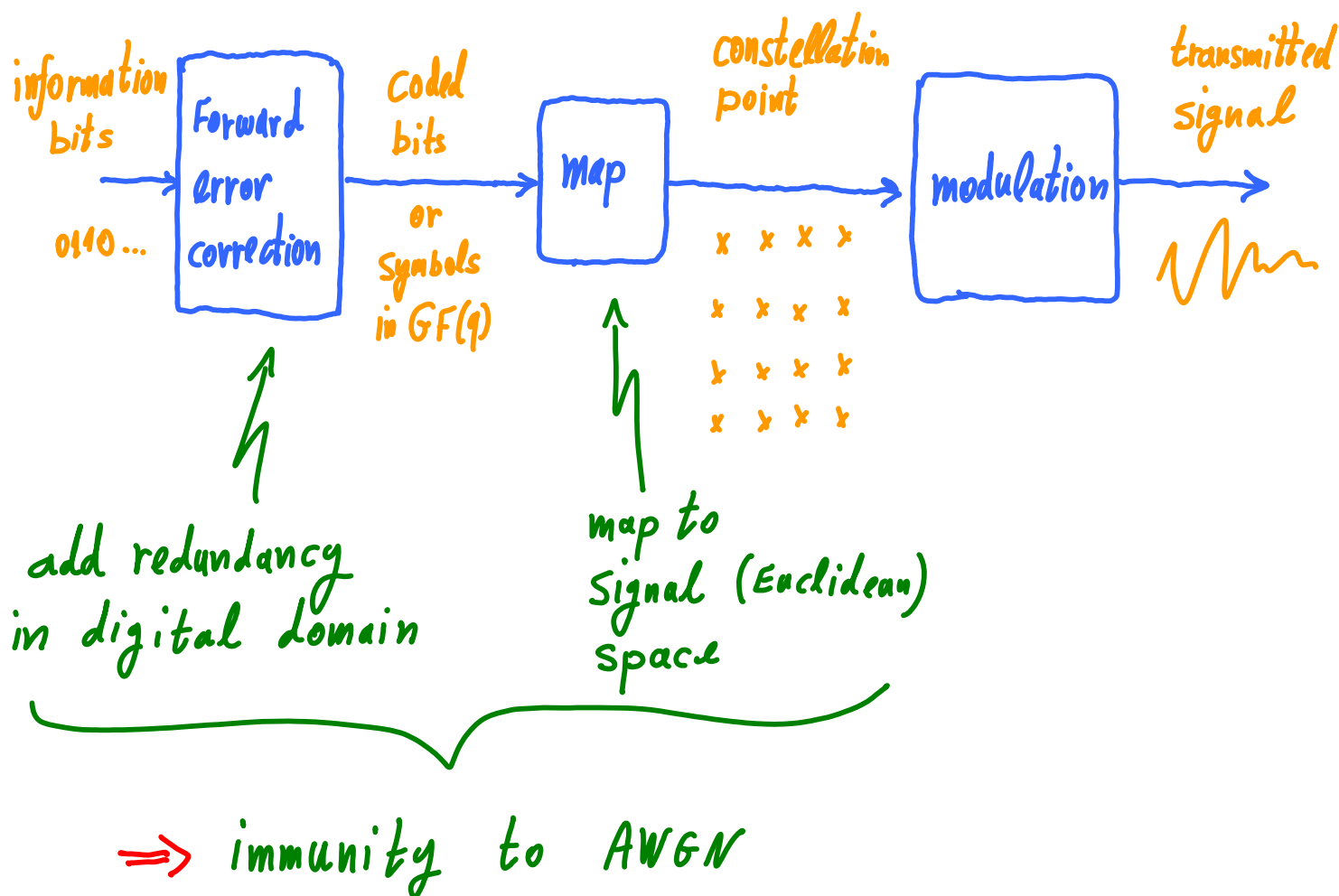
1. Error correction in signal space (AWGN channel):



Block diagram of a digital modulator

# Lattice Codes as an "Alternative Language" for Digital Communication

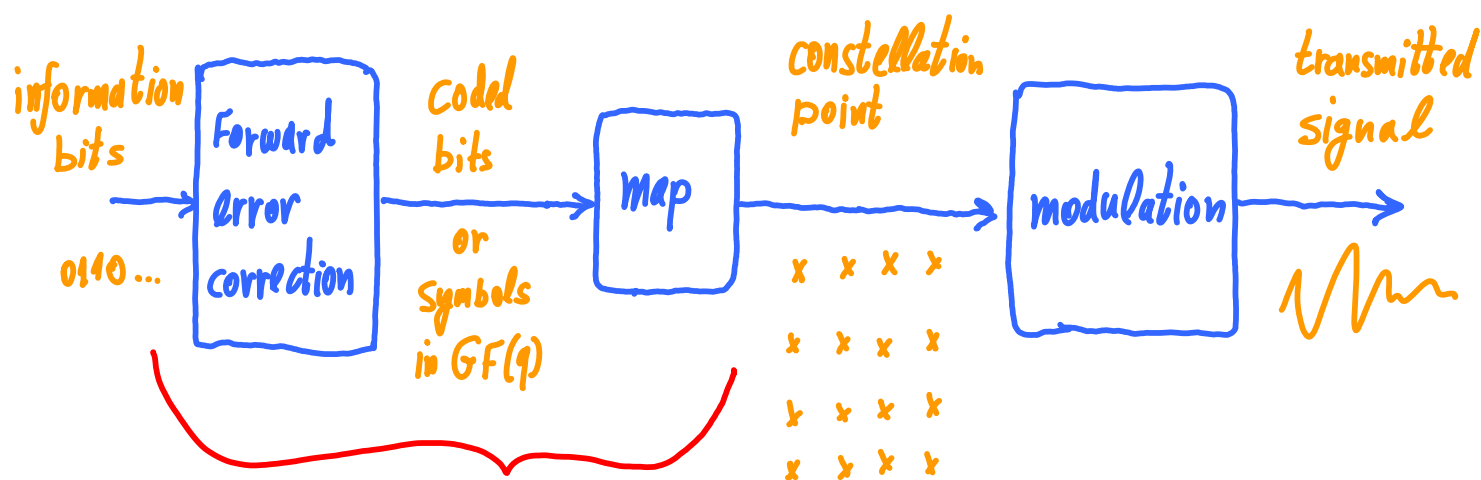
1. Error correction in signal space (AWGN channel):



Block diagram of a digital modulator

# Lattice Codes as an "Alternative Language" for Digital Communication

1. Error correction in signal space (AWGN channel):



Replace by a lattice code:  
info bits  $\rightarrow \Lambda$

Block diagram of a digital modulator

# What is a lattice?



\* picture editing  
by Kesseem Zamir

## n-dimensional lattice: Definition

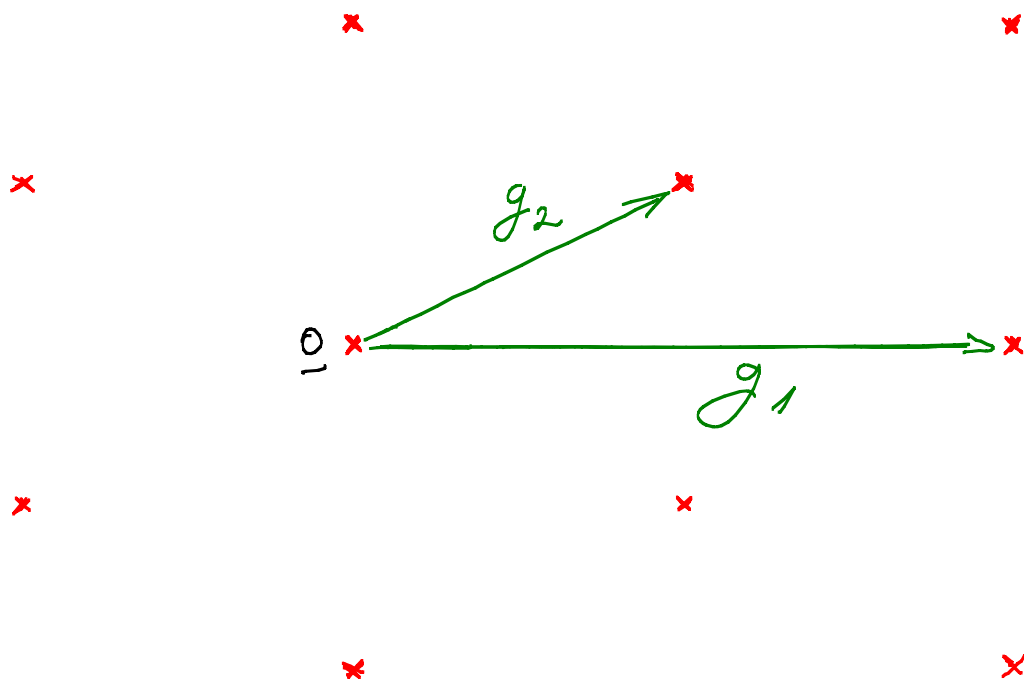
Let  $\underline{g}_1, \dots, \underline{g}_n$  - linearly independent vectors in  $\mathbb{R}^n$

$$\underline{G} = \left( \begin{array}{c|c|c} \underline{g}_1 & \dots & \underline{g}_n \end{array} \right) = \text{generator matrix}$$

$$\Lambda(G) = \{ i_1 \underline{g}_1 + \dots + i_n \underline{g}_n : i_1, \dots, i_n \in \mathbb{Z} \}$$

$$= \{ \underline{G} \cdot \underline{i} : \underline{i} \in \mathbb{Z}^n \}$$

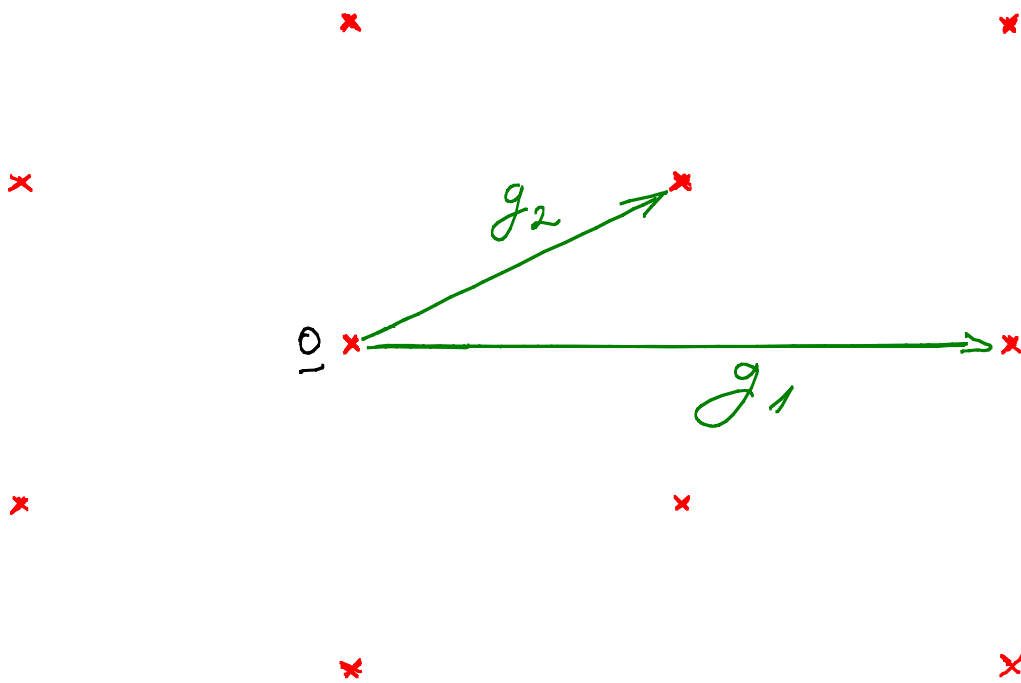
$$= \underline{G} \cdot \mathbb{Z}^n$$



# n-dimensional lattice: Definition

Let  $\underline{g}_1, \dots, \underline{g}_n$  - linearly independent vectors in  $\mathbb{R}^n$

