Behnaam Aazhang

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Context Aware Wireless Network

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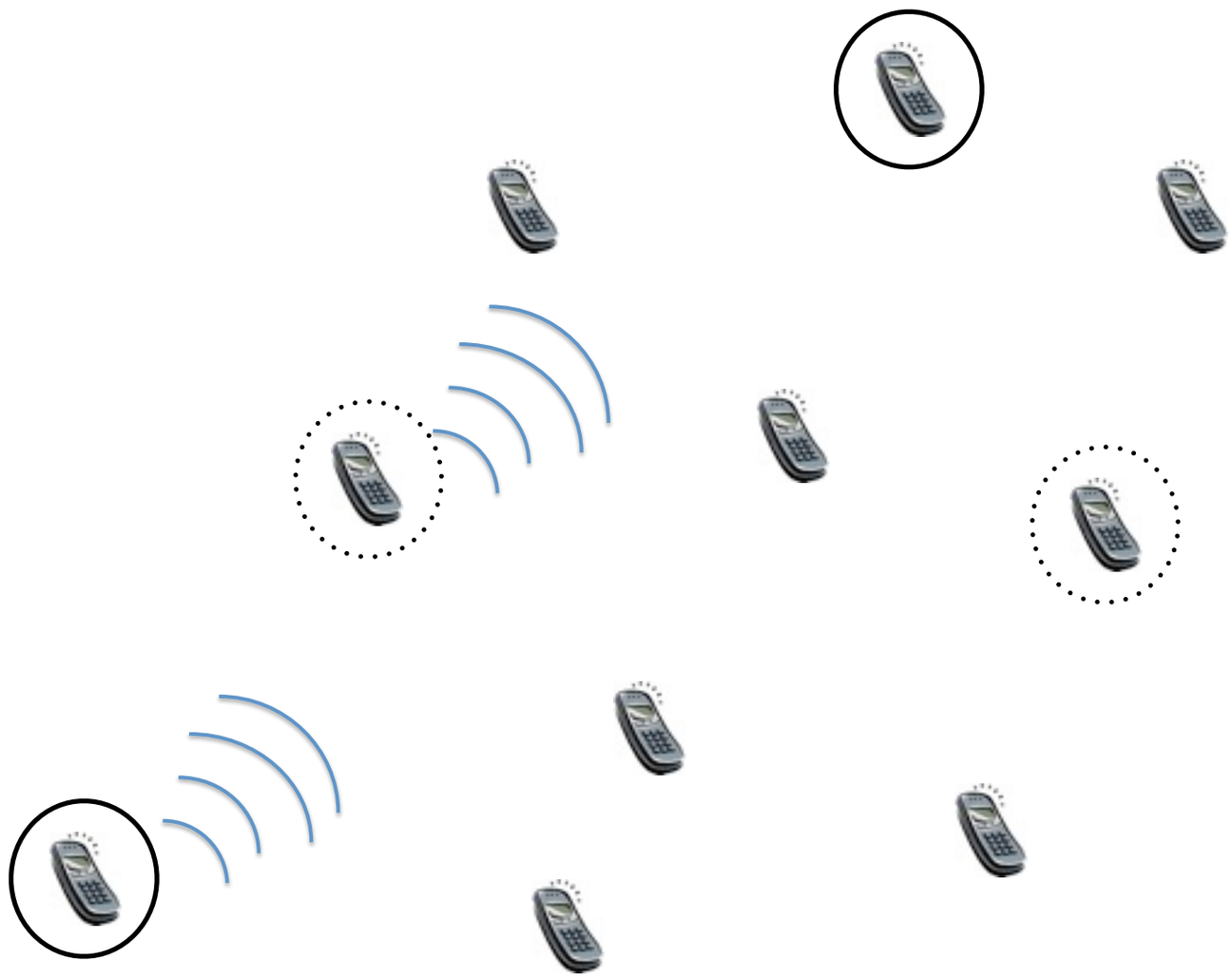
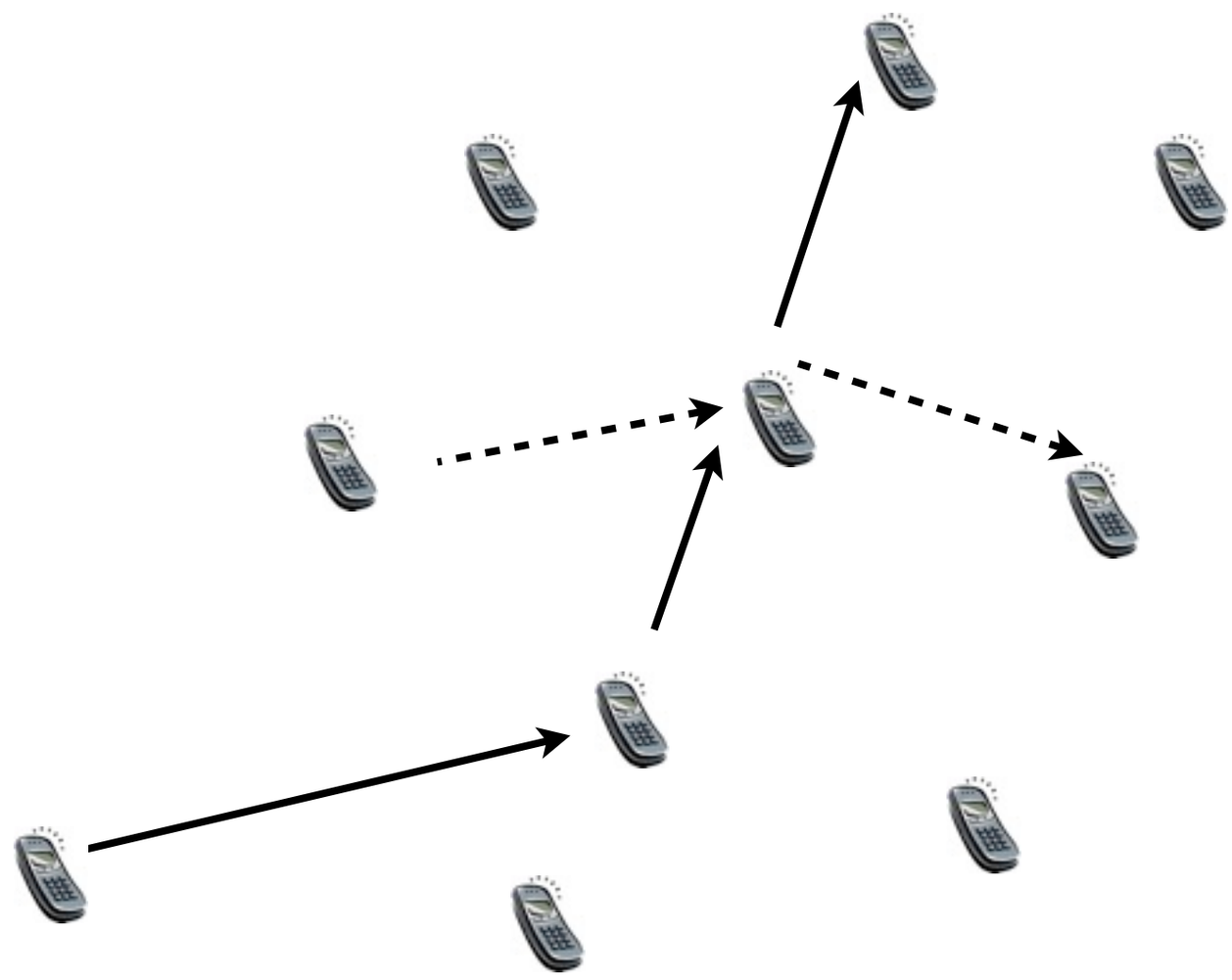
The Team

- Rice
  - Brett Kaufman, Matthew Nokleby, Corina Ionita, David Ramirez,
- Oulu
  - Qiang Xue, Kalle Lahetkangas, Nuwan Ferdinand

- Bandwidth *W*
- Time *T*
- Power





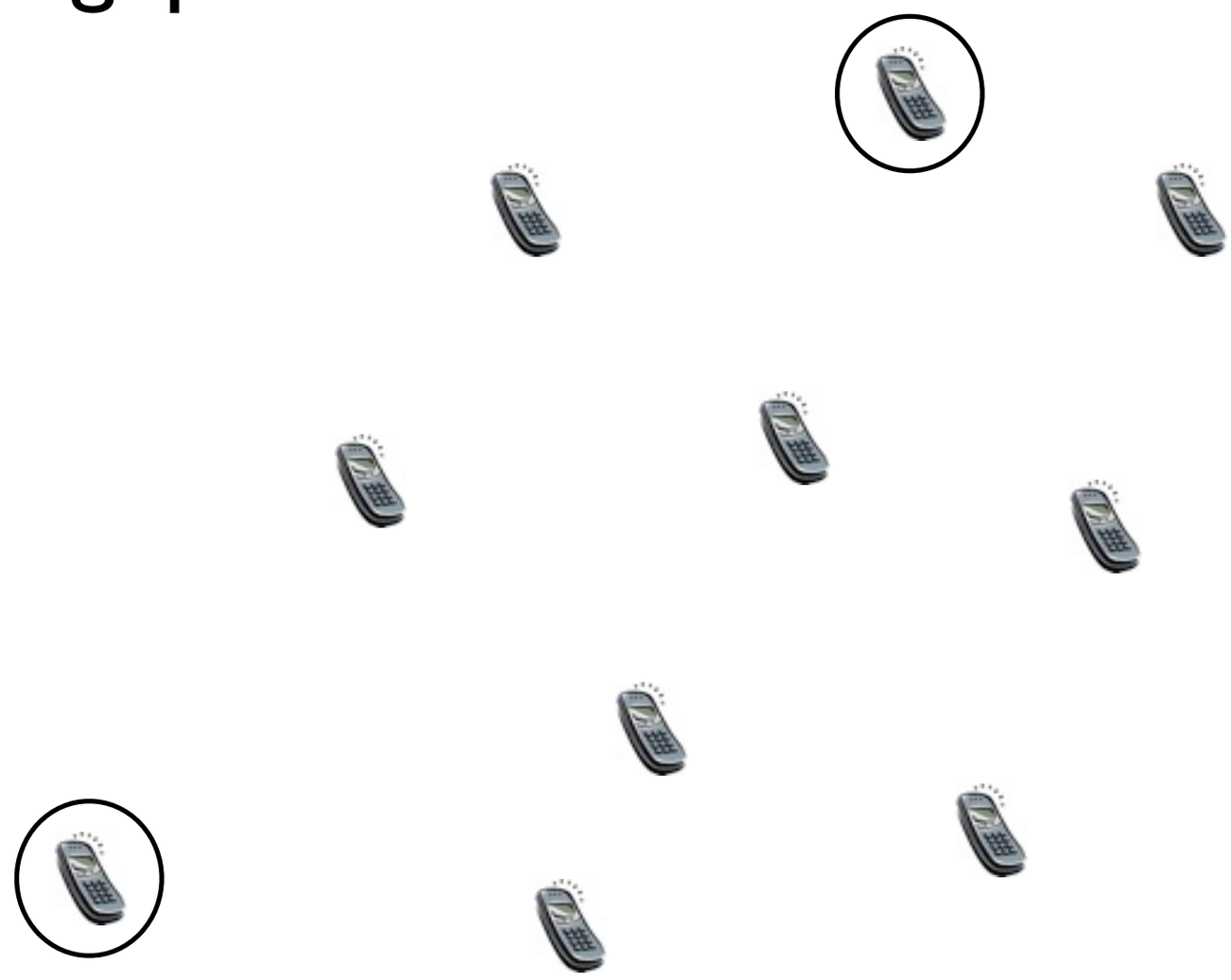
Applications

- Network with Infrastructure
  - Cellular and WiFi

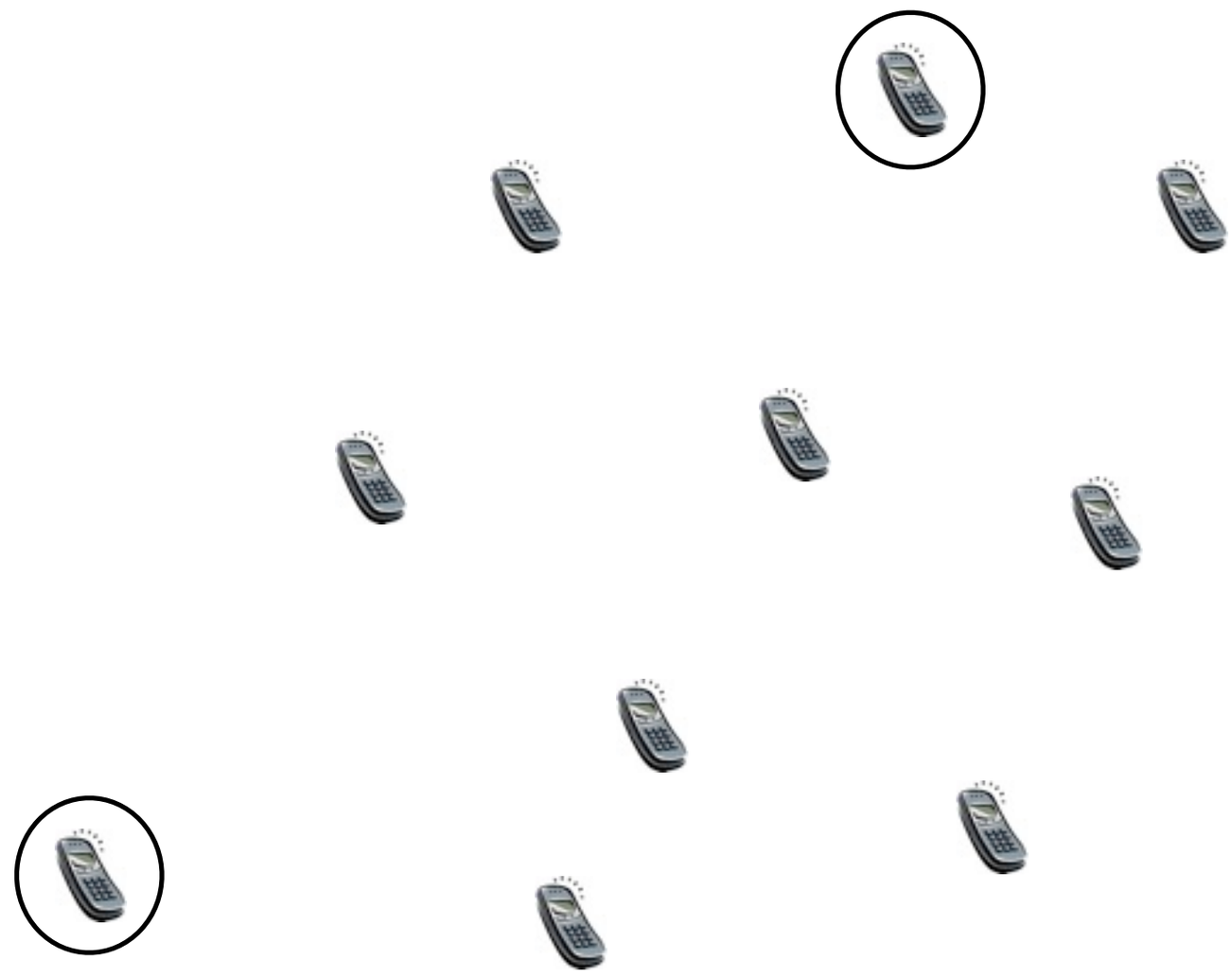
Applications

- Network with Infrastructure
  - Cellular and WiFi
- Ad hoc network
  - Rural
  - First responders
  - Machine to machine
    - Medical / Robotics
    - Transportation