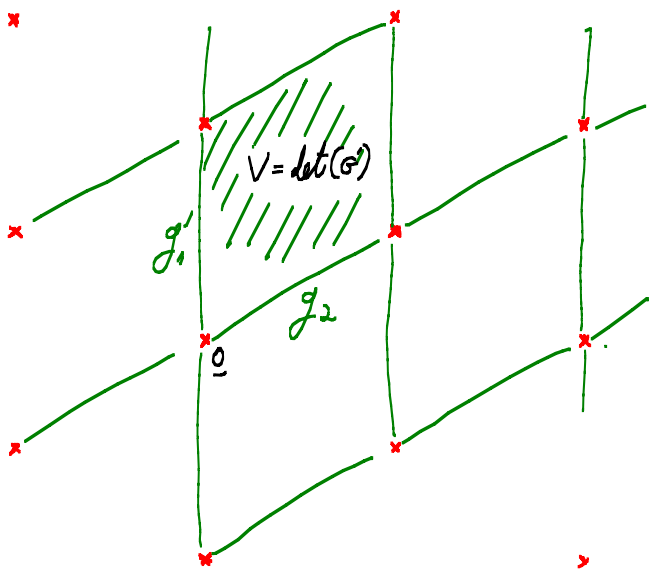
$$\underline{G} = \left( \begin{array}{c|c|c} \underline{g}_1 & \dots & \underline{g}_n \end{array} \right) = \text{generator matrix}$$



Linearity:

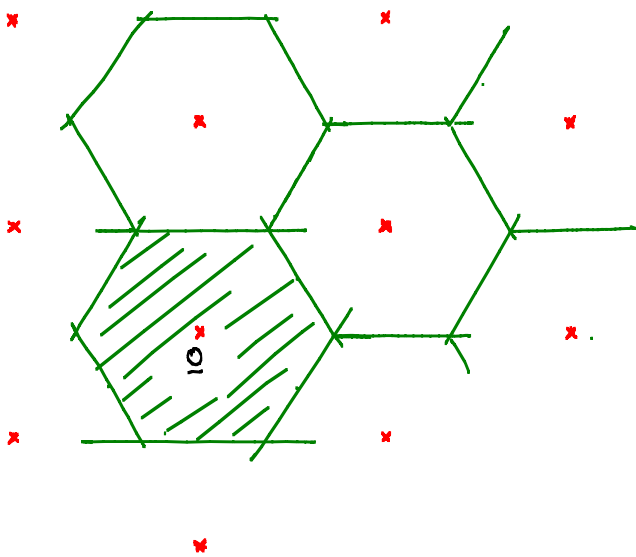
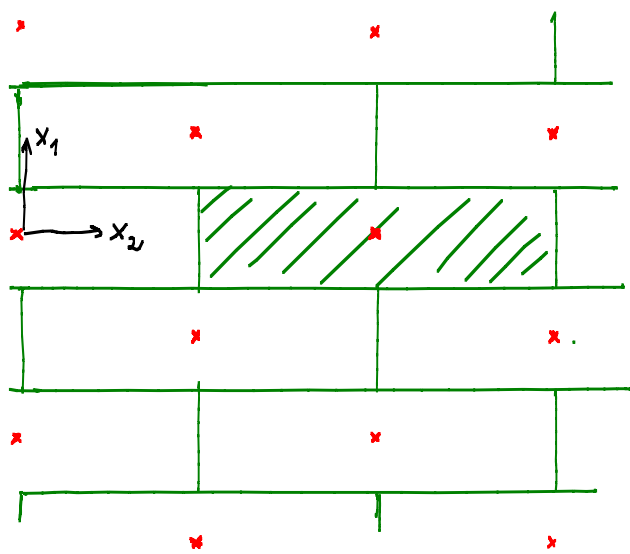
$$\lambda_1, \lambda_2 \in \mathcal{L} \Rightarrow \lambda_1 \pm \lambda_2 \in \mathcal{L}$$

# Partitions, Fundamental Cells



Other Basis  $\Rightarrow$   
 other parallelepiped  
 $\Rightarrow$  Cell Volume  $V$  is  
 invariant of partition

Sequential  
 Quantization



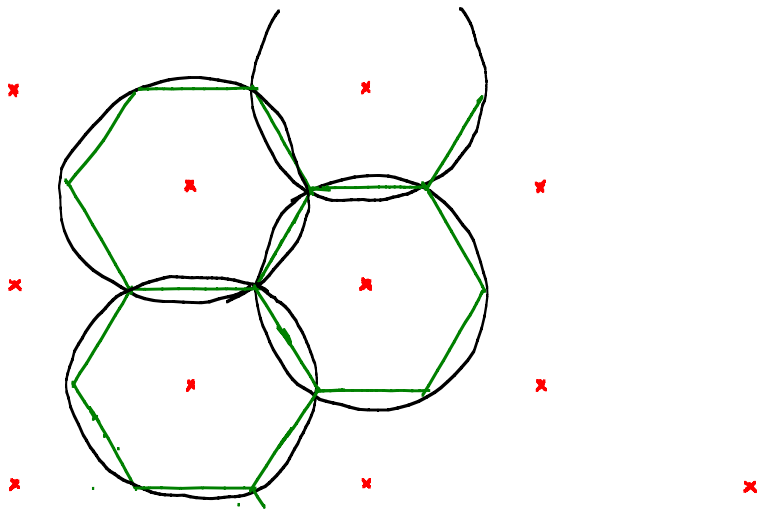
Voronoi Partition

$$P_0 = \left\{ x : \|x\| \leq \|x - l_i\| \right\}$$

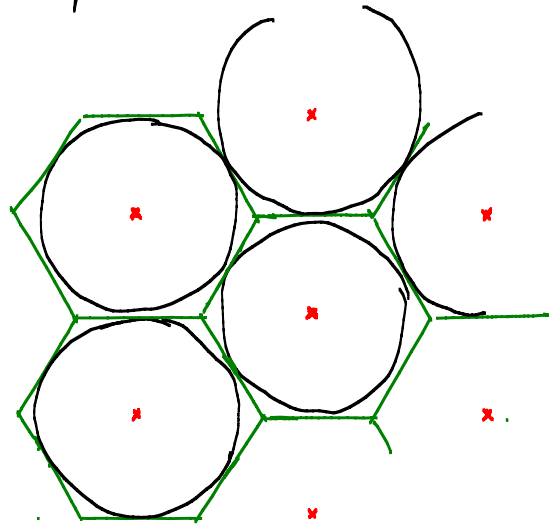
$\forall l_i \in \Lambda$

# Covering, Packing, Kissing Number & More....

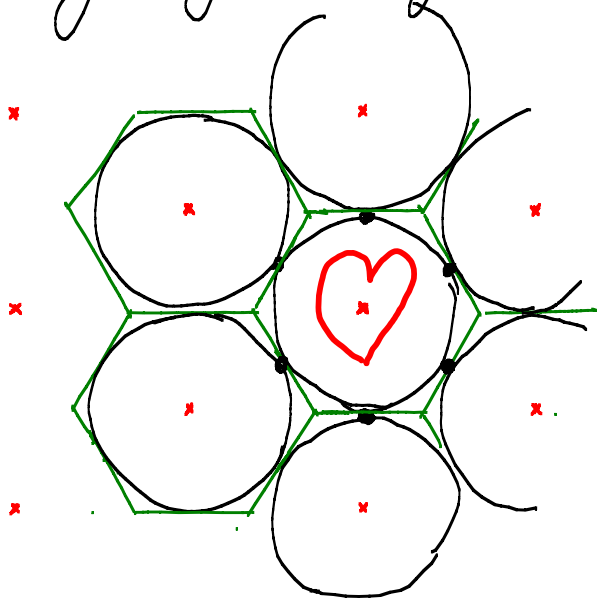
Covering  $\mathbb{R}^n$  with (few) Spheres



Packing (many) spheres in  $\mathbb{R}^n$



Kissing by (many) Spheres

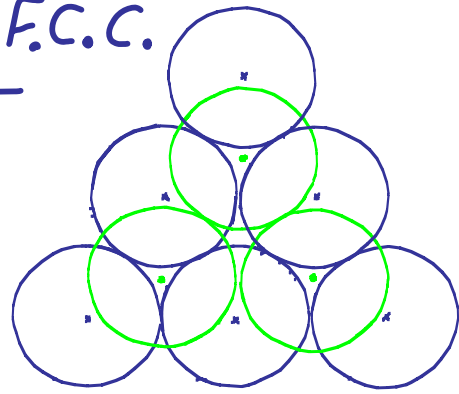


& good arrangements for quantization and AWGN channel coding



# Not an "All-Purpose" Lattice!

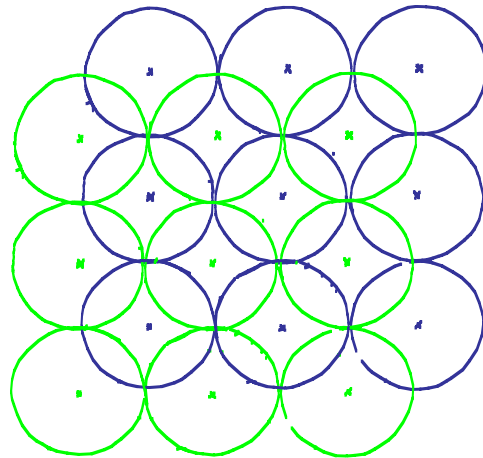
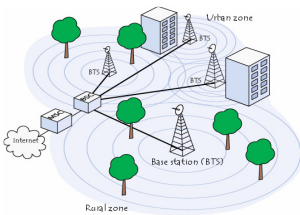
⇒ Best 3-dim Packing: F.C.C.



each layer = hexagonal  $\wedge$   
layers are staggered

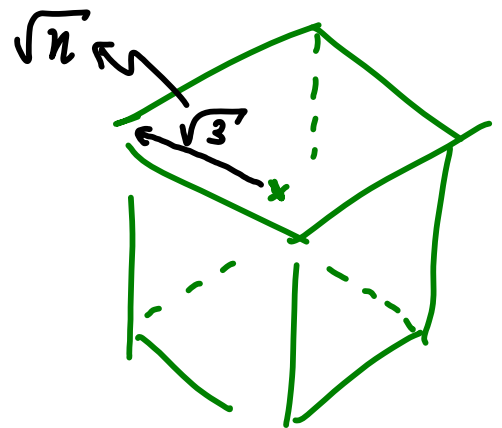
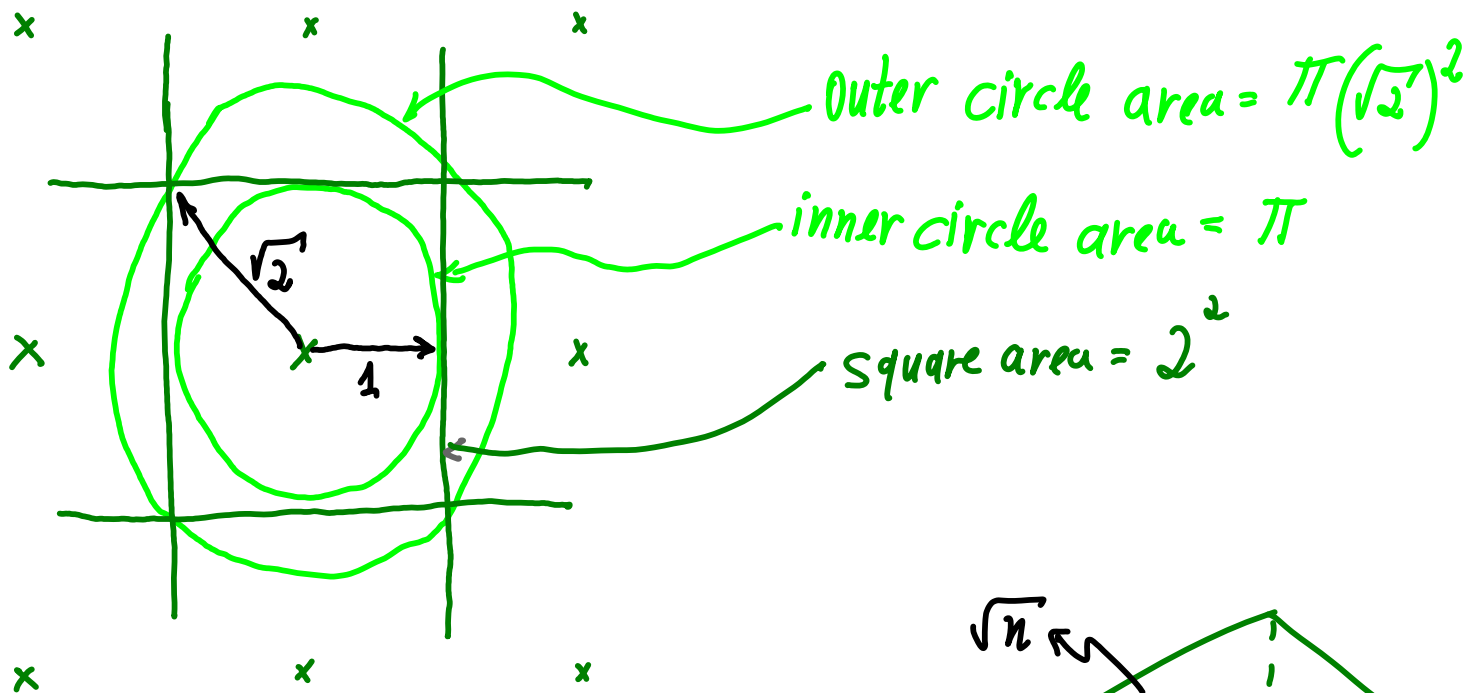
⇒ Best 3-dim Covering: B.C.C.

each layer = cubic  $\wedge$   
layers are staggered

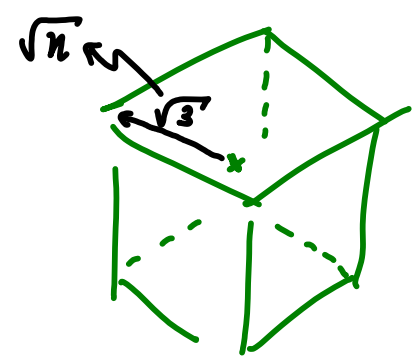
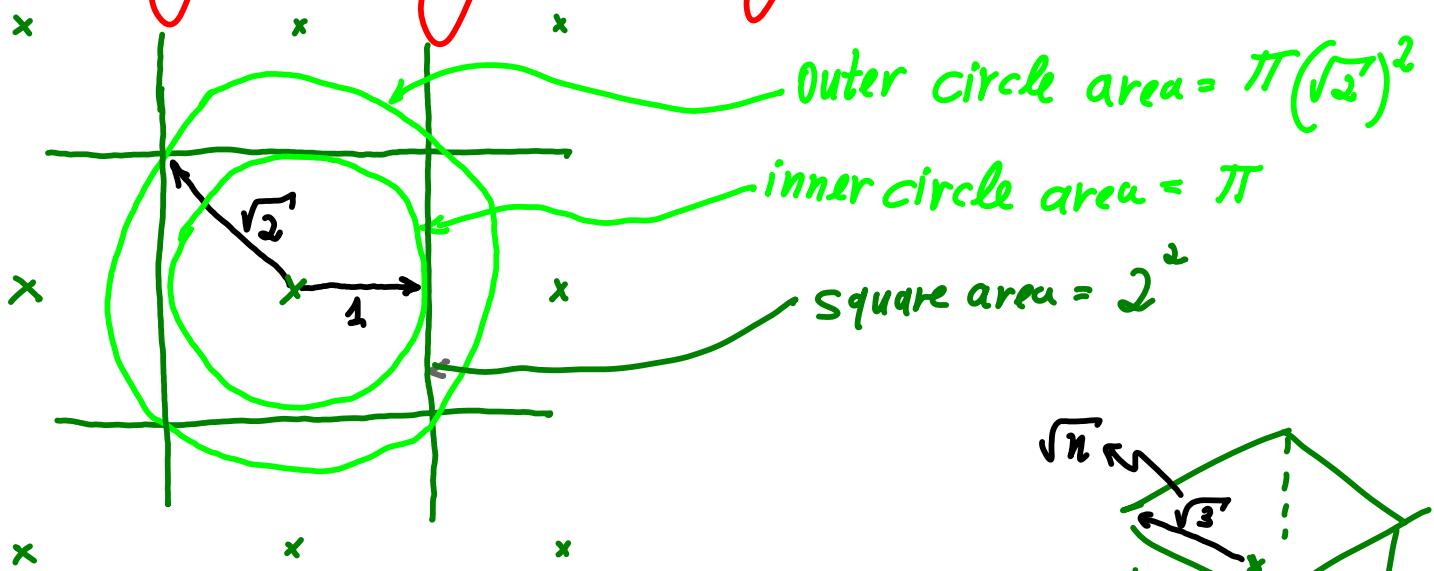


As  $n \rightarrow \infty$ , most lattices are "good" for almost everything!

# Packing & Covering efficiency of the cubic lattice



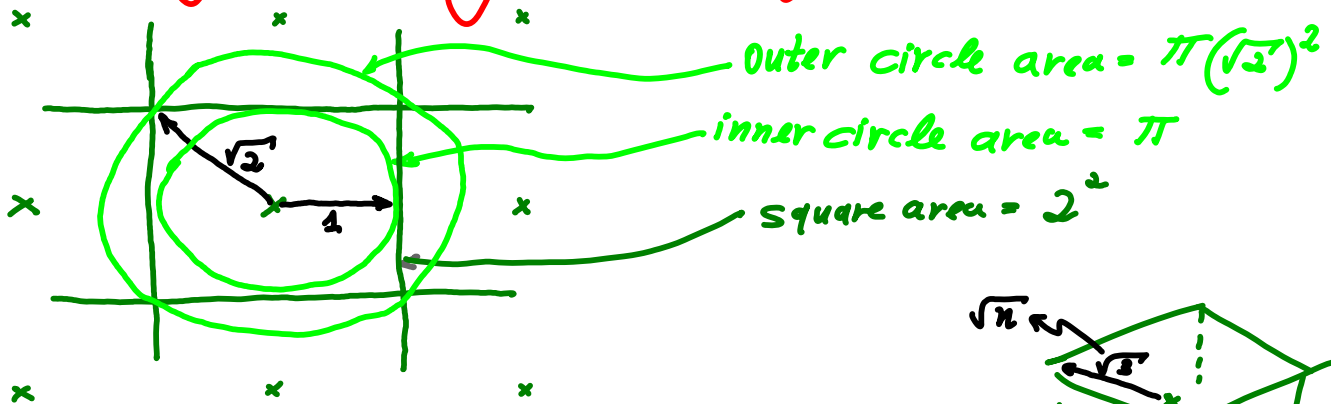
# Packing & Covering efficiency of the cubic lattice



## Behavior @ general dimension $n$ :

- \*  $n = 1, 2, 3, \dots, n$
- \* cubic cell volume =  $2, 2^2, 2^3, \dots, 2^n$  ↗
- \* inner ball " =  $2, \pi, \frac{4\pi}{3}, \dots, V_n$  ↘
- \* outer ball " =  $2, \pi(\sqrt{2})^2, \frac{4\pi}{3}(\sqrt{3})^3, \dots, V_n \cdot (\sqrt{n})^n$  ↗
- \* where  $V_n \triangleq$  volume of unit radius  $n$ -dim ball  $\sim \left(\frac{2\pi e}{n}\right)^{n/2}$

# Packing & Covering efficiency of the cubic lattice



Behavior @ general dimension  $n$ :

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- \* where  $V_n \triangleq$  volume of unit radius  $n$ -dim ball  $\sim \left(\frac{\sqrt{2\pi e}}{n}\right)^n$

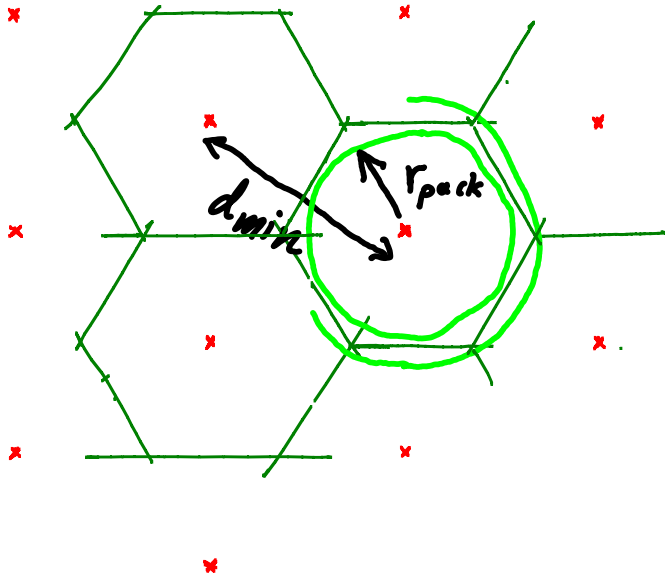


Packing efficiency  $\triangleq \sqrt[n]{\frac{\text{Packed balls volume}}{\text{space volume}}} \rightarrow 0 \Rightarrow \text{bad...}$

while

Covering efficiency  $\triangleq \sqrt[n]{\frac{\text{Covering balls volume}}{\text{space volume}}} \rightarrow \sqrt{\frac{\pi e}{2}} = 2 \Rightarrow \text{quite good!}$

The nominal coding gain of a (good) lattice



$$d_{min} = 2 \cdot r_{pack}$$

$$d_{min}(\text{hexagonal}) \approx 1.074 \times d_{min}(\text{square}) / \Rightarrow \Gamma_c^{nom} \approx 0.62 \text{ dB}$$

@ same cell volume

$$d_{min}(\text{FCC}) \approx 1.122 \times d_{min}(\text{cubic}) / \Rightarrow \Gamma_c^{nom} \approx 1 \text{ dB}$$

@ same cell volume

Why is  $\Gamma_c^{nom}$  important?

It's a dominant factor in determining error probability in the presence of Additive White Gaussian Noise

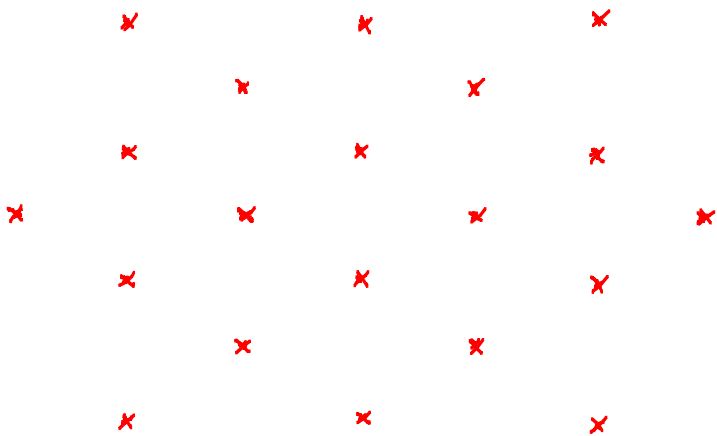


# Lattice Codes in Signal Space

square ( $\mathbb{Z}$ )-lattice  $\Rightarrow$  Uncoded constellation  
("bad lattice")



More "interesting" lattice  $\Rightarrow$  Coded constellation  
("good lattice")



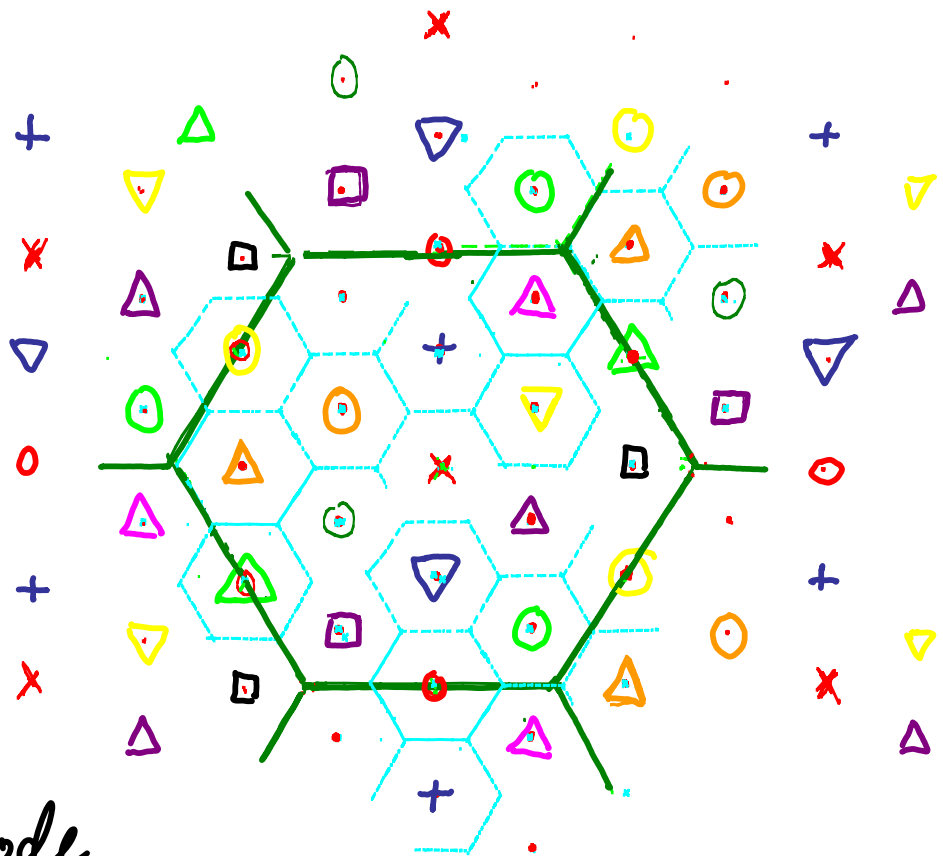
# Nested Lattices

$$\Lambda_2 \subset \Lambda_1 \Rightarrow \underline{\underline{G_2}} = \underline{\underline{G_1}} \cdot \underline{\underline{J}}$$

Relative Cosets =  $\Lambda_2 / \Lambda_1$

Coset  $\triangleq l_1 + \Lambda_2$ , for some  $l_1 \in \Lambda_1$

$$|\Lambda_2 / \Lambda_1| = V_2 / V_1 = |\det(J)|$$



$\Rightarrow$  Lattice Code

Back to ...