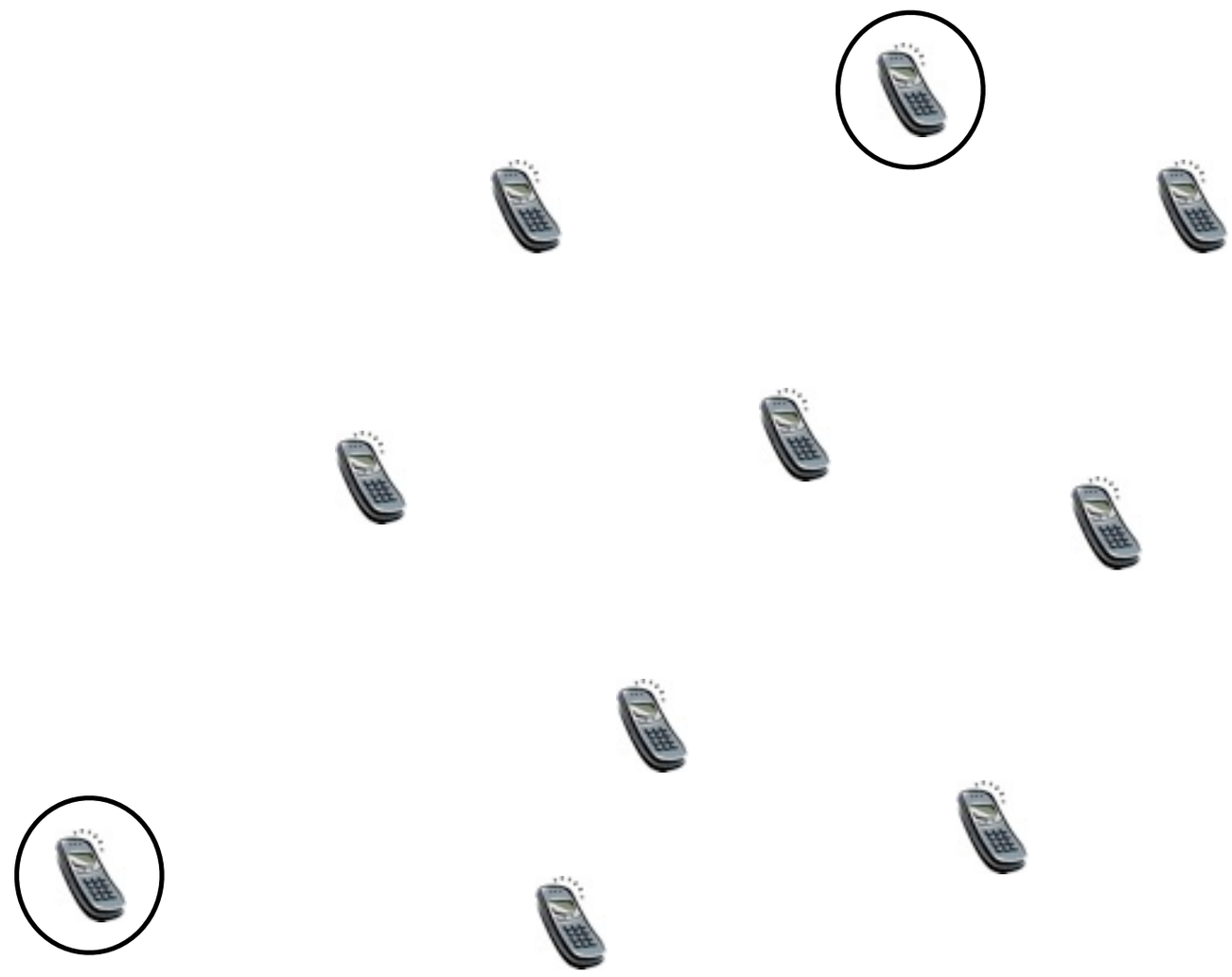
- Objective
  - Aggregate throughput
  - Energy



- Physical layer view
- Scarce
  - Energy
  - Spectrum



- Physical layer view
- Scarce
  - Energy
  - Spectrum
- Cheap
  - Computation
  - Memory



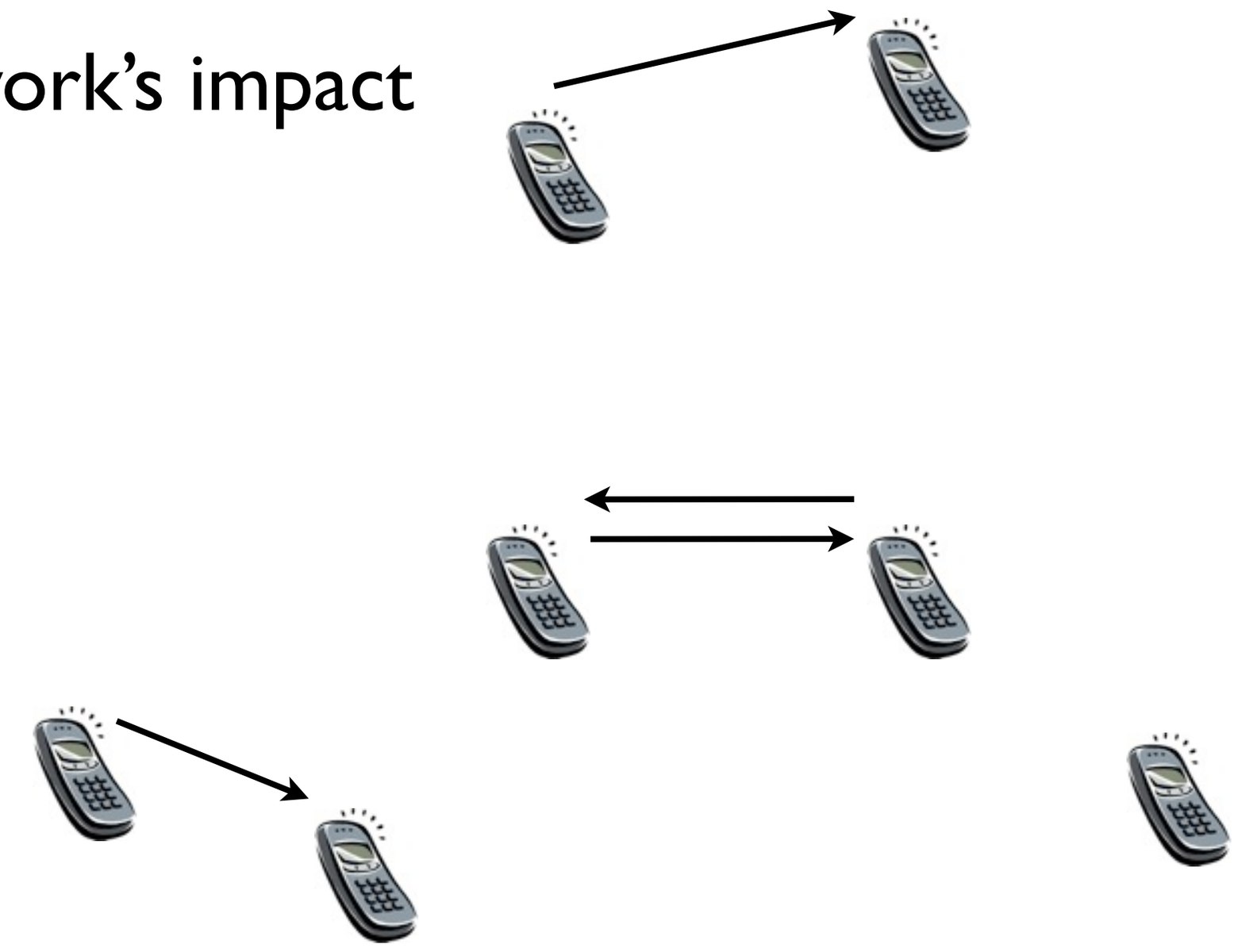
Wireless

Wireless

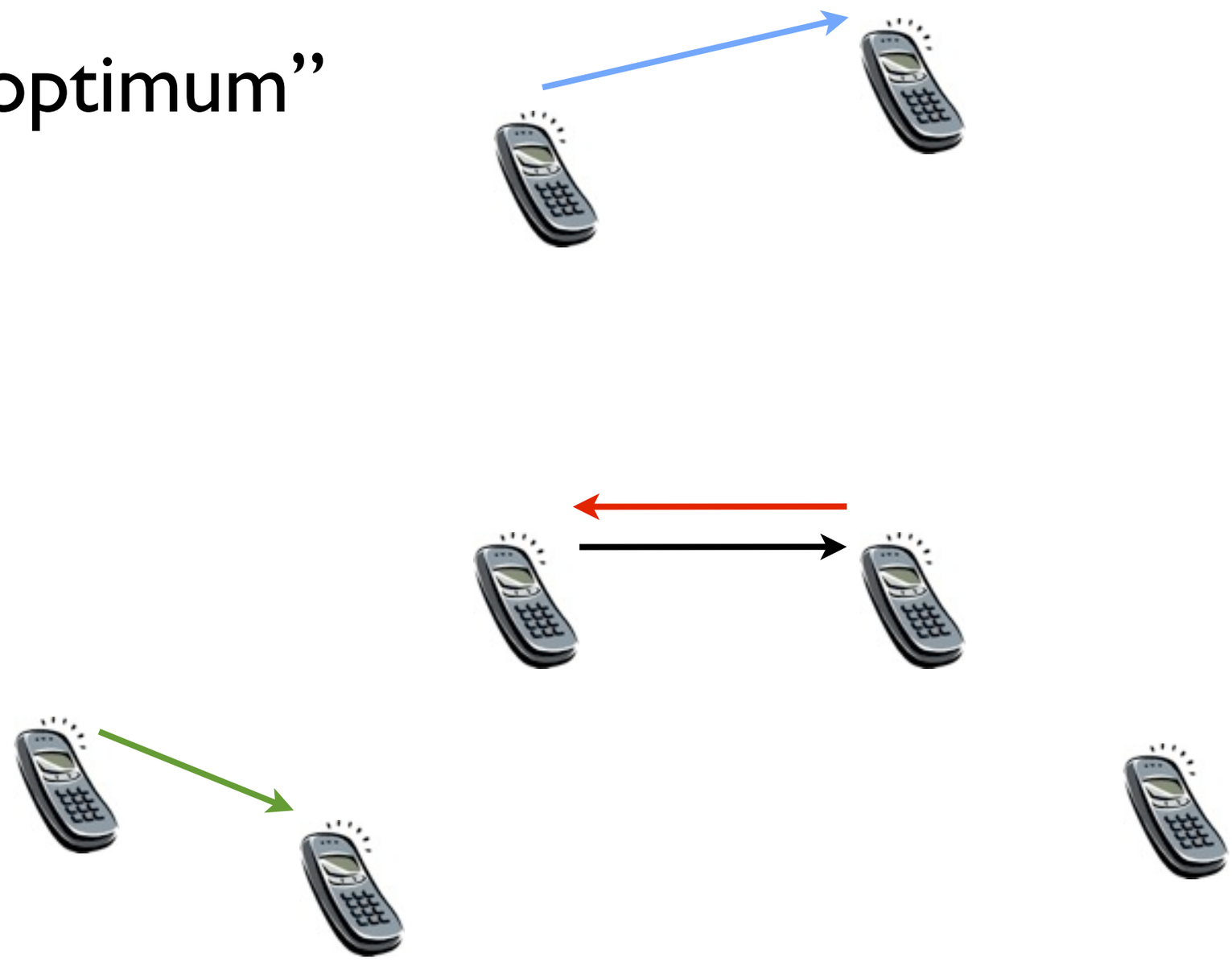
- Well understood
  - *DoF* = signal dimensions = *TW*
  - Reliable rate per *DoF* = $\log(1 + \frac{P_i d_i^{-\alpha}}{N_0})$

- Well understood
  - *DoF* = *TW*
  - Reliable rate per *DoF* = $\log(1 + \frac{P_i d_i^{-\alpha}}{N_0})$
- Required information
  - Minimal
  - LDPC, Turbo, Polar

- Less understood
  - Network's impact

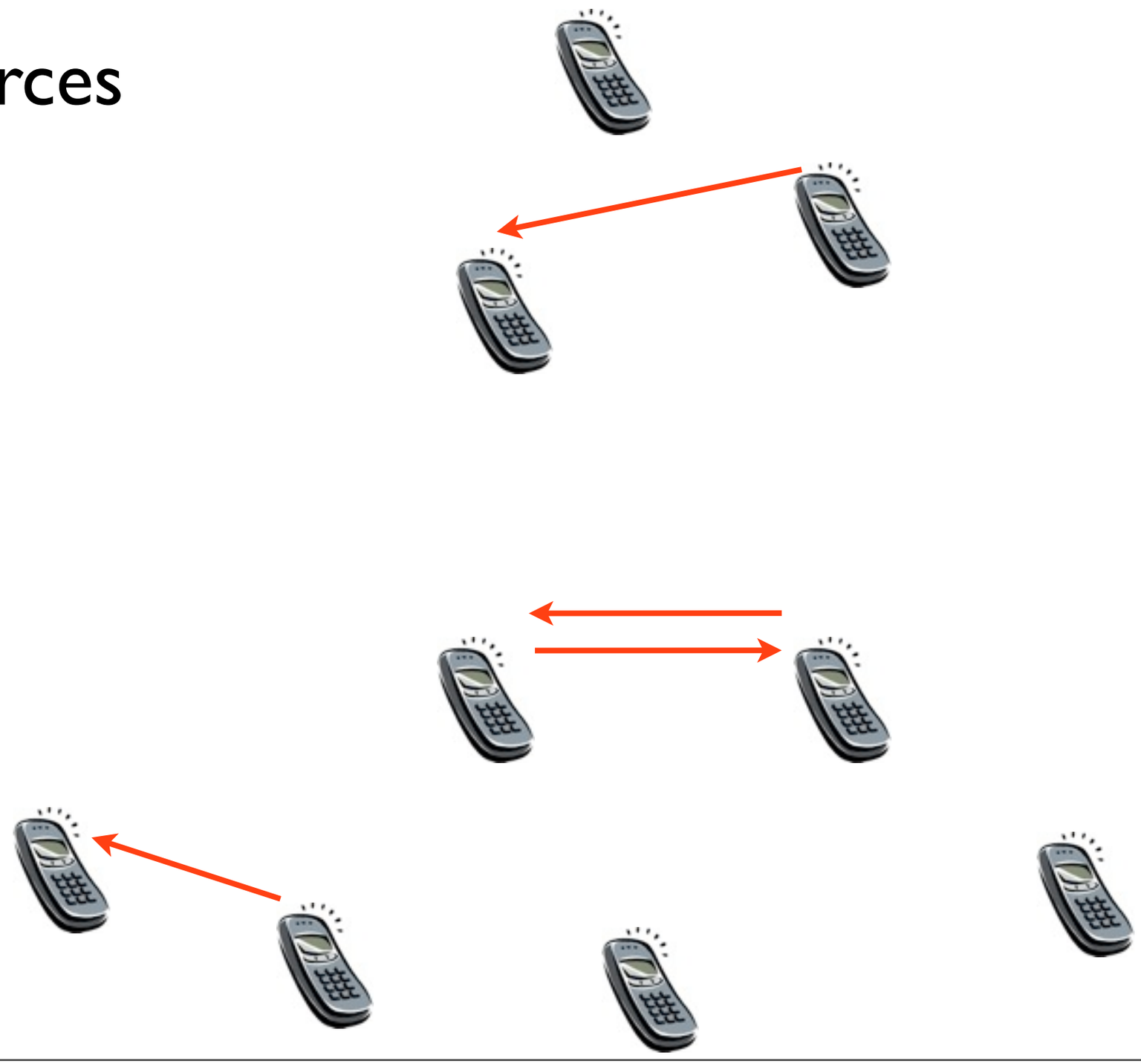


- Well understood
  - Not “optimum”

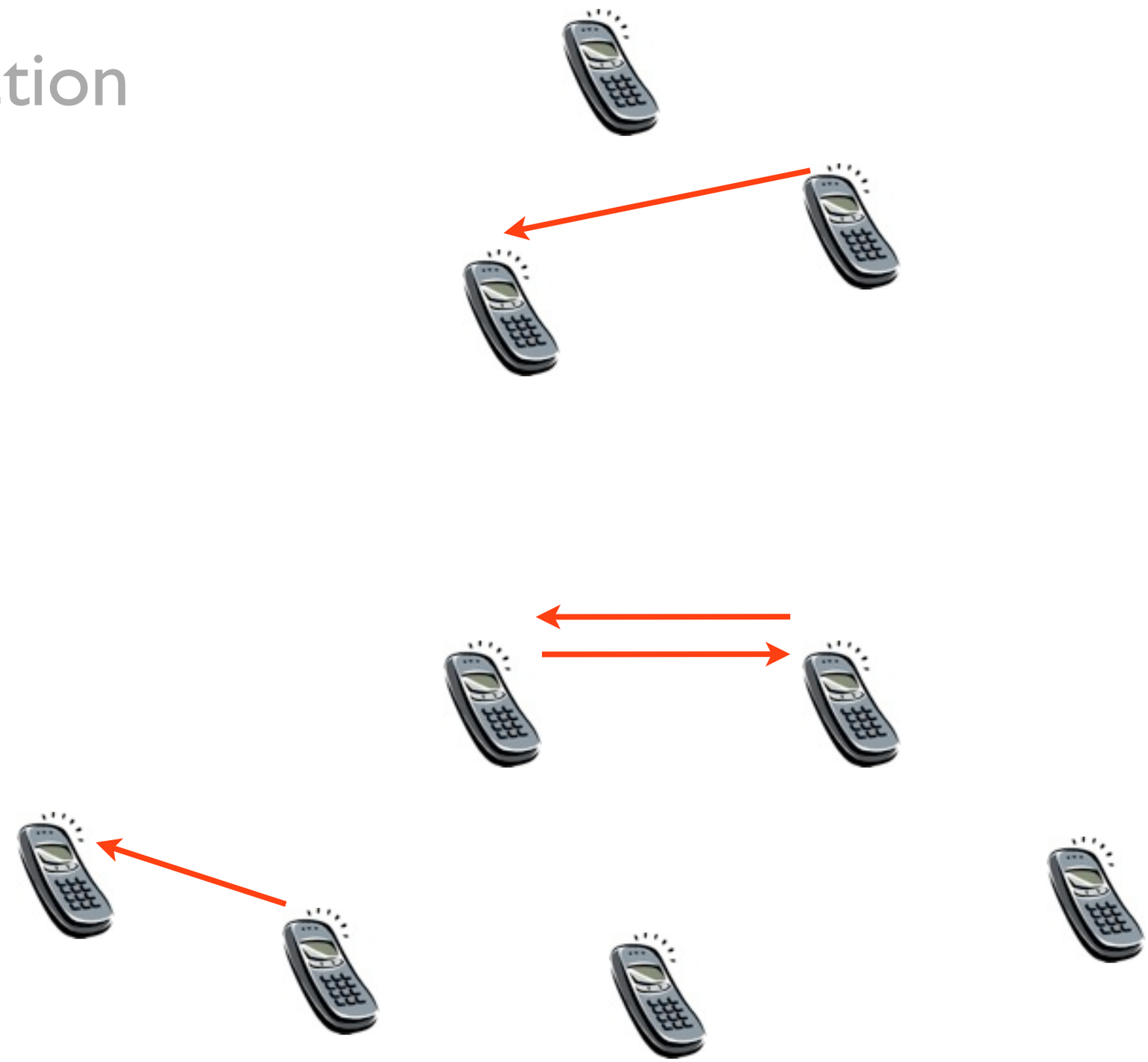


A Framework

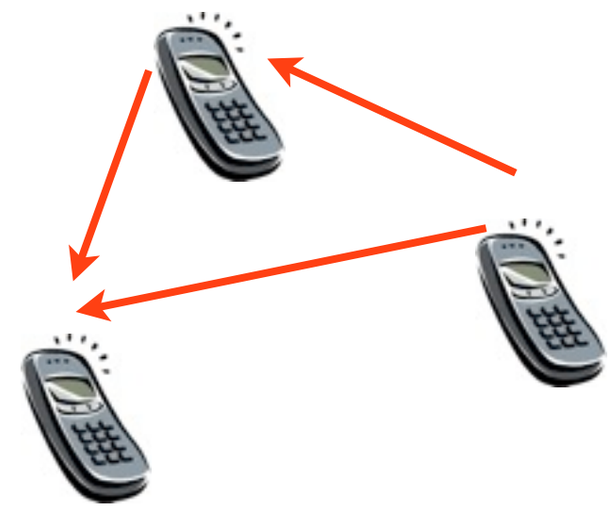
- Share resources

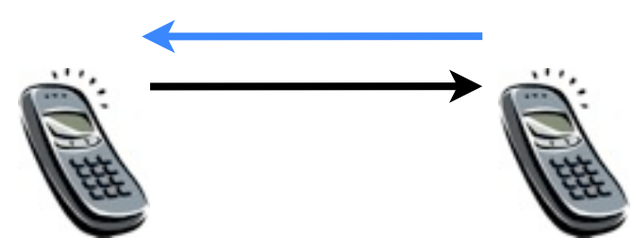


- Partial abstraction
- Share
  - Time
  - Bandwidth
  - Spatial *DoF*

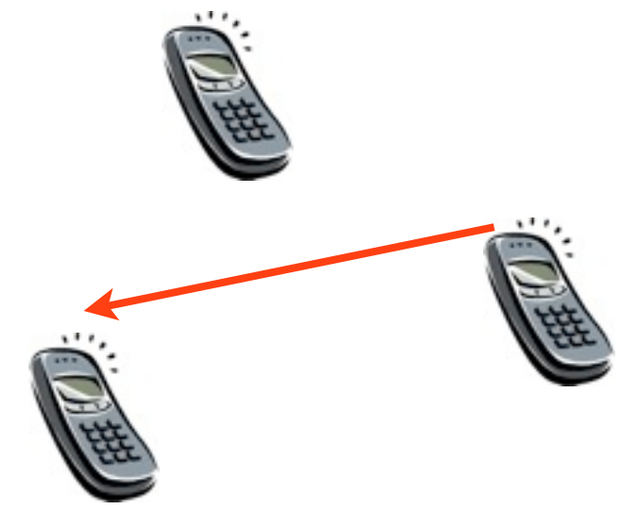


- Partial abstraction
- Share
  - Time
  - Bandwidth
  - Spatial *DoF*



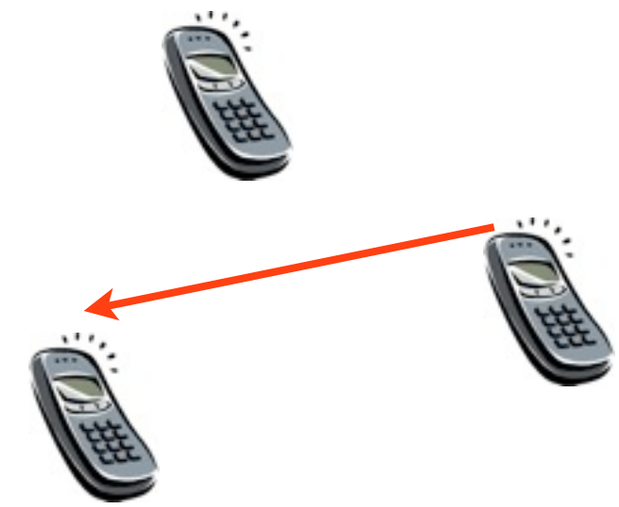


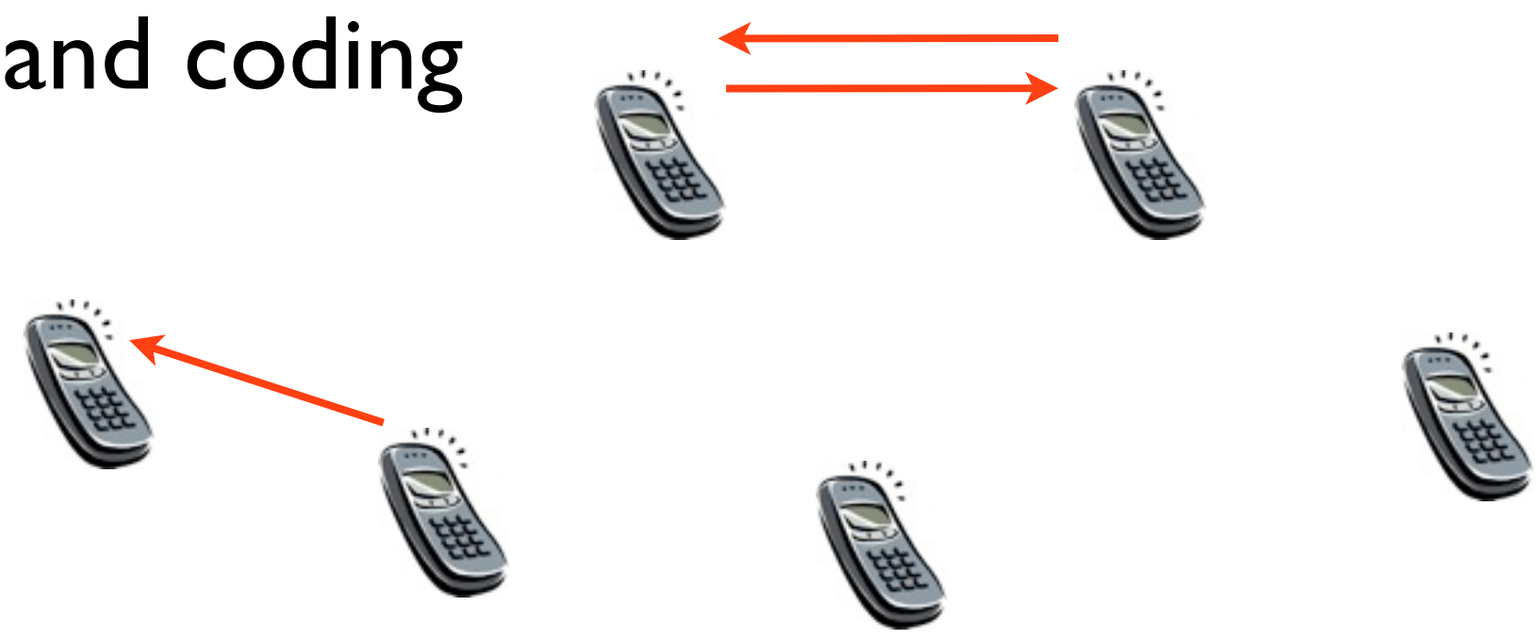
- Questions
  - Routing
  - Scheduling
  - Power control
  - Modulation and coding



- Questions
  - Routing
  - Scheduling
  - Power control
  - Modulation and coding

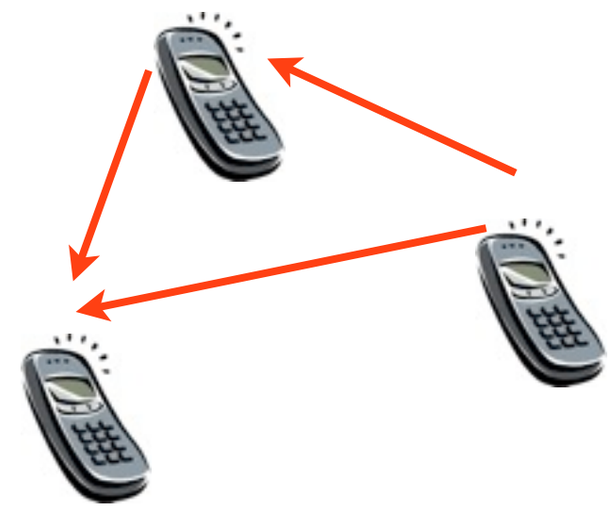
Too hard!