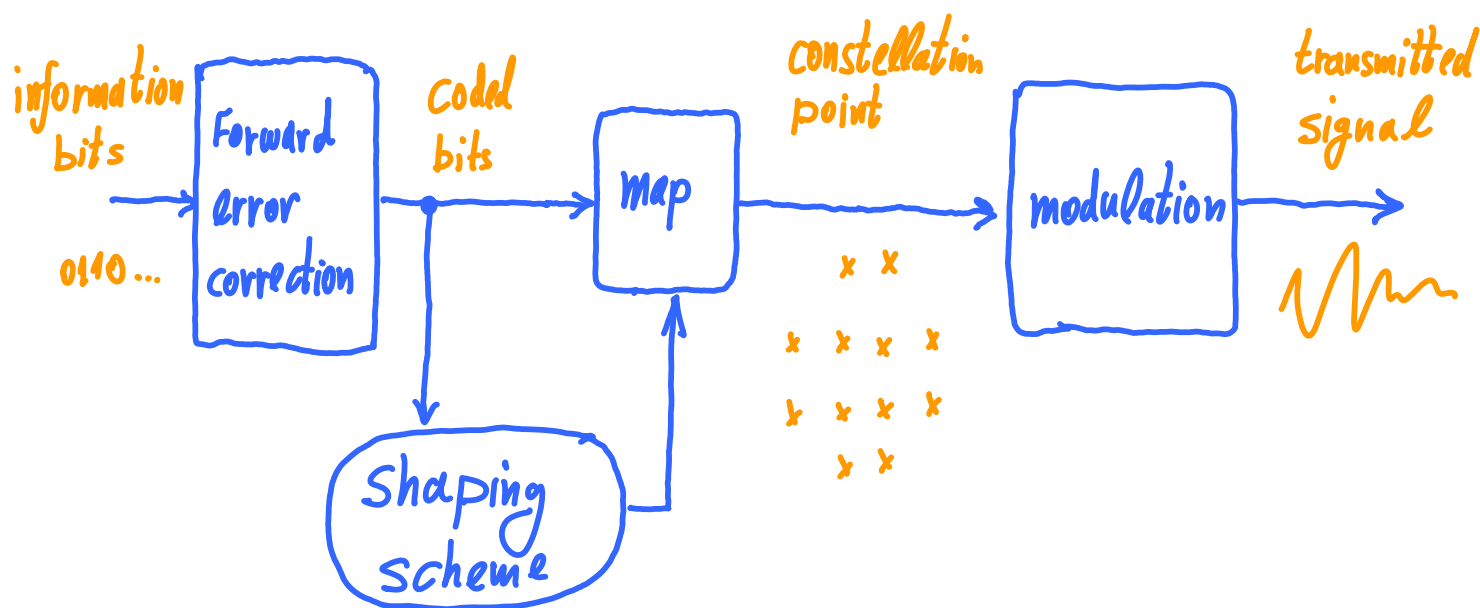
Lattice Codes as an "Alternative Language"  
for Digital Communication

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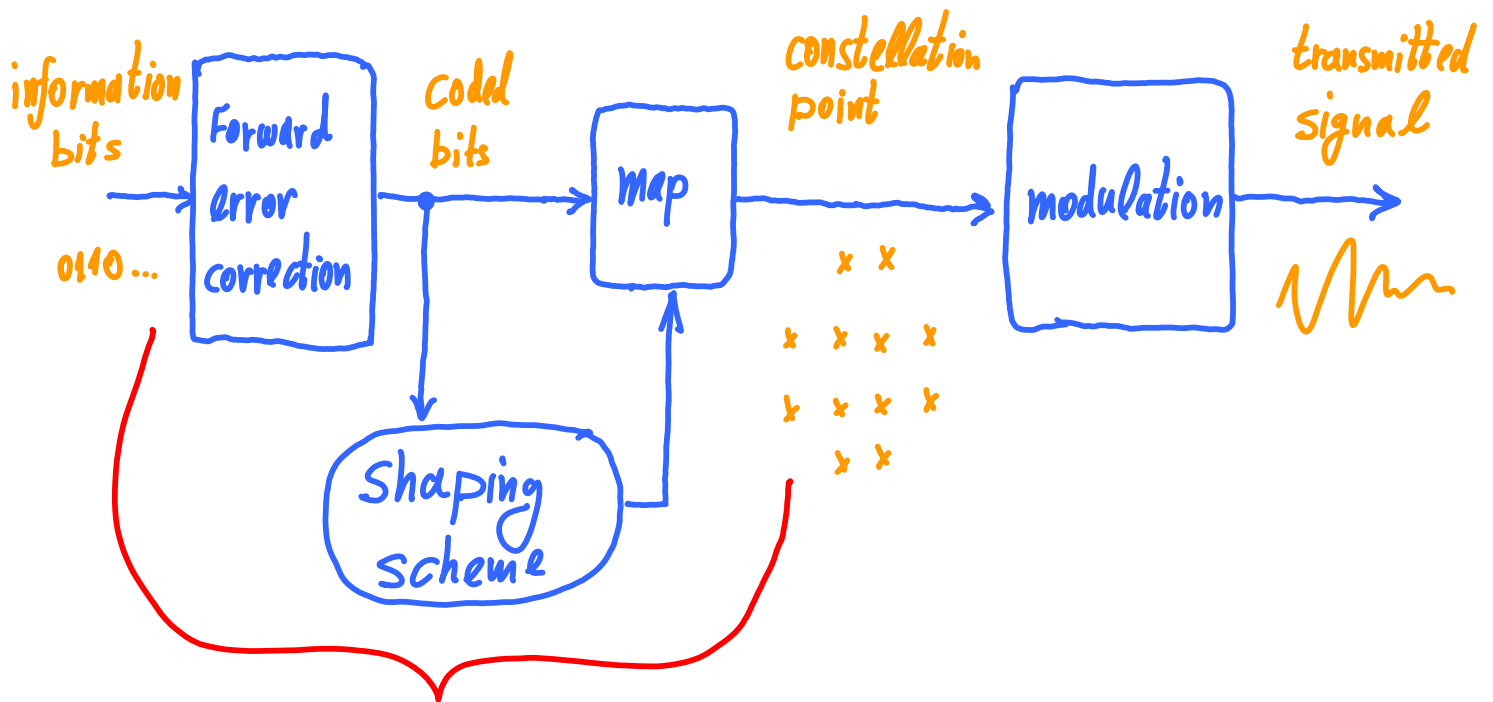
# Lattice Codes as an "Alternative Language" for Digital Communication

2. Shaping : power & peak amplitude control :



Block diagram of a digital modulator

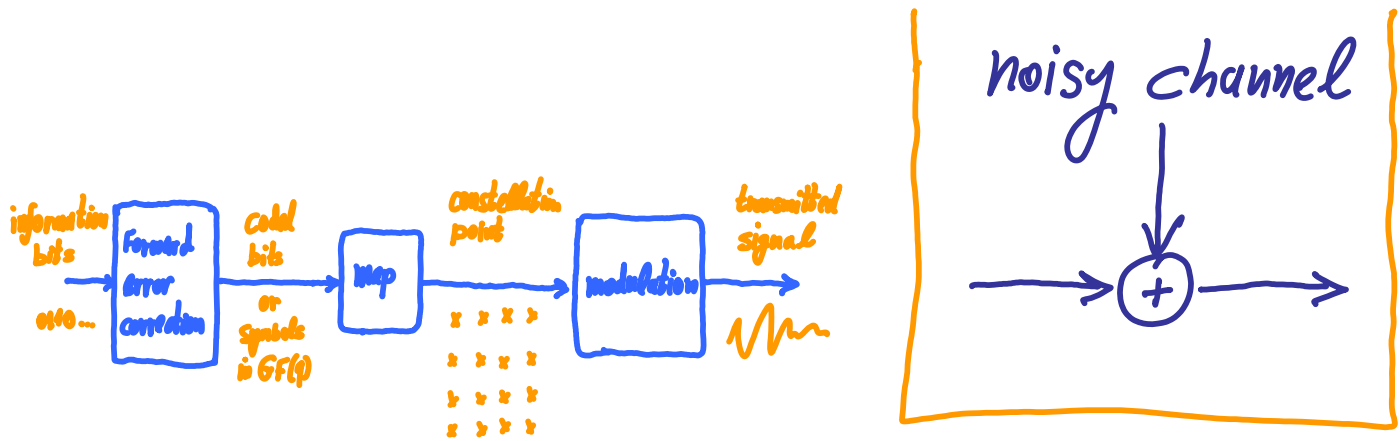
## 2. Shaping : power & peak amplitude control :



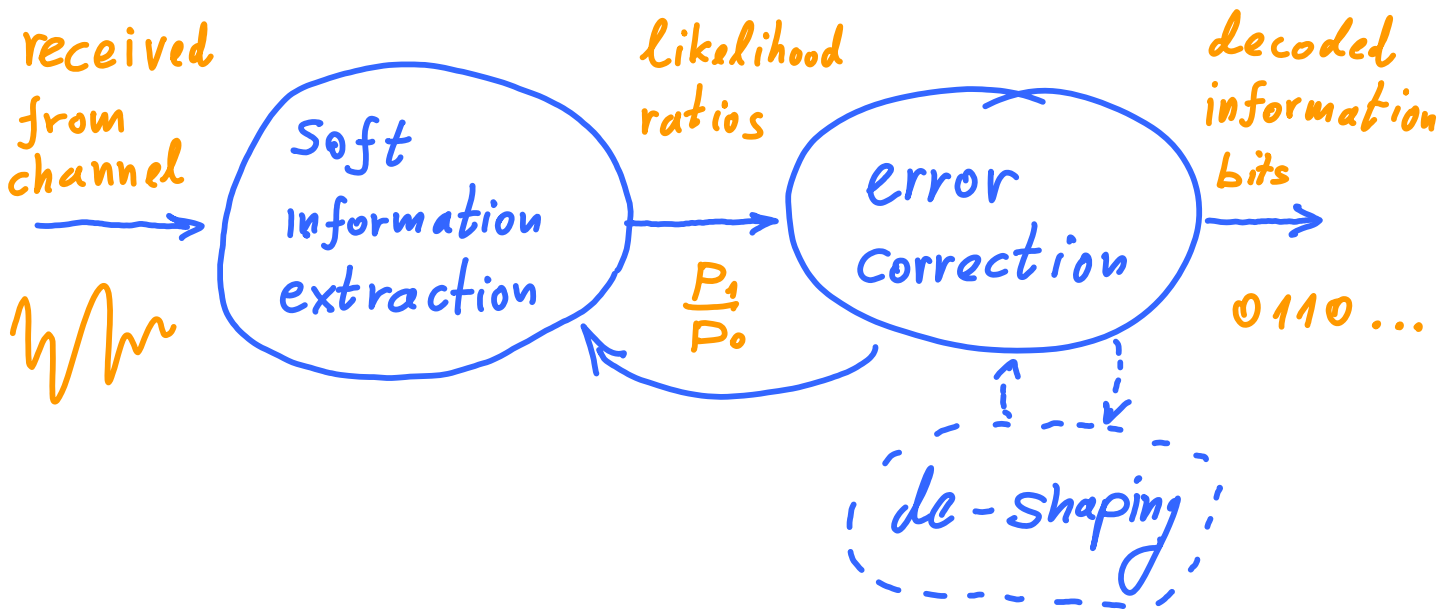
Replace by a Voronoi constellation :

info bits  $\rightarrow$   $\Lambda_{\text{coding}}$  /  $\Lambda_{\text{shaping}}$