Approach

- Granularity
  - Session/flow
  - Packet
  - Symbol
  - Signal



- Granularity
  - Session/flow
  - Packet
  - Symbol
  - Signal
- Examples
  - Spectrum sharing
  - Scheduling
  - Cooperation/network coding
  - Beamforming

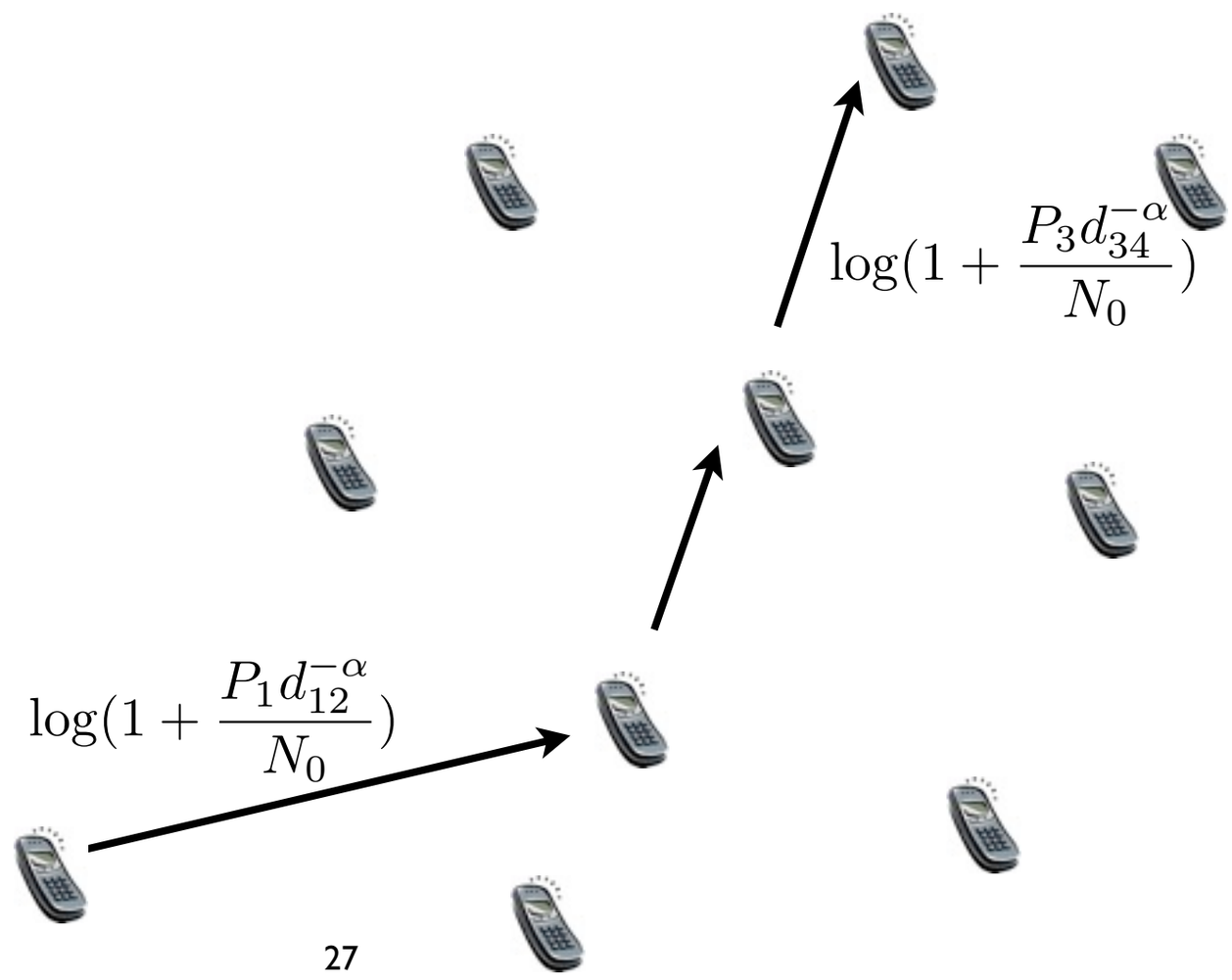
- Granularity
  - Session/flow
  - Packet
  - Symbol
  - Signal