Block diagram of a digital modulator

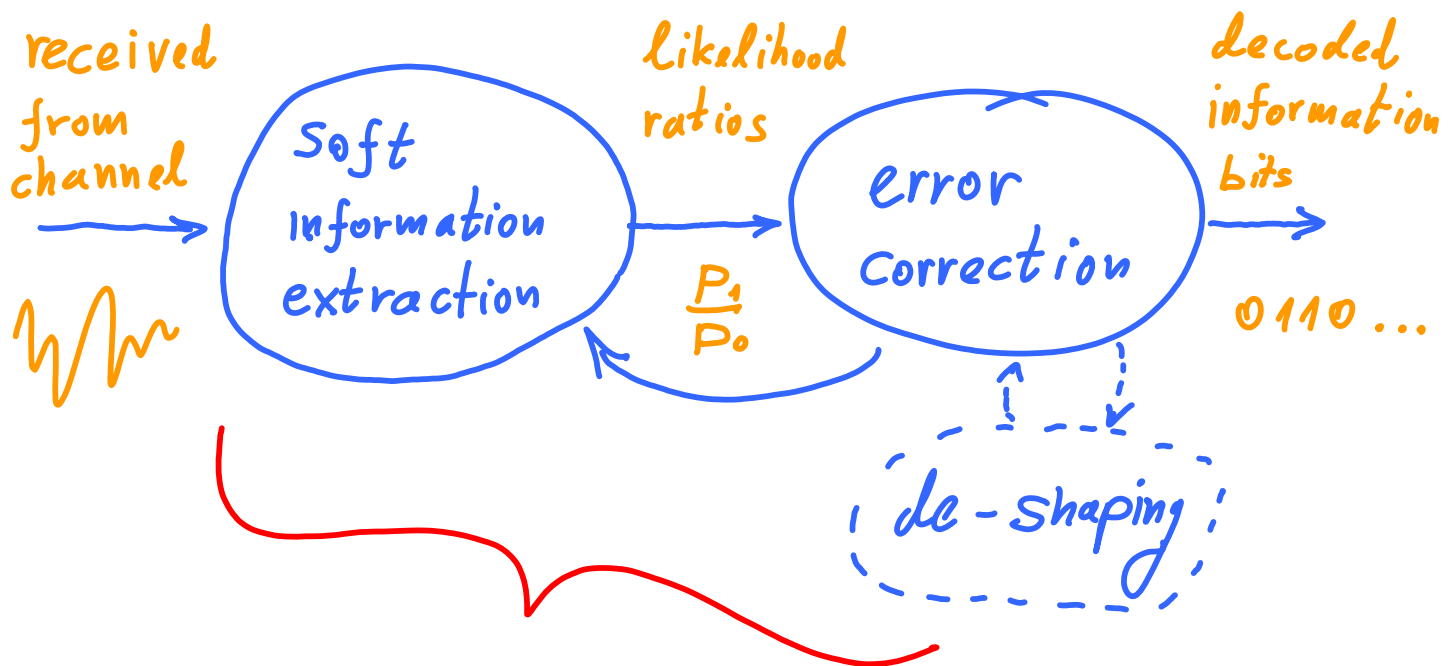


### 3. Practical receiver/decoder structure:



Block diagram of a digital **de**-modulator

### 3. practical receiver/decoder structure:

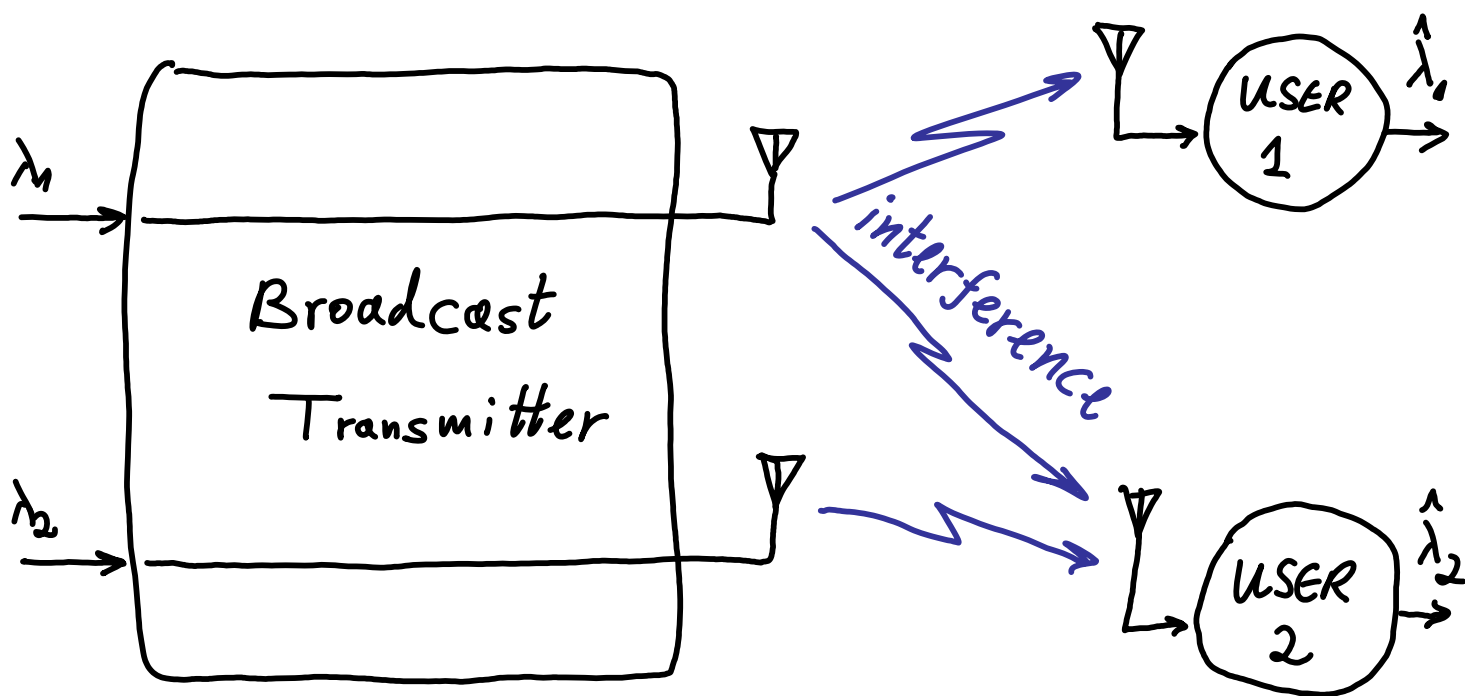
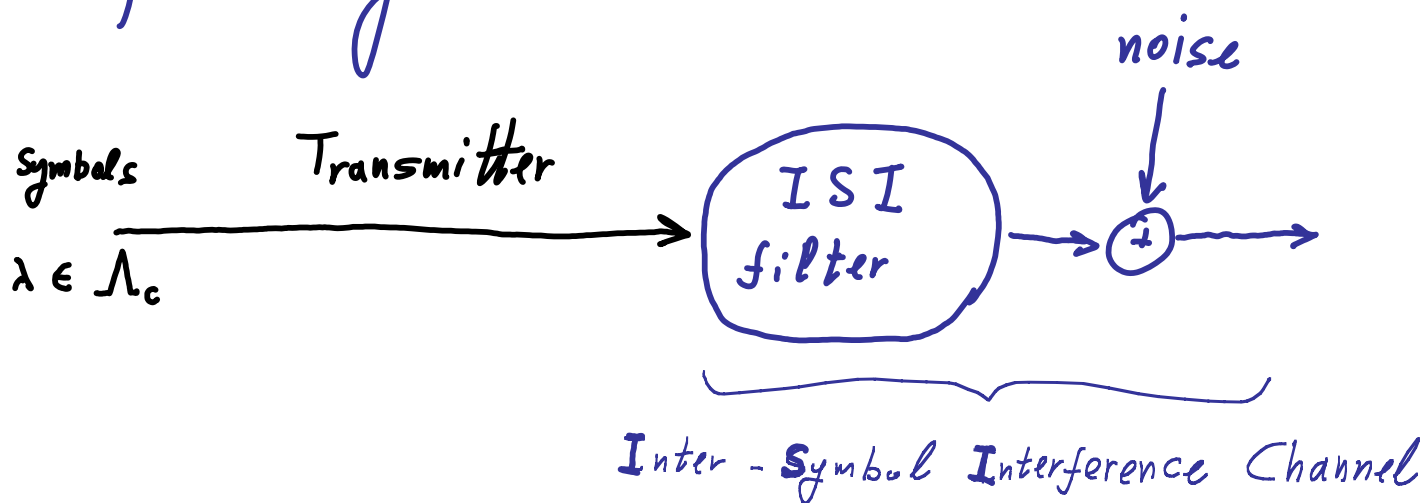


lattice decoding:

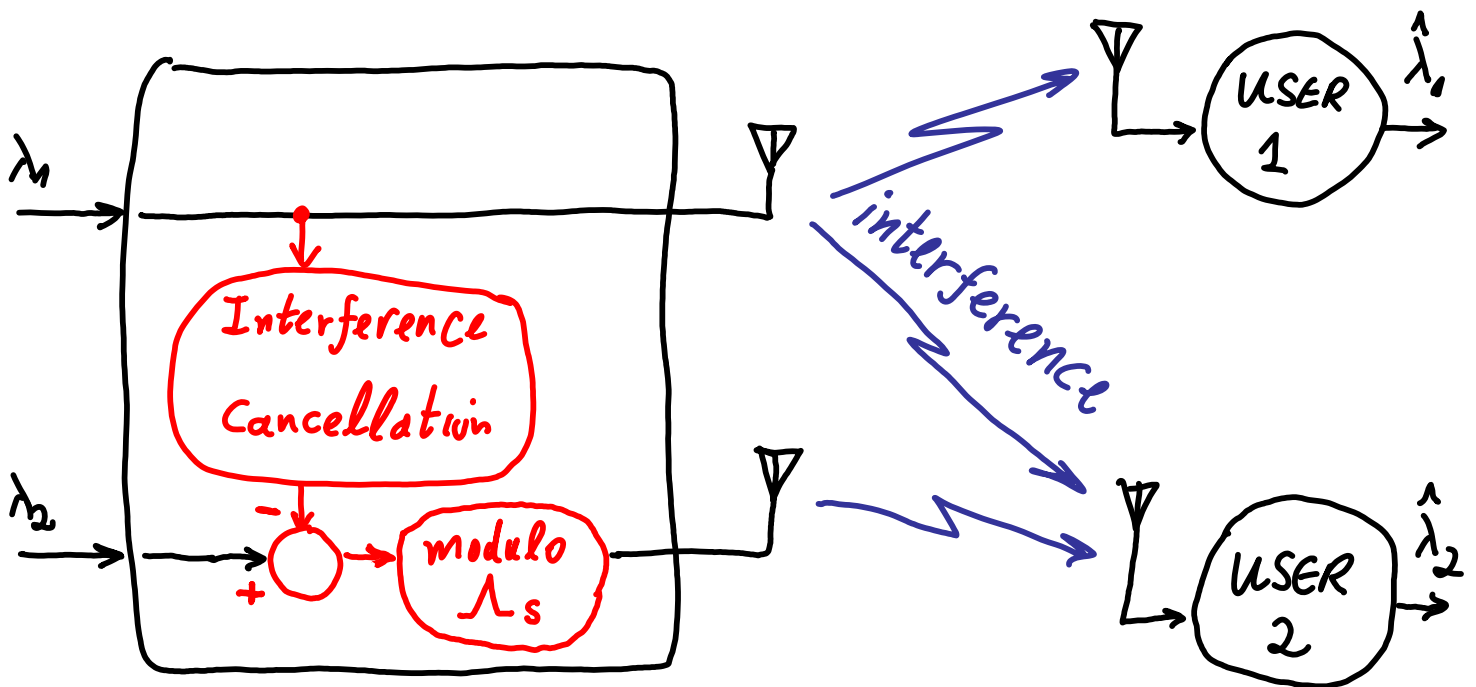
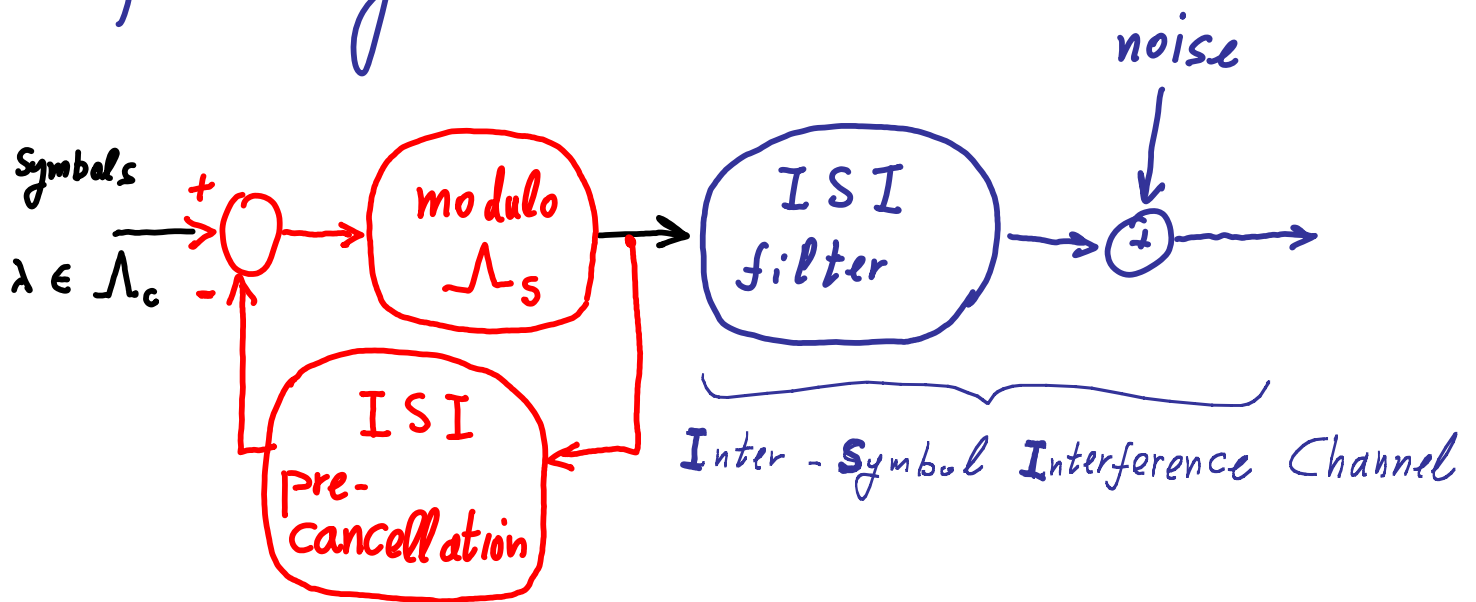
$$\Lambda_c / \Lambda_s + \text{noise} \rightarrow \Lambda_c \rightarrow \text{info bits}$$

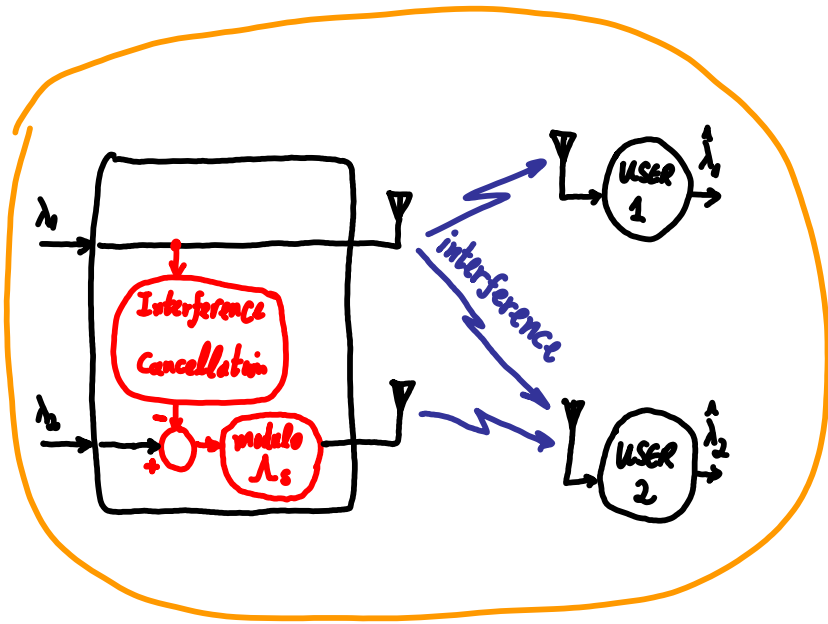
Block diagram of a digital **de**-modulator

#### 4. Precoding (equalization, Multi-User MIMO):



#### 4. Precoding (equalization, Multi-User MIMO):





MIMO Broadcast  
 by  
 Dirty-paper coding  
 [Caire - Shamai 2002]

⇒ lattice binning

⇒ alternative language for  
 multi-user information theory!

Many Cons, what about Pros?

⬡ Beauty of lattices

⬡ History

⬡ Circumstances

⬡ Teaching (basis for a course)

⬡ Anecdotes, Future ...



How did it all start?



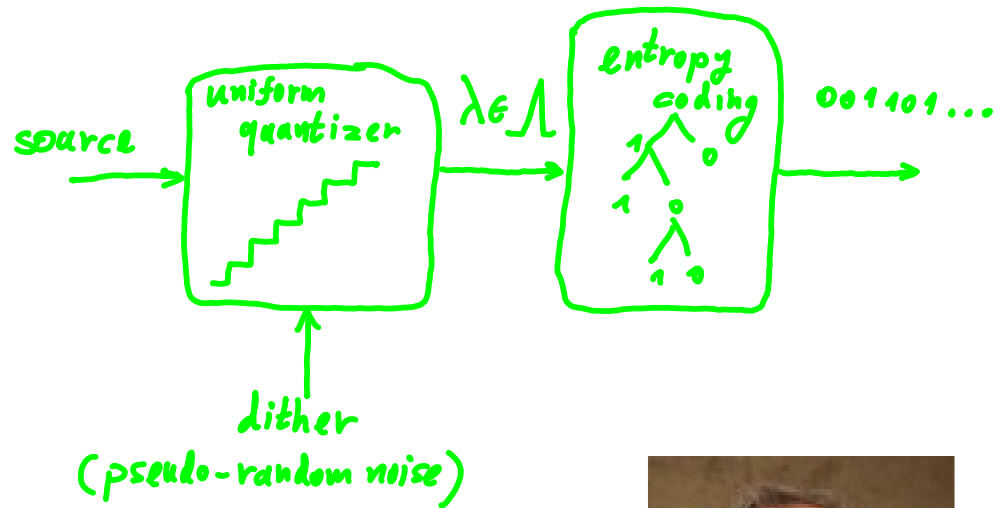
Meir Feder

data compression class 1989...



Jacob Ziv

universal (dithered) quantization [1985]



Gersho's conjecture [1979]



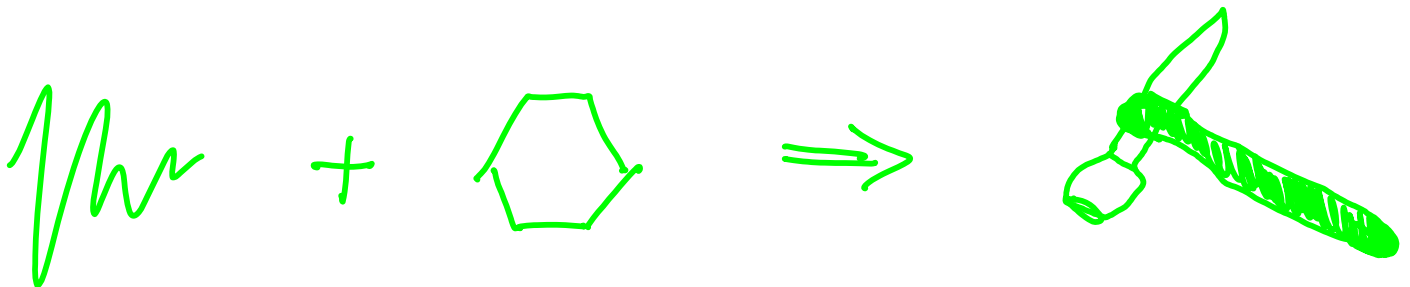
Allen Gersho

⇒  $MS_c$  [~ Jan 1991]

Moral 1:

Dither (randomization) + Lattice

⇒ a promising analytic tool!



# How did it all start?



Meir Feder



Yair Beery

~ 1991  
seminar on the...  
first book about lattice codes



John  
Conway



Neil Sloane



Gregory  
Poltyrev



Simon Litsyn

~ 1992  
challenge: dithered modulation ?!

~ 1993  
covering  $\iff$  quantization

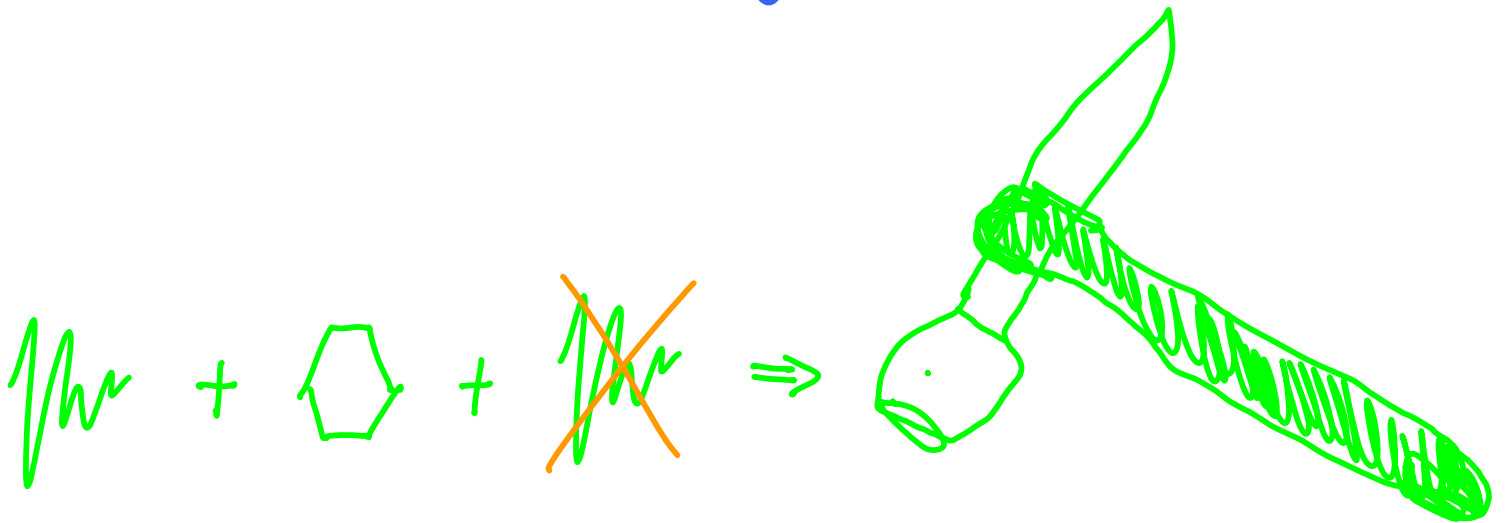
$$G(\Lambda_n) \longrightarrow \frac{1}{2\pi\epsilon}$$