- Complexity ↑
- Network information required ↑
- Performance ↑

- Granularity
  - Session/flow
  - Packet
  - Symbol
  - Signal

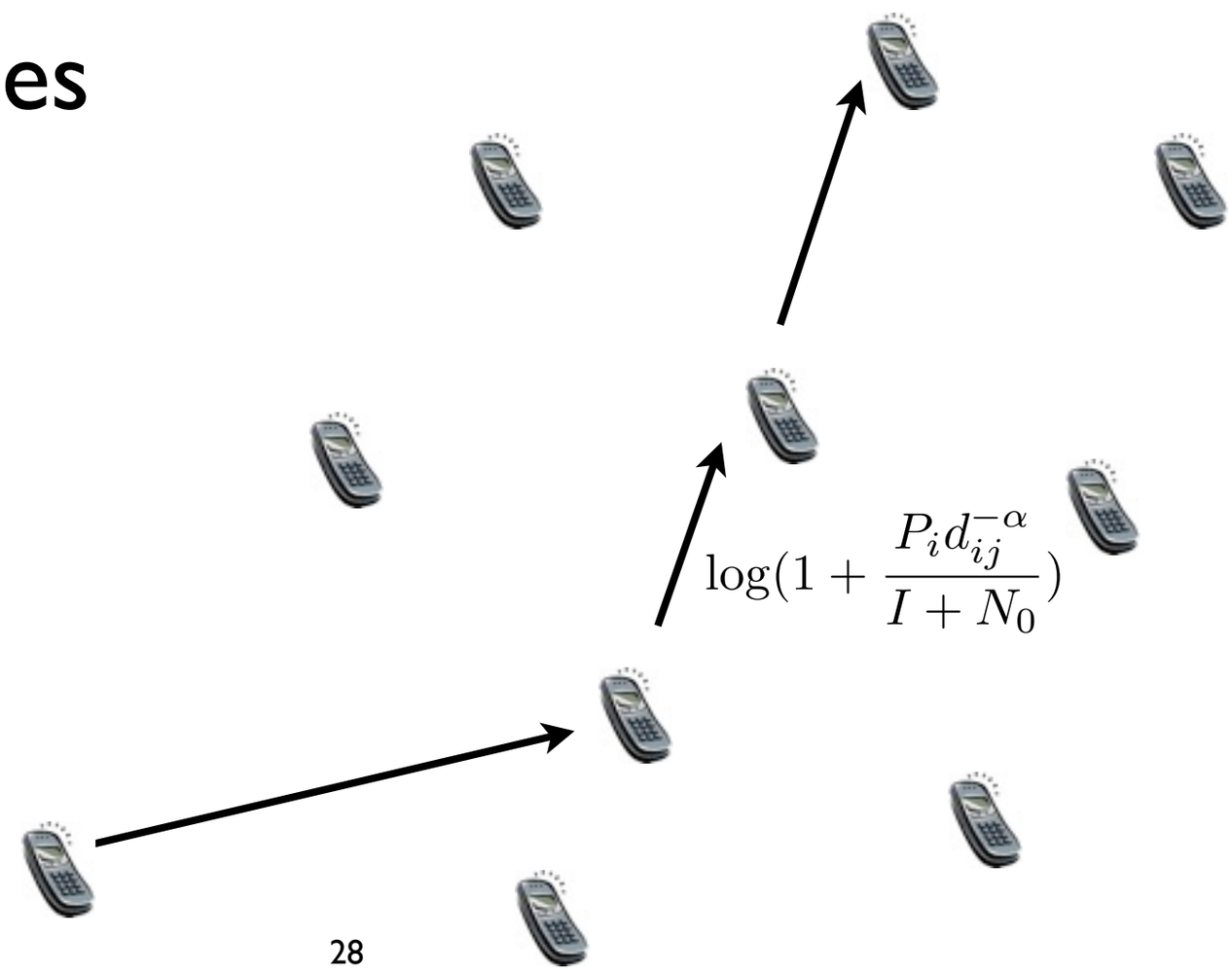
Packet

- David Ramirez
  - Multiple hops



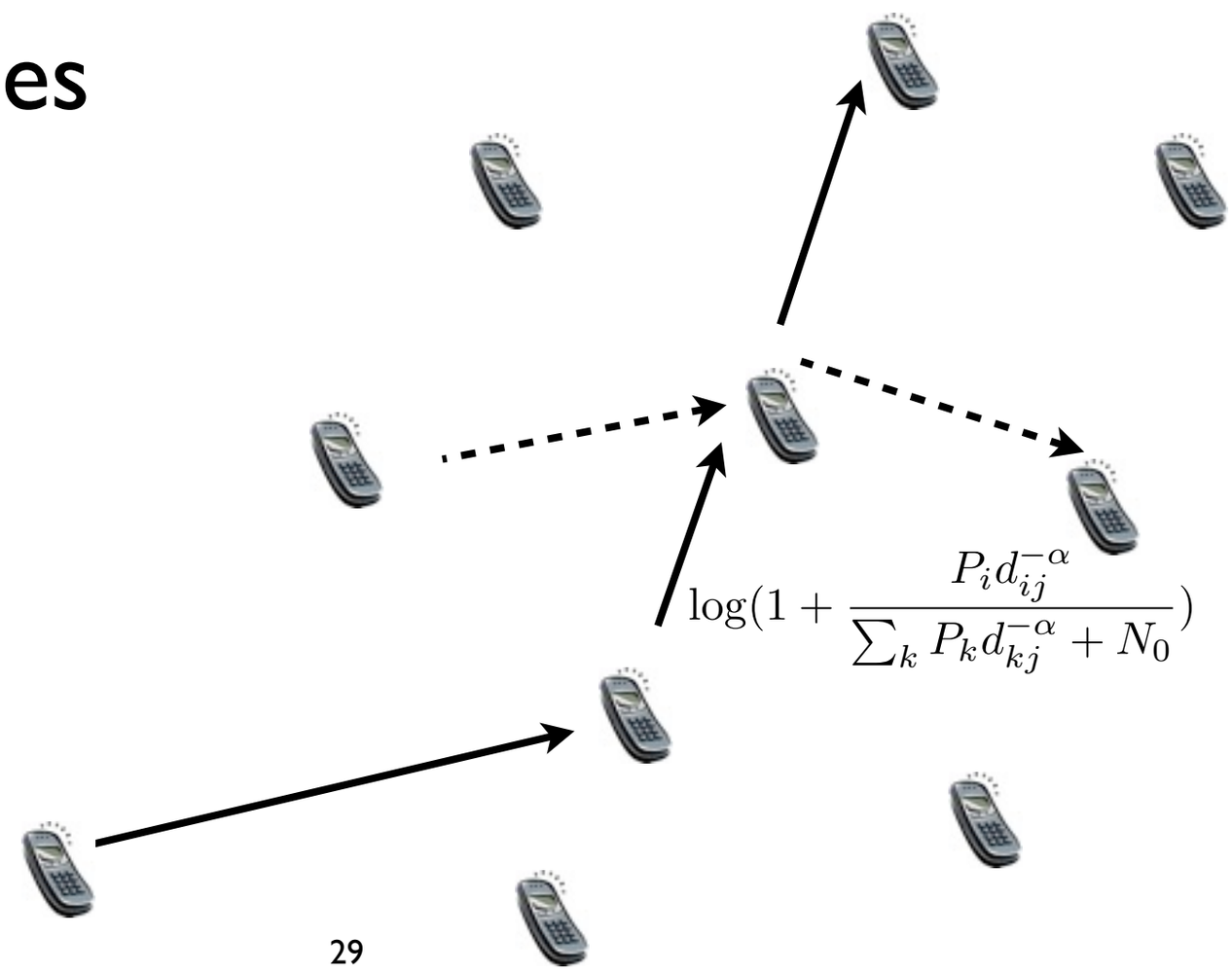
Packet

- David Ramirez
  - Multiple hops
  - Full duplex nodes



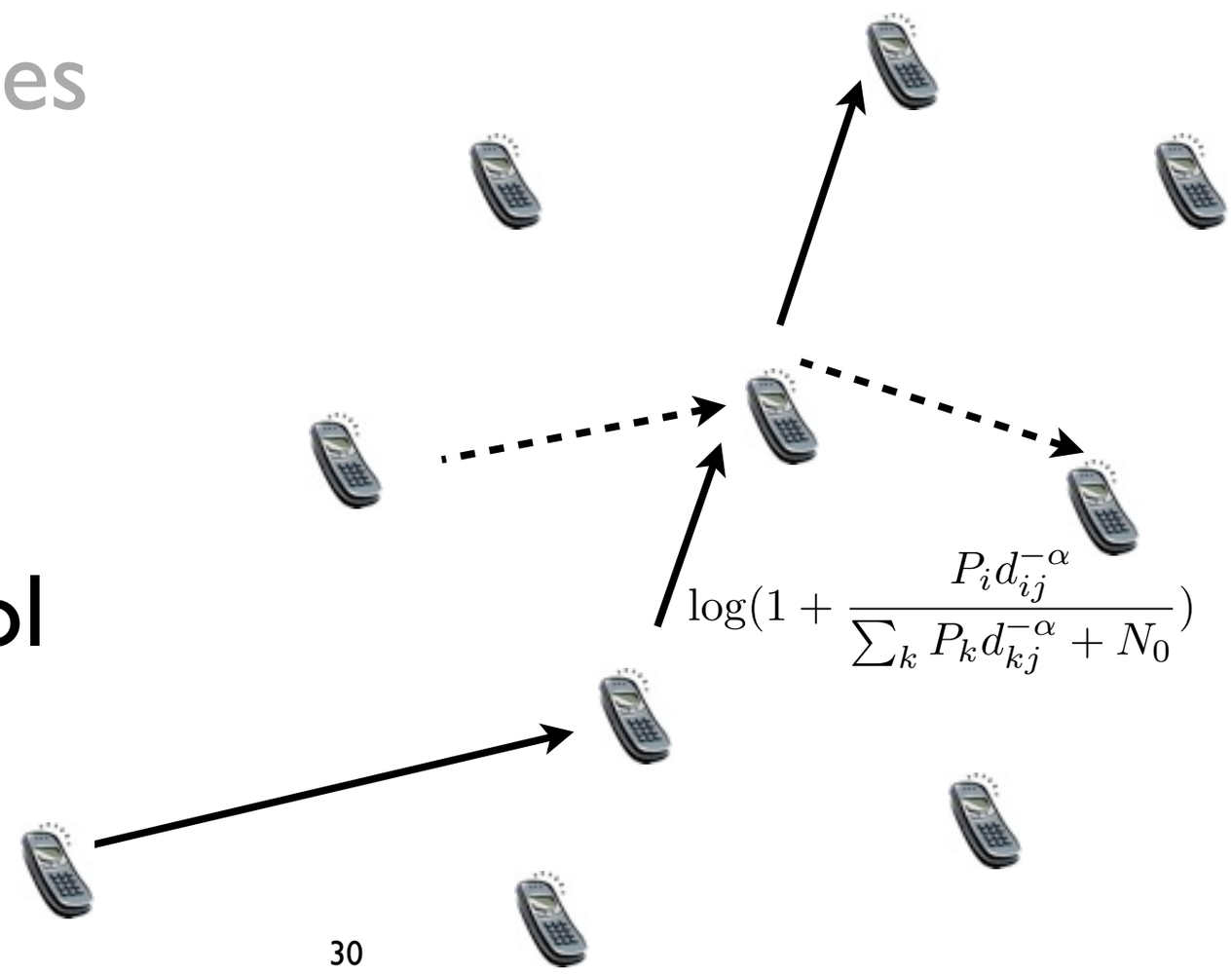
Packet

- David Ramirez
  - Multiple hops and multiple flows
  - Full duplex nodes



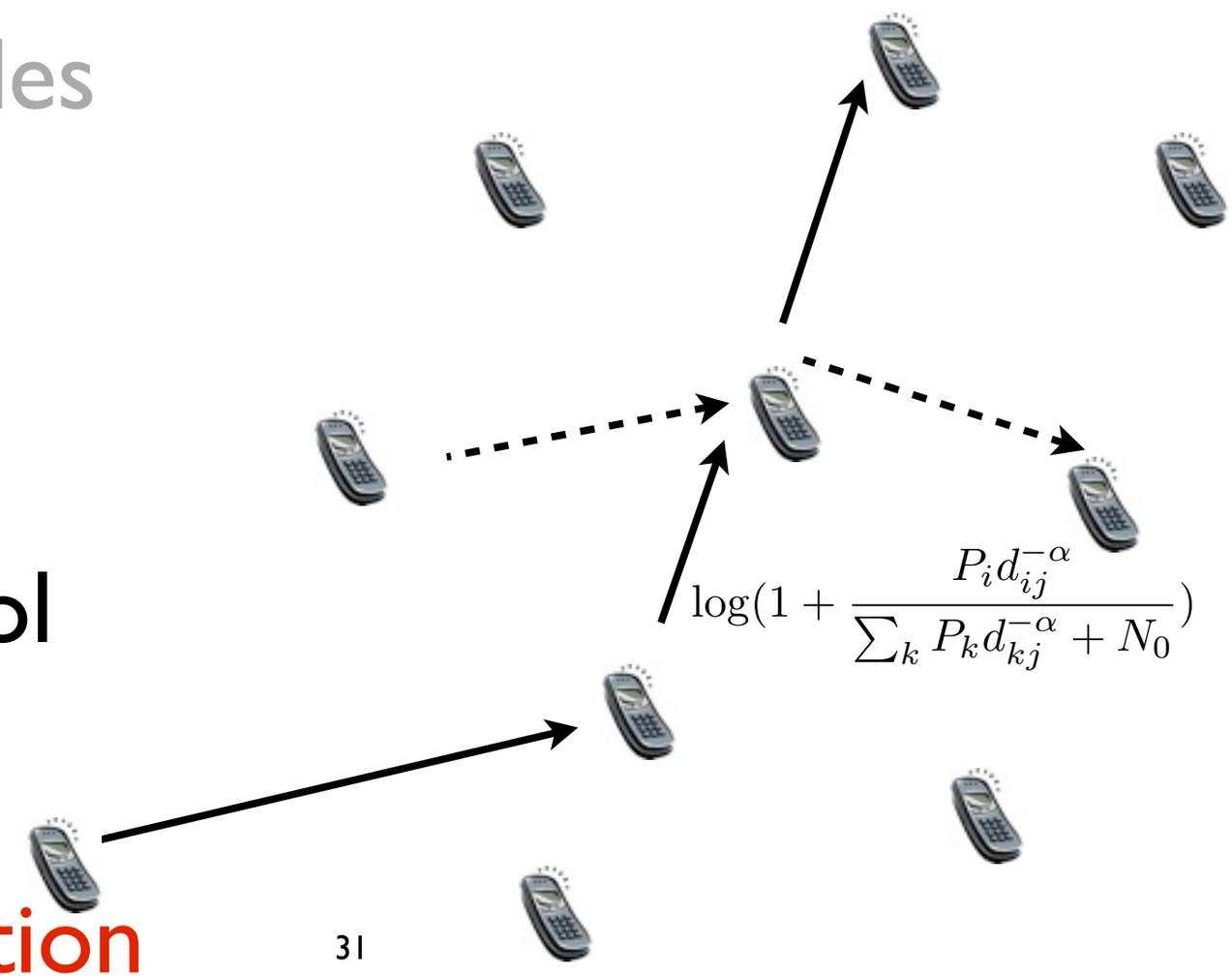
Packet

- David Ramirez
  - Multiple hops and multiple flows
  - Full duplex nodes
    - Routing
    - Scheduling
    - Power control



Packet

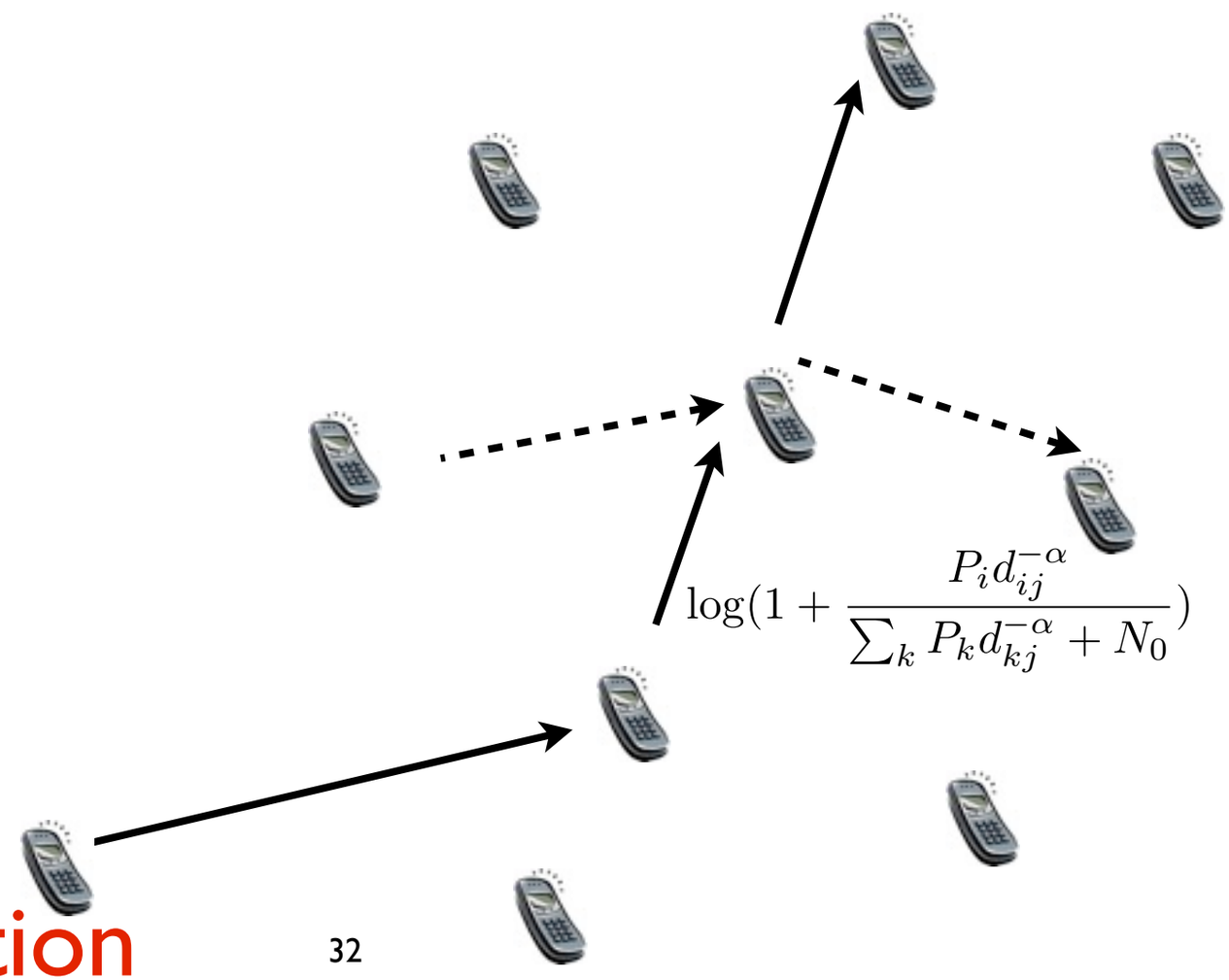
- David Ramirez
  - Multiple hops and multiple flows
  - Full duplex nodes
    - Routing
    - Scheduling
    - Power control



Mixed integer/real
non convex optimization

Packet

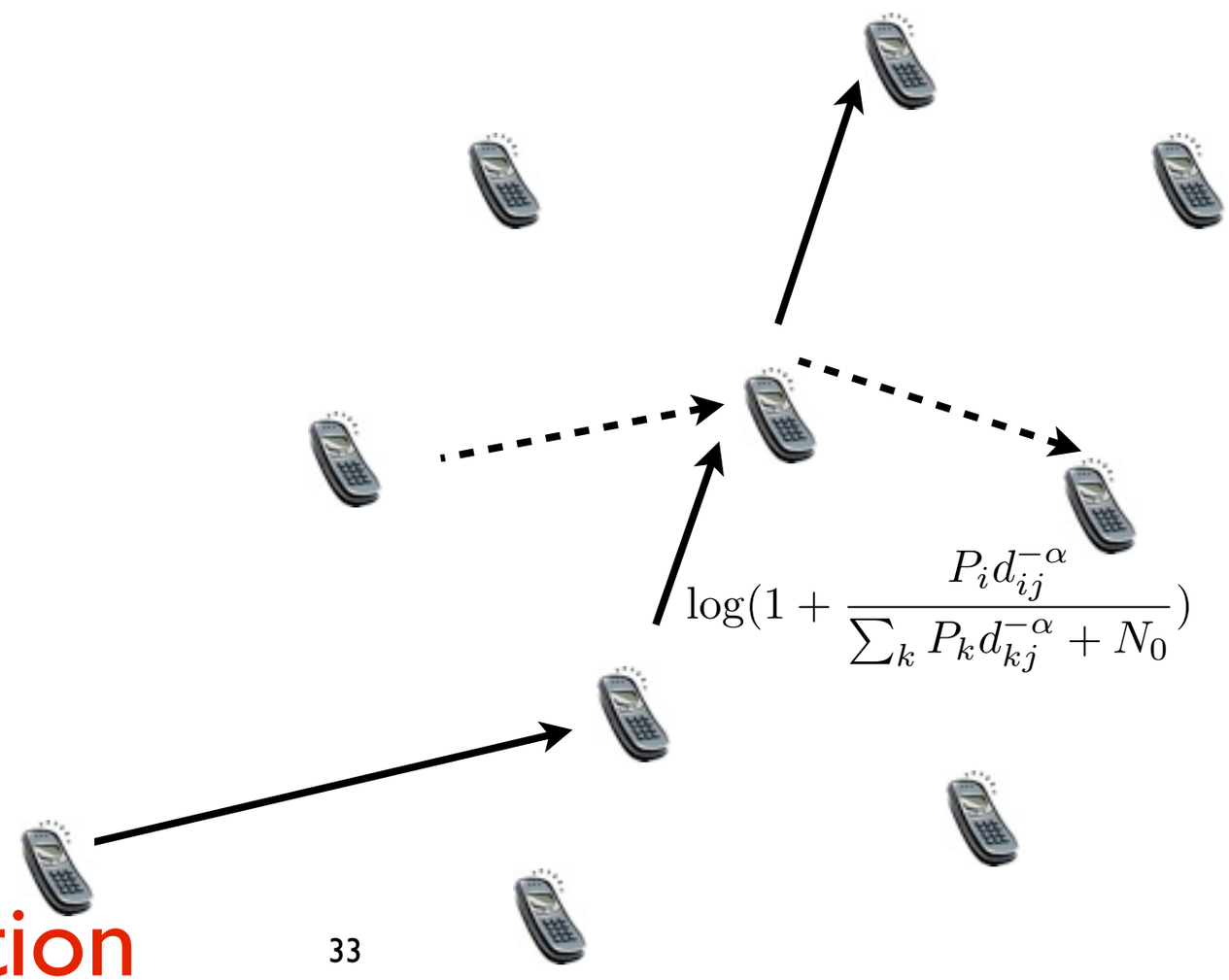
- Global network knowledge
  - NP-hard



Mixed integer/real
non convex optimization

Packet

- Global network knowledge
  - NP-hard
- Decompose
  - Spatially
  - Temporally
- Clustering



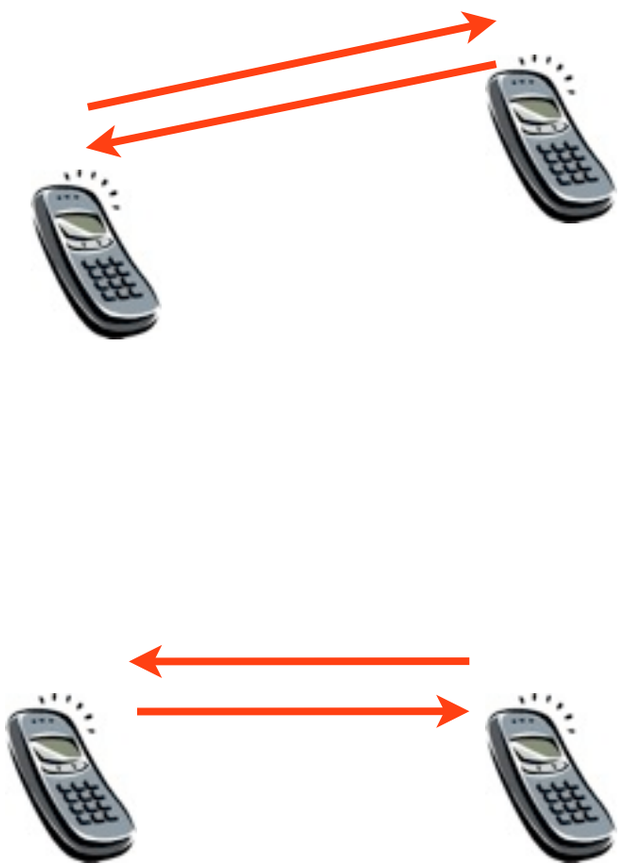
Mixed integer/real
non convex optimization

- Granularity
  - Session/flow
  - Packet
  - Symbol
  - Signal

- Complexity ↑
- Network information required ↑
- Performance ↑

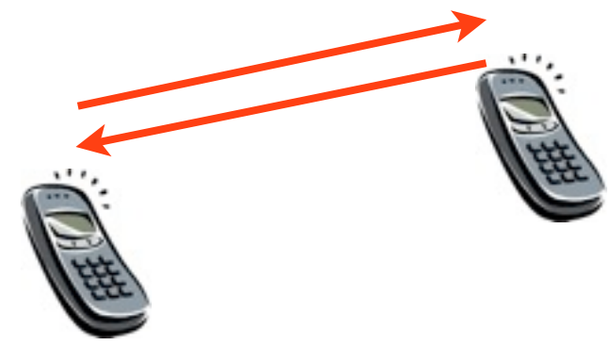
Symbol

- Brett Kaufman
  - Full duplex
  - Interference channel



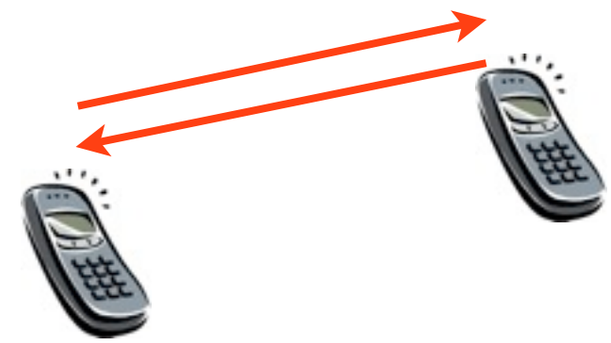
Symbol

- Brett Kaufman
  - Full duplex
  - High order modulation
  - Low density lattice coding



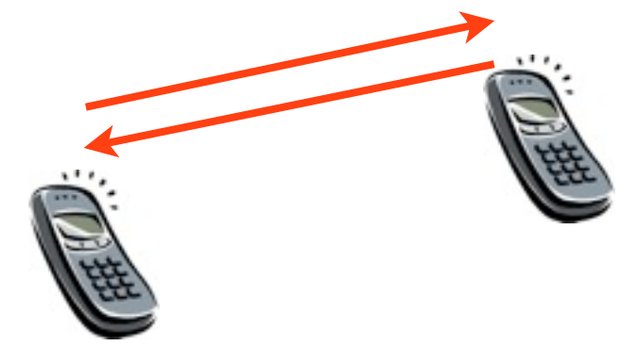
Symbol

- Brett Kaufman
  - Full duplex
  - High order modulation
  - Low density lattice coding
    - Cancelation
      - Self interference



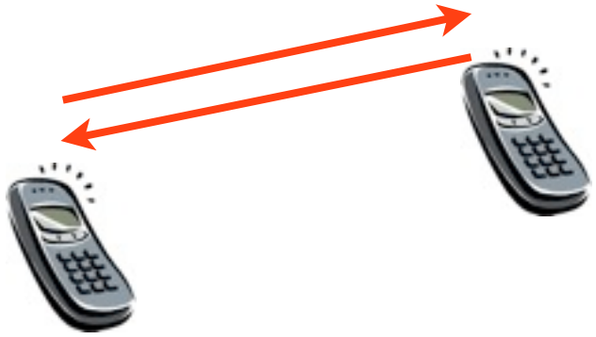
Symbol

- Brett Kaufman
  - Full duplex
  - High order modulation
  - Low density lattice coding
    - Cancelation
      - Self interference
      - Other flows



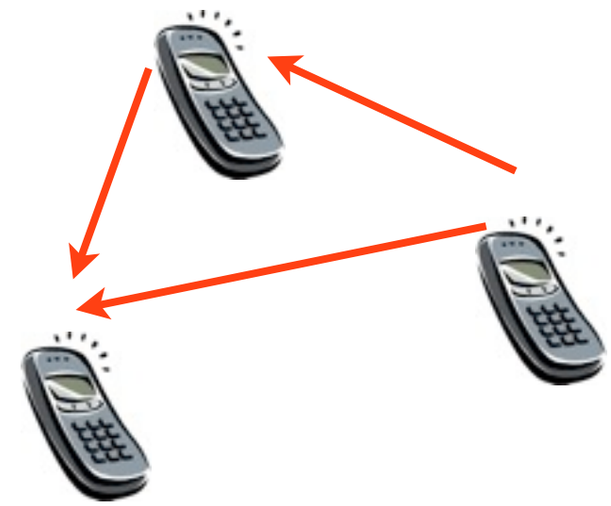
Symbol

- Brett Kaufman
  - Full duplex
  - System model
    - Analog RF cancelation
  - Baseband cancelation
    - Analog
    - Digital



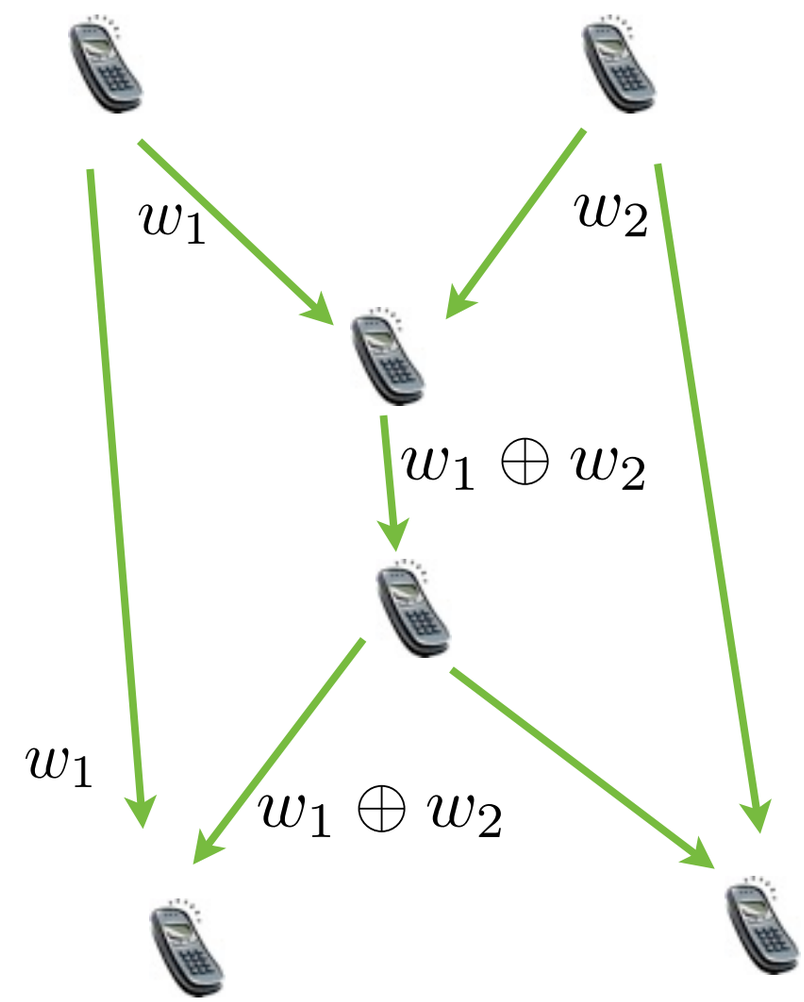
Symbol

- Cooperation
- Network coding



Network Coding

- Linear network coding is "optimum"

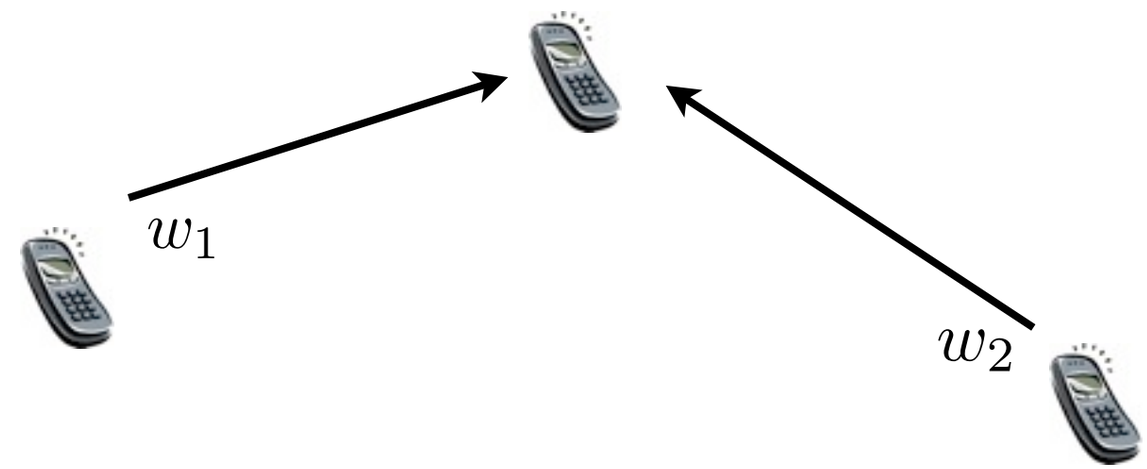


Symbol

- Network information
  - Node discovery
  - Global channel state information
- Overhead and complexity

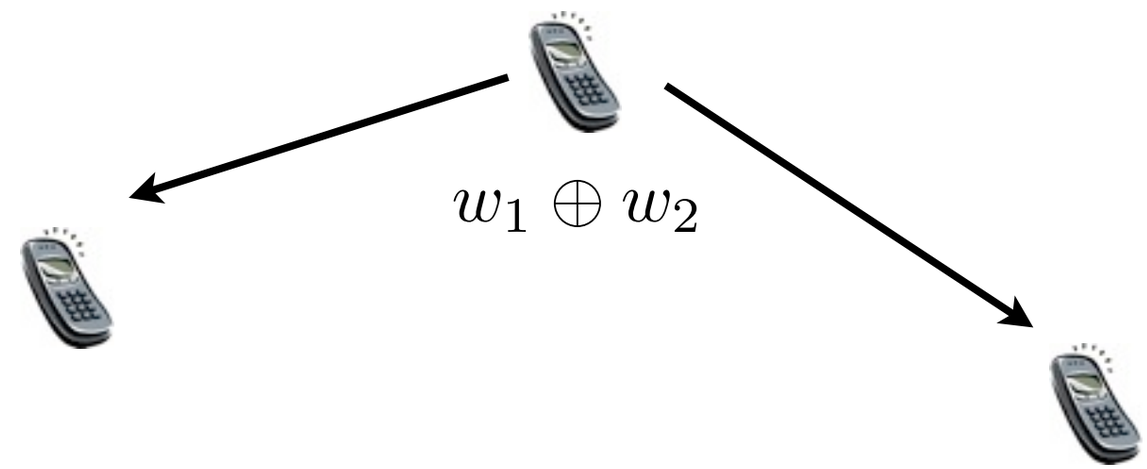
Network Coding with Relay

- Corina Ionita



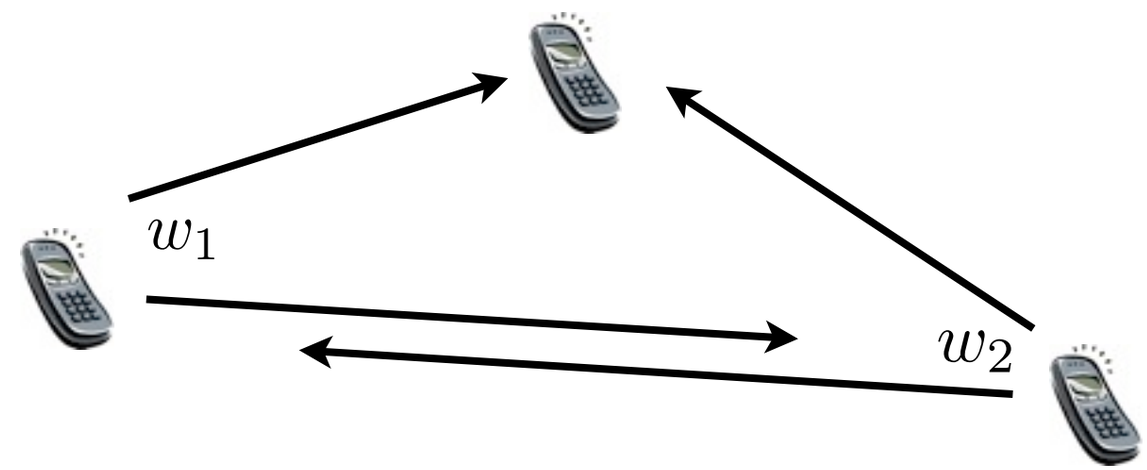
Network Coding with Relay

- Corina Ionita



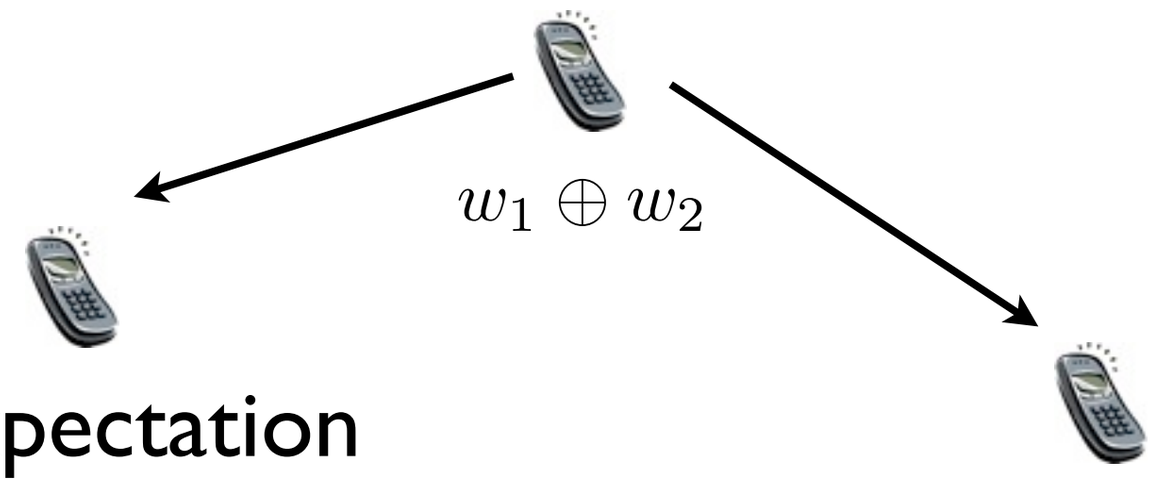
Network Coding with Relay

- Corina Ionita



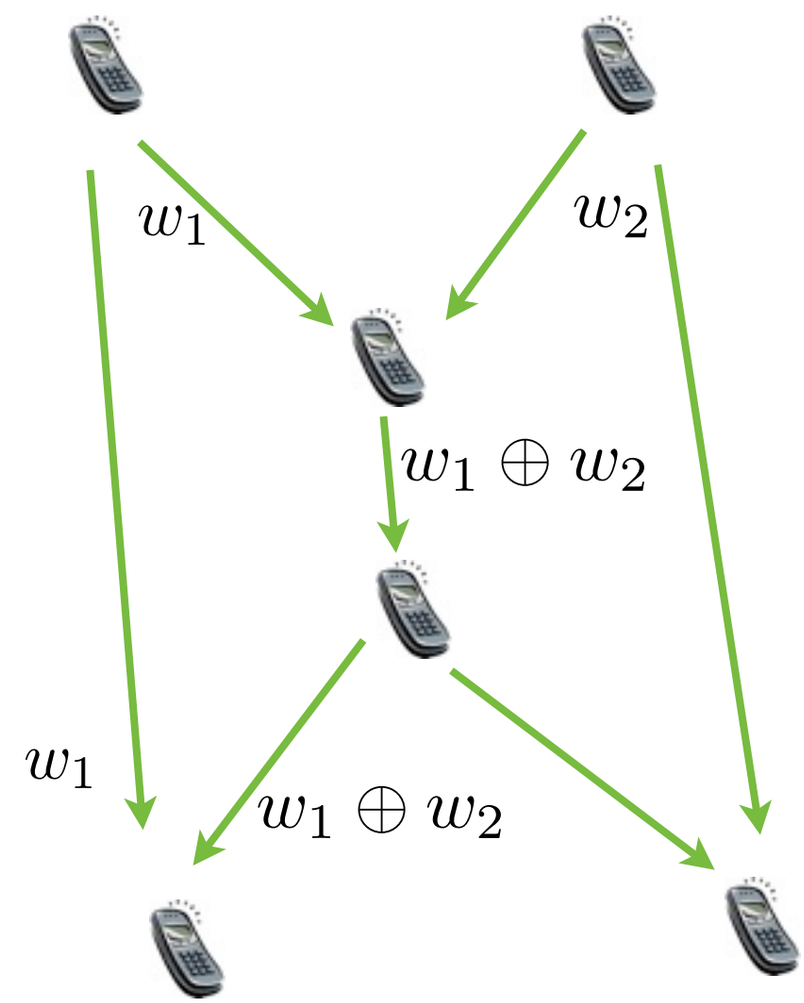
Network Coding with Relay

- Corina Ionita
  - Estimate
    - Conditional expectation
  - MAP detection
  - Uncoded/coded
  - Implementation on WARP