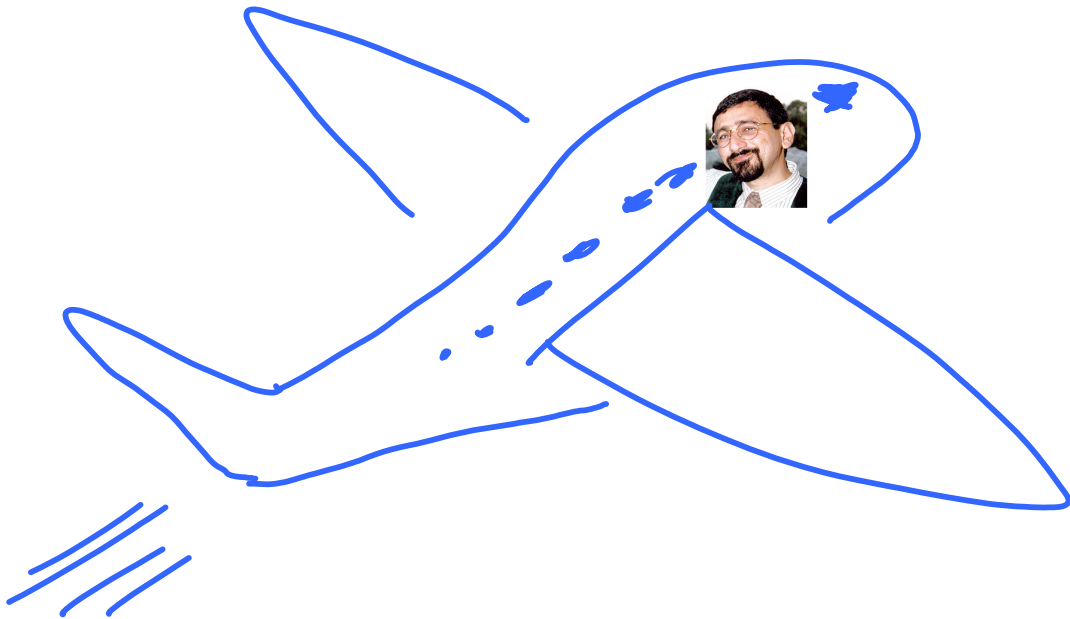
$\implies$  PHD [1993, 1994]

Moral 2:

Dither + Lattice + Wiener<sup>(MMSE)</sup> estimation

⇒ a very promising analytic tool!!!





July 1994 - going to post doc ...



Toby Berger

Mathematical Theory of Data Compression [1971]  
& Multi-terminal source coding [1978+]

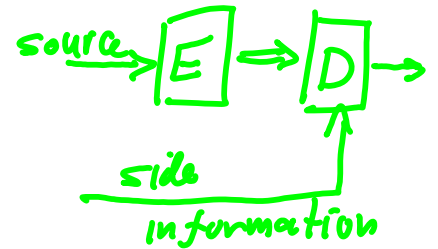
Wyner-Ziv Problem



Aaron  
Wyner



Jacob  
Ziv



nested binary/lattice

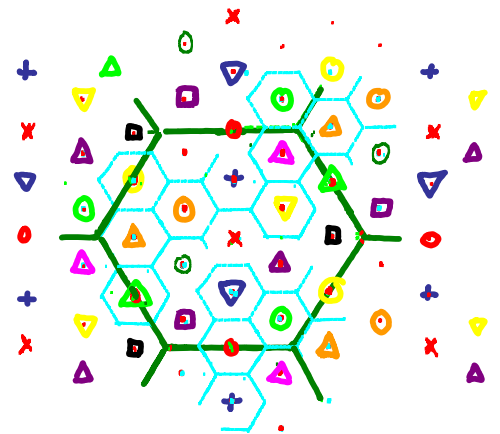
Wyner-Ziv coding



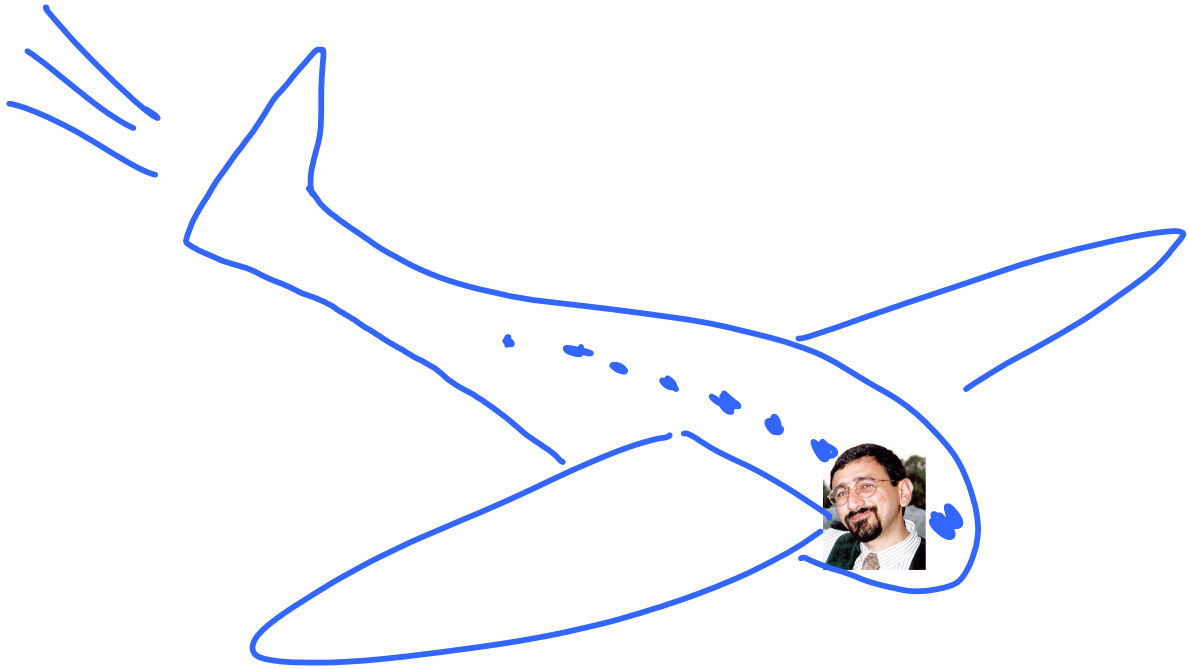
Shlomo  
Shamai



Sergio  
Verdu



post doc



July 1996 - back to TAU ...



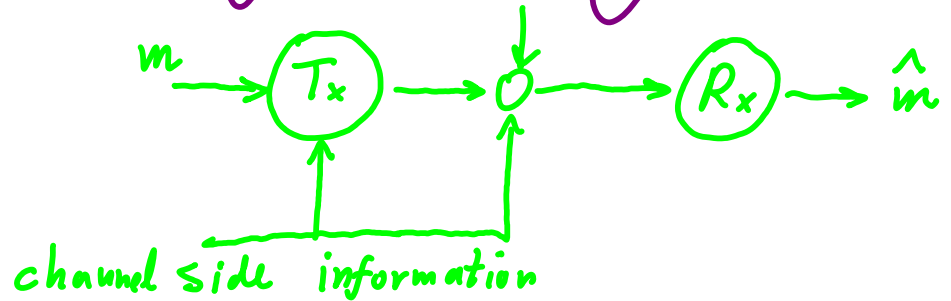
Uri Erez

advanced information theory class 1997:  
side-information @ transmitter

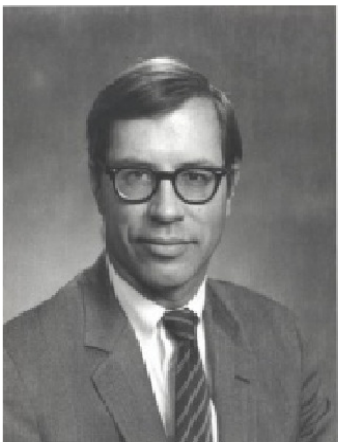


Shlomo Shamai

dirty-paper coding [Costa 1983]



⇒ lattice DPC !

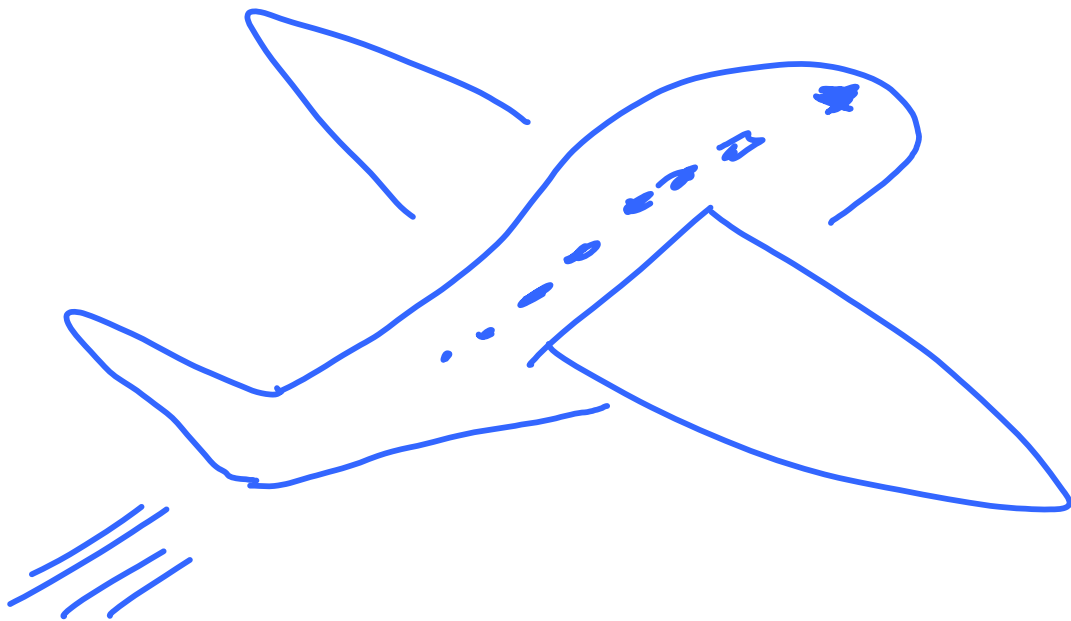


David Forney

achieving  $\frac{1}{2} \log(1 + \text{SNR})$  with  
lattice  $(\Lambda_c / \Lambda_s)$  coding

⇒ first PHD student





Aug. 2002: going to sabbatical @ MIT

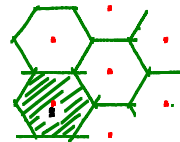
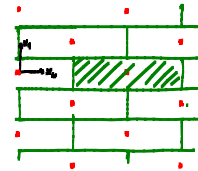
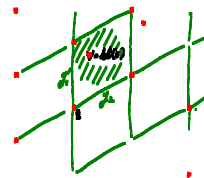
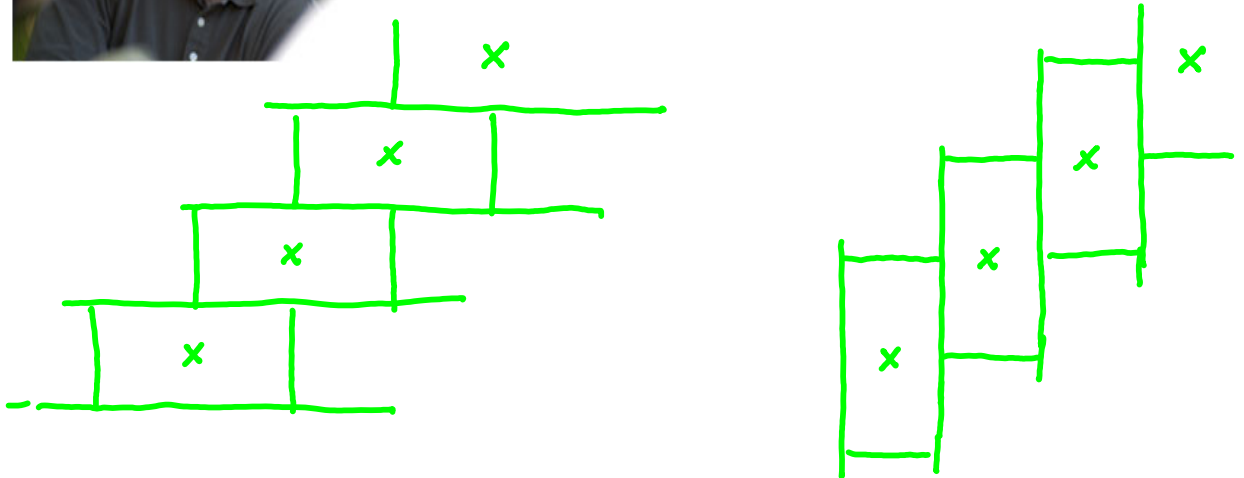