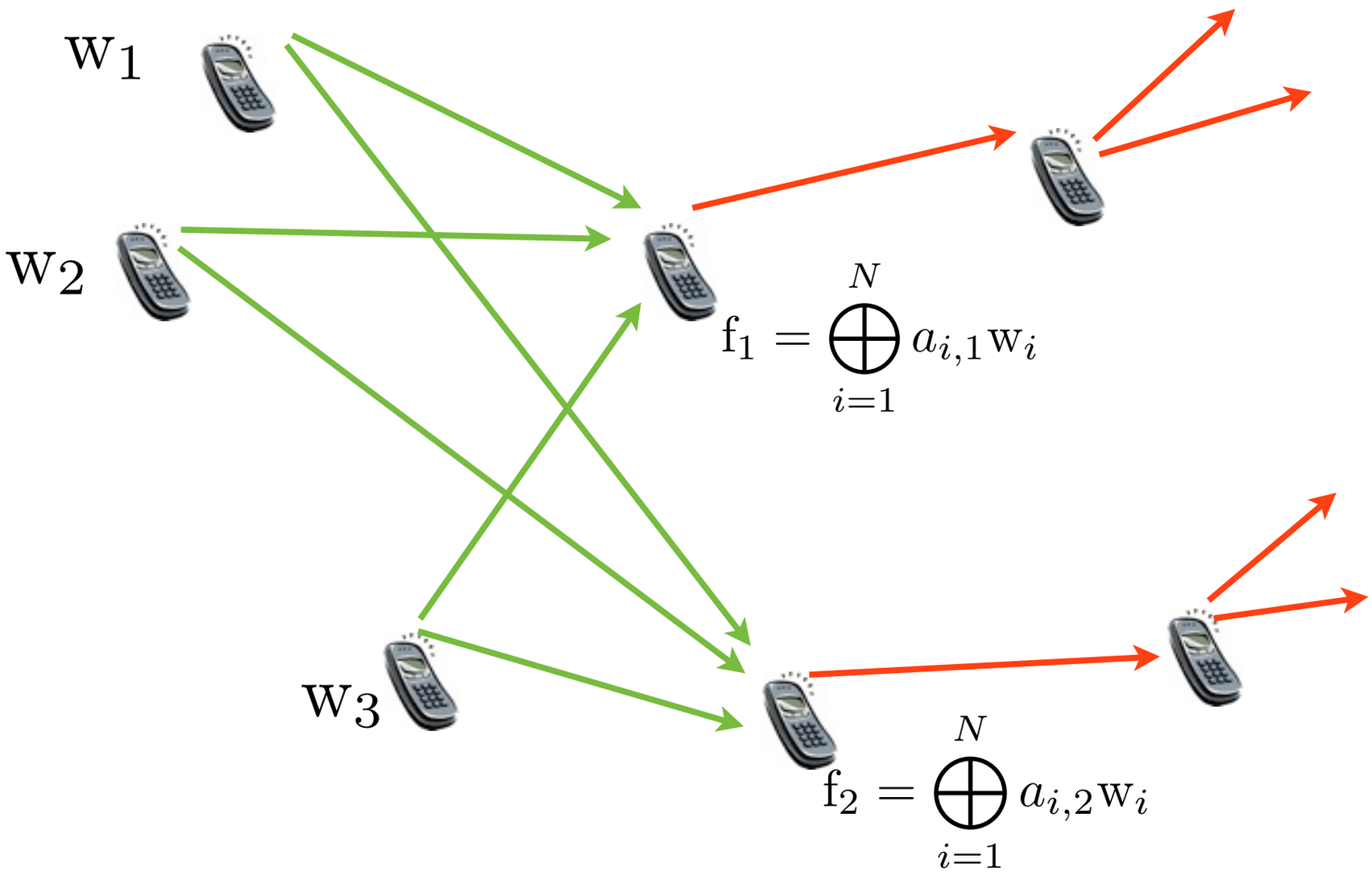


Network Coding

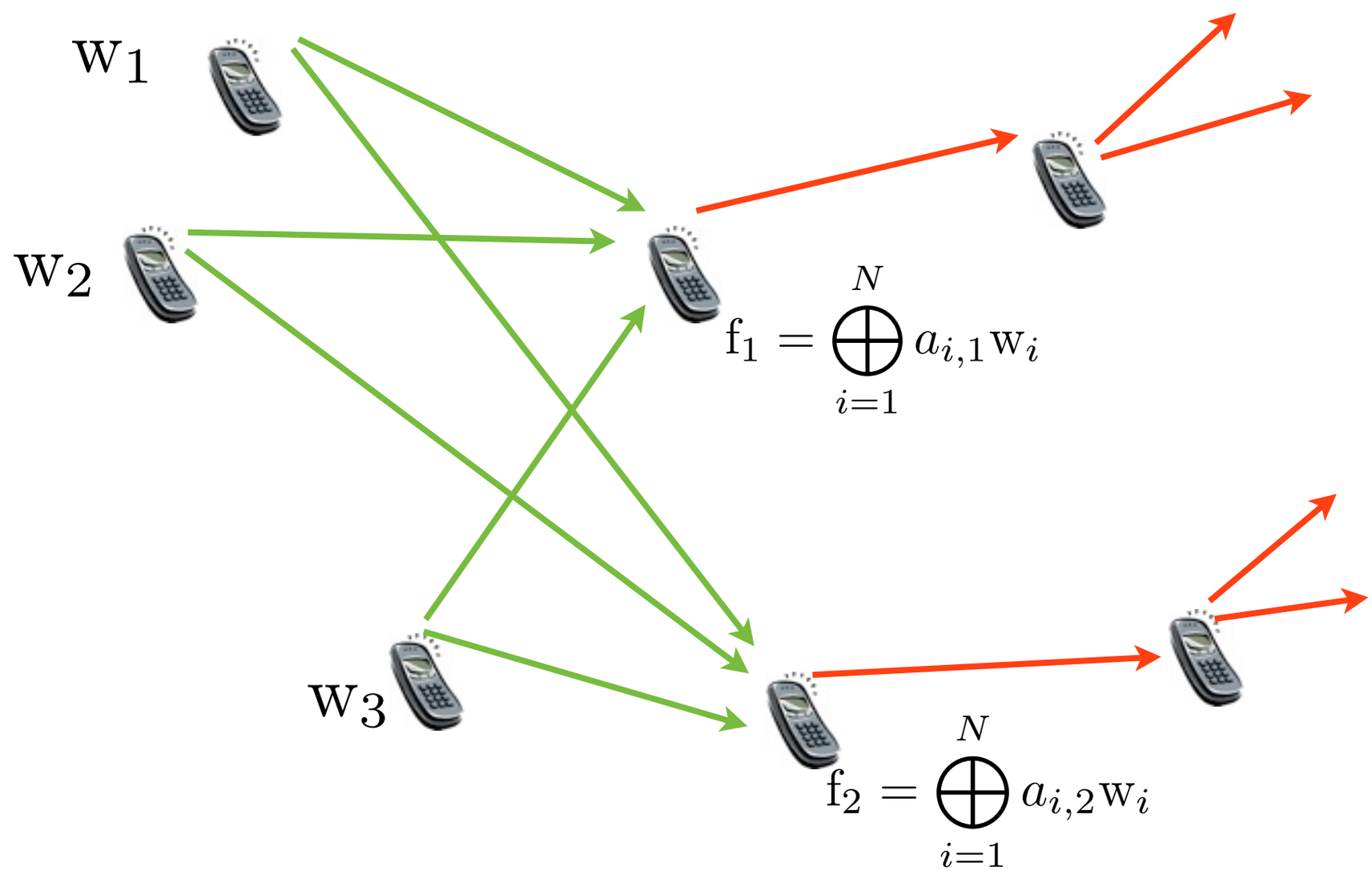
- Matt Nokleby



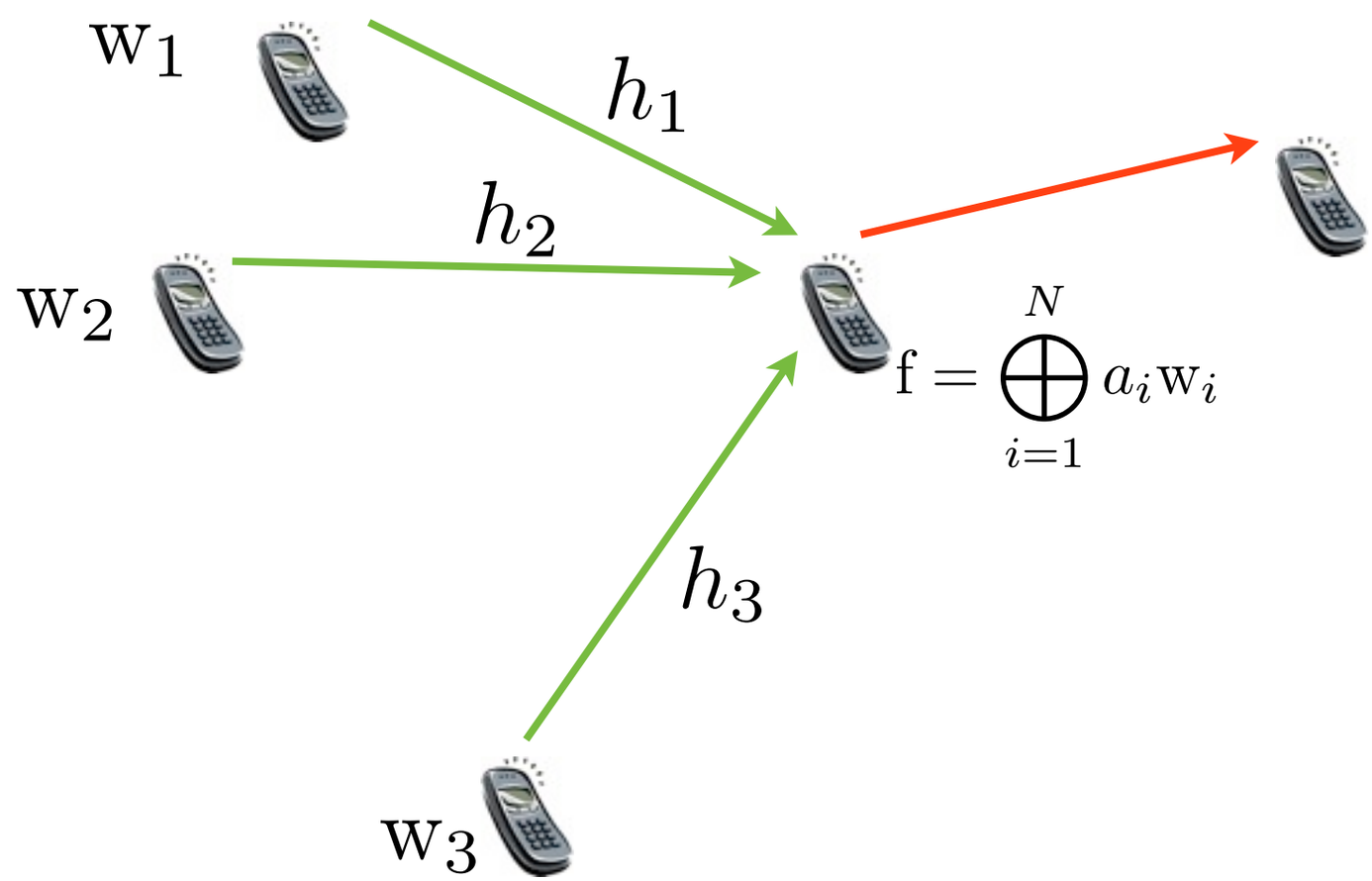
- Matt Nokleby



- Achievable "computation" rate [Nazer, Gasptar-2011]
  - Lattice codes
  - Only AWGN
- Fading?