Greg  
Wornell

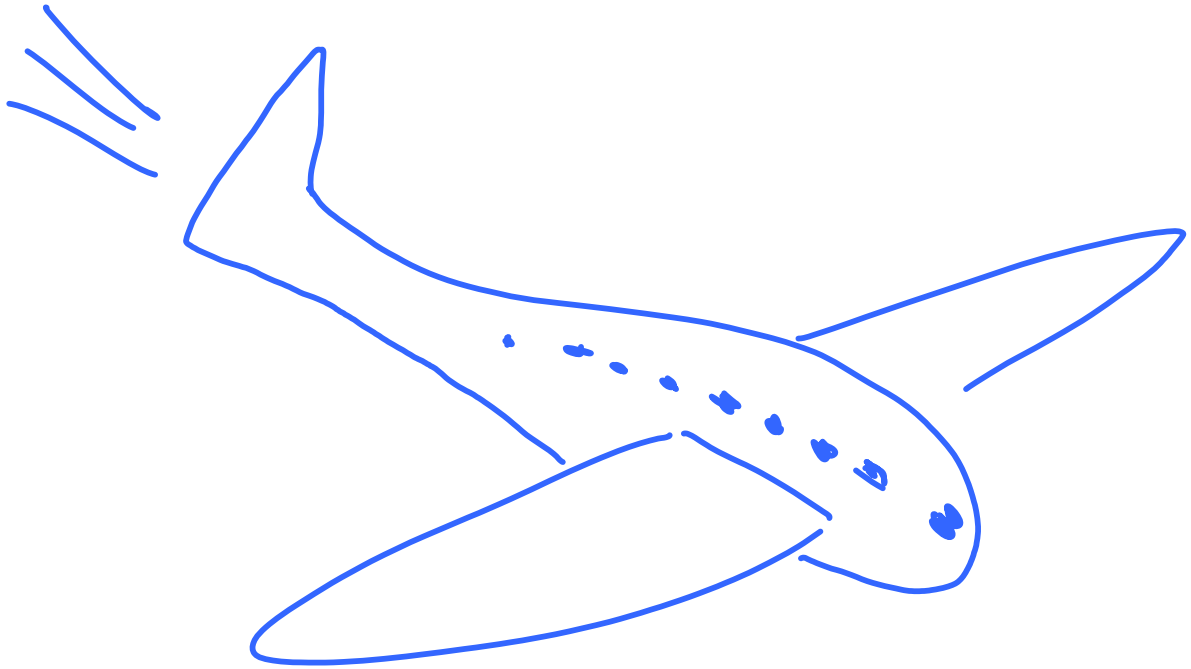
distortion side information  
using

Variable partition codes

Emin  
Martinian



professorship



back to TAU ...



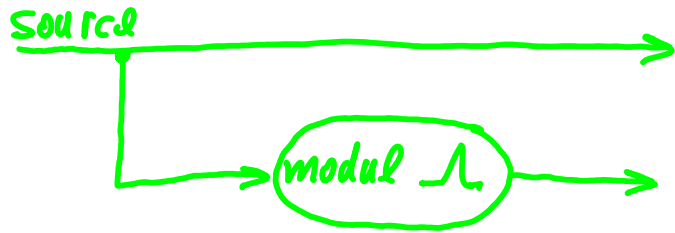
Tal Phylkosof

Yuval Kochman

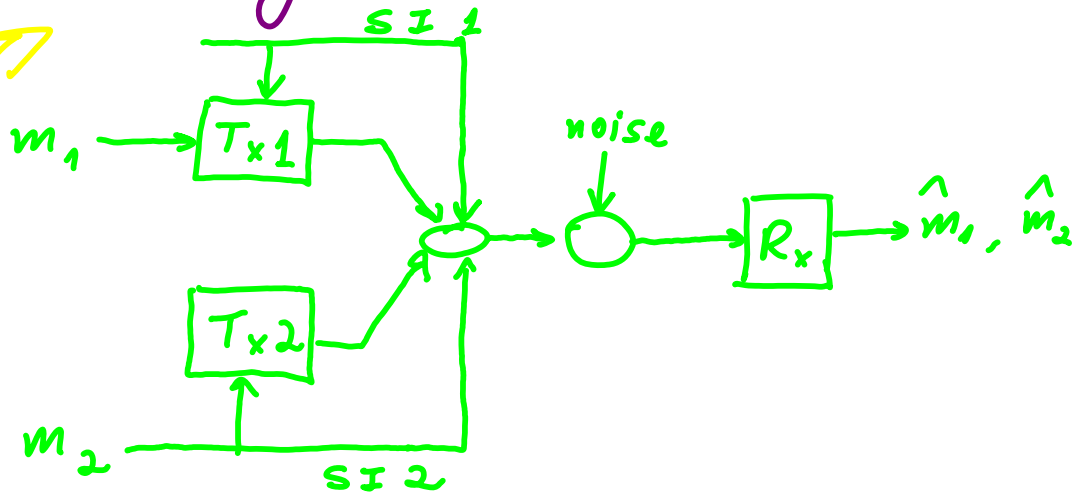


Zvi Reznic

### modulo-lattice modulation



### dirty multiple-access channel



Uri Erez

Many Cons, what about Pros?

⬡ Beauty of lattices

⬡ History

⬡ Circumstances

⬡ Teaching (basis for a course)

⬡ Anecdotes, Future ...

# Triggers to start writing...

## \* Followers & competitors



Sandeep Pradhan

binning  
via syndromes [1999]  
Lattice Korner-Marton  
[2007]



Bobak Nazer



Michael Gastpar

compute & forward  
[2007]

## \* Full professor



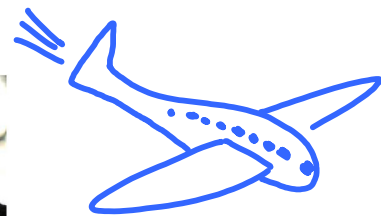
## \* Next generation



Tal Phyllosof @ GM

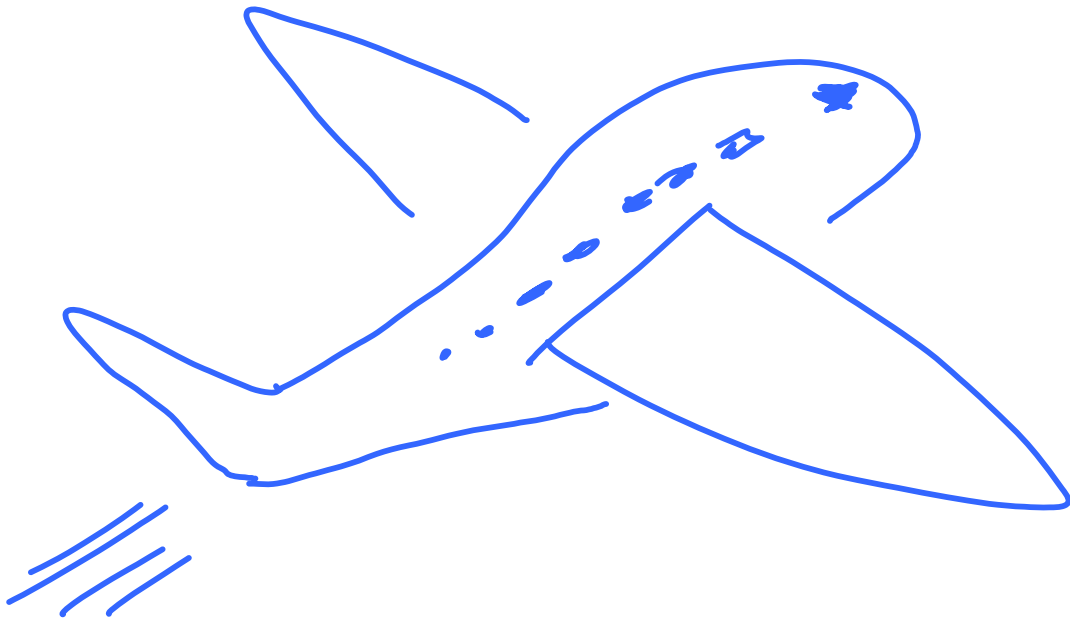


Uri Erez  
@ TAU



Yuval Kochman @ HUJI

## \* So what's next? ...



Aug. 2008 - going to sabbatical @ ETH

# Triggers to start writing...

\* Followers & competitors

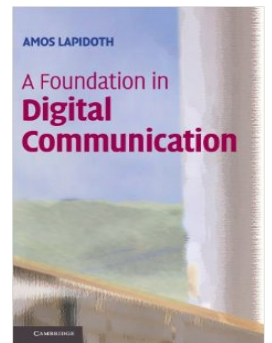
\* Full professor



\* Next generation

\* So what's next?

\* Colleagues who did it!  
(Sabbatical @ ETH)



Amos Lapidot

\* Colleagues who encouraged  
(visit @ Aalborg University Denmark)



Jan Østergaard



Many Cons, what about Pros?

⬡ Beauty of lattices

⬡ History

⬡ Circumstances

⬡ Teaching (basis for a course)

⬡ Anecdotes, Future ...

# Draft 1 : Tutorial @ ITA 2009 (UCSD, Feb. 2009)

=====

Title: Lattices are Everywhere!

"Lattice Codes, Signals and Networks"

Author: Ram Zamir

=====

## Abstract:

As bees and crystals (and people selling oranges in the market) know it for many years, lattices provide efficient structures for packing, covering, quantization and channel coding. In the recent years, interesting links were found between lattices and coding schemes for multi-terminal networks. This book covers close to 20 years of my research in the area; of enjoying the beauty of lattice codes, and discovering their power in problems like: dithered quantization, dirty paper coding, Wyner-Ziv video coding, modulo-lattice modulation, distributed interference cancellation, and more.

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=====

Chapter 1: Lattice Figures of Merits

Chapter 2: Waveform Coding I: Dithered Quantization

Chapter 3: Nested Lattices and Side Information Problems

Chapter 4: Waveform Coding II: Reversed Equalization

Chapter 5: Modulo-Lattice Modulation for Joint Source-Channel Coding

Chapter 6: Noisy Network Coding

# Draft 2: Proposal to Cambridge University Press (May 2003)

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~ first 6 lectures in every course

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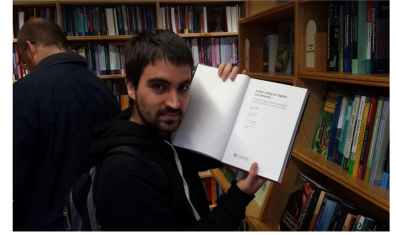
⬡ Anecdotes, Future ...



# Anecdotes

- Who can help me with the figures ?

(Itai Bistriz)



- Collaboration in writing Chapters 11 and 12

(Yuval Kochman & Bobak Nazer)



- Story of a book ...

(Shannon - Slepian - Wyner - Berger - Ephremides)



# Future ...

Home CFP Committee Program Registration About ▾



2015 IEEE Information Theory Workshop  
Jerusalem, ISRAEL | April 26 – May 1



## CFP

The Information Theory Workshop (ITW) is an international conference on advances broadly related to the transmission, storage, processing and manipulation of information.

pdf version of CFP is here:



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## Dates

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- Acceptance notification: January 10, 2015
- Final paper submission: March 1, 2015 (23:59:59pm PDT)

## Dates for invited papers

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- Final manuscript: March 1, 2015 (23:59:59pm PDT)

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## Scope

Original contributions in information and coding theory are solicited. The scope of topics is broad, with emphasis on the following themes:

IT and CS

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## Recent Posts

New submission deadline: Oct. 31, 2014

"Jerusalem Explained" video added

Submission now open through EDAS

Plenary speakers and invited sessions added

Welcome TPC members!

## Categories

News

Last but not least ...

Student @ Lab 102



The  
Zamir  
Family



Thank / You !