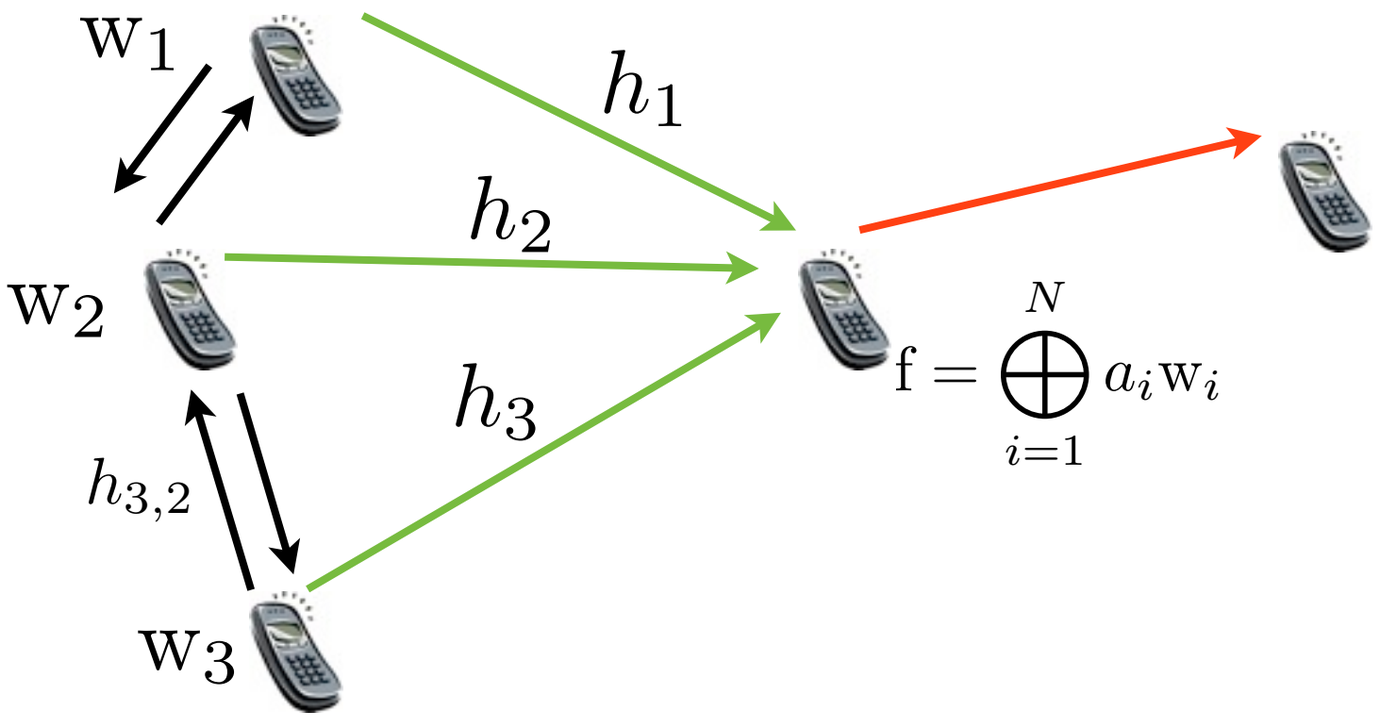
- Network coding
  - Fading
  - Chained



$$y = \sum_{i=1}^{N} h_i x_i + \mathrm{n}$$

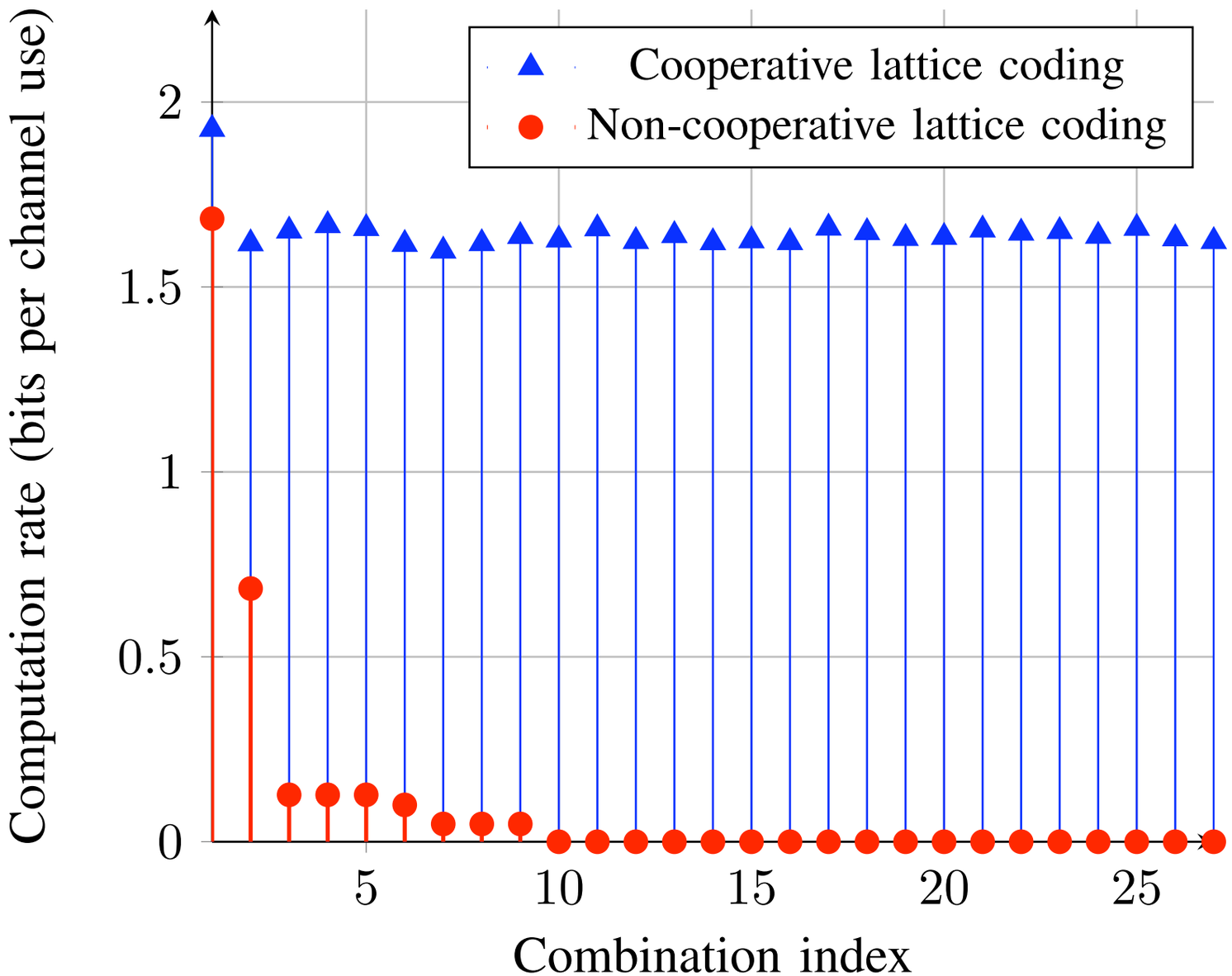
$$\text{Computation rate} \propto \log(\cdots < \underline{h}, \underline{a} >)$$

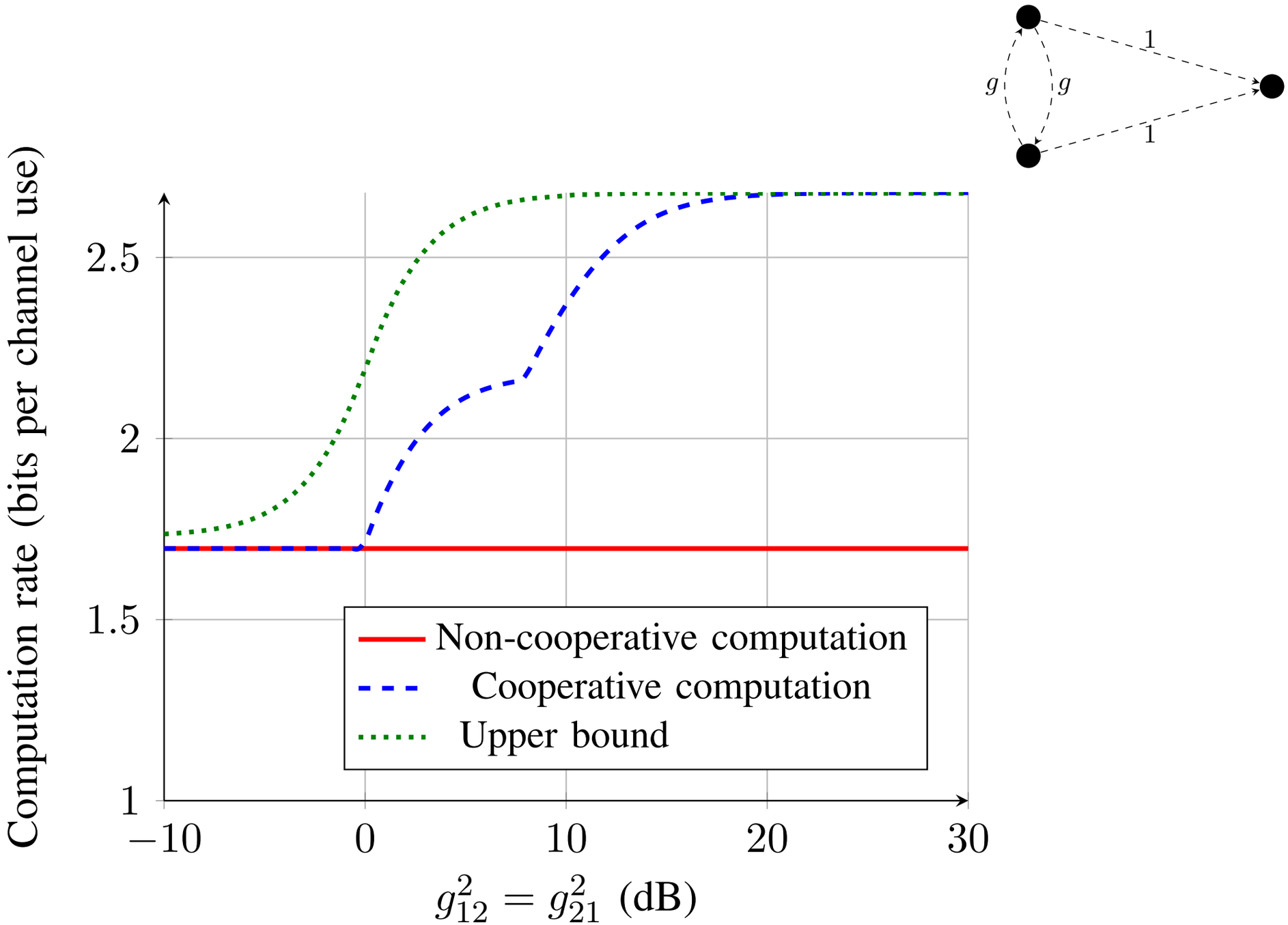
- Network coding
  - Fading
  - Chained



$$y = \sum_{i=1}^{N} h_i x_i + \mathrm{n}$$

$$y_j = \sum_{\substack{i=1 \\ i \neq j}}^{N} h_{i,j} x_i + \mathrm{n}_j$$


Cooperative lattice coding
Non-cooperative lattice coding
Computation rate (bits per channel use)
2
1.5
1
0.5
0
5
10
15
20
25
Combination index


1
g
g
1
Computation rate (bits per channel use)
2.5
2
1.5
1
−10
0
10
20
30
$g_{12}^2 = g_{21}^2$ (dB)
Non-cooperative computation
Cooperative computation
Upper bound

To Achieve

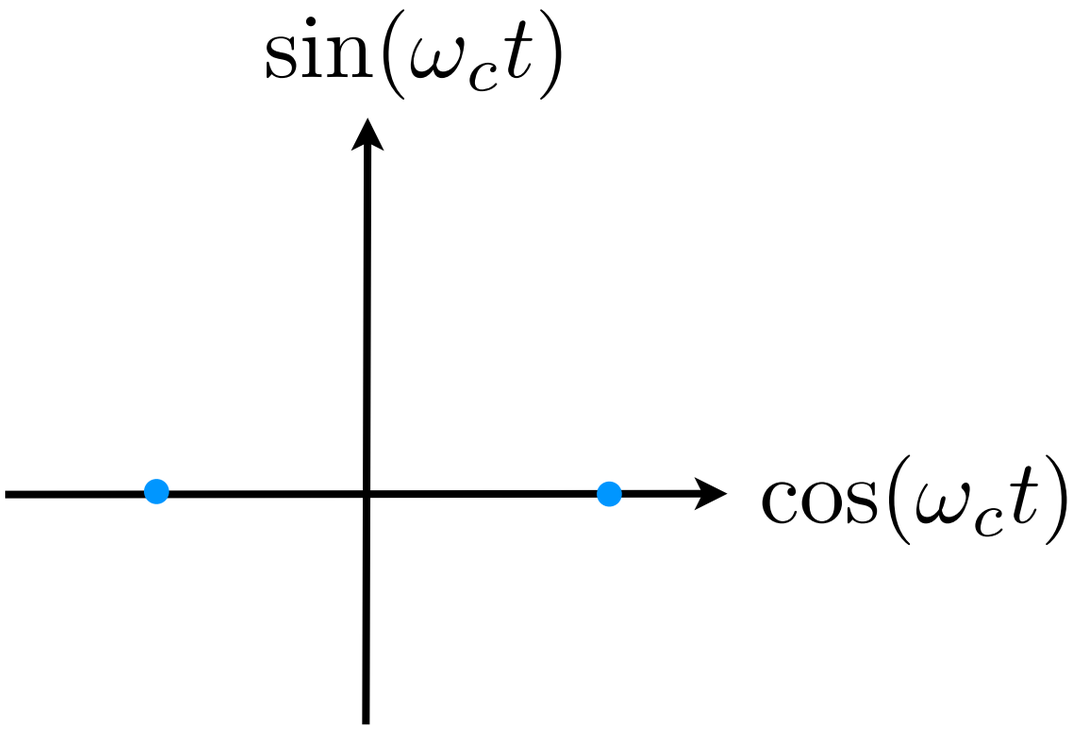
- Rates within a network
  - Coding and modulation
  - Medium to high SNR

To Achieve

- Rates within a network
  - Coding and modulation
  - Medium to high SNR
- Context
  - Interference
  - Cooperation
  - Side information

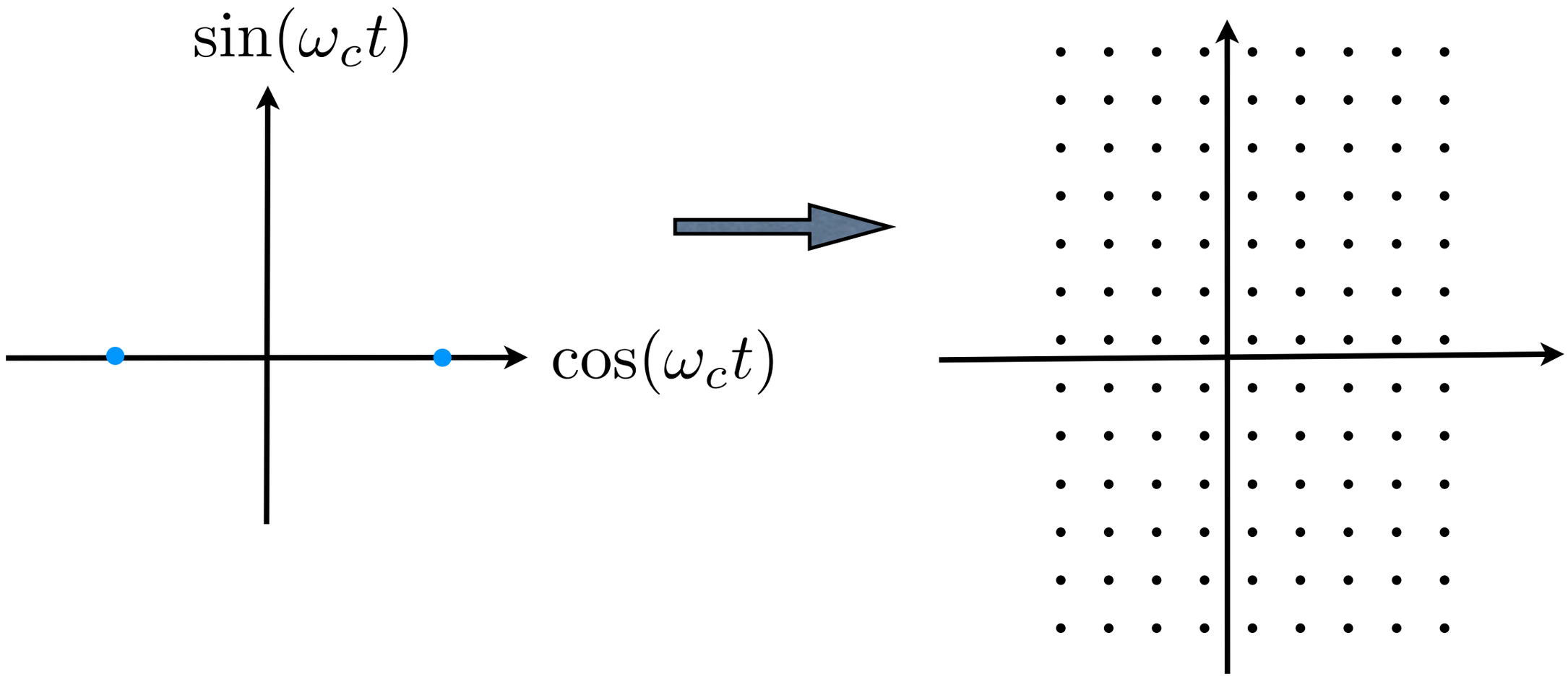
To Achieve

- BPSK?



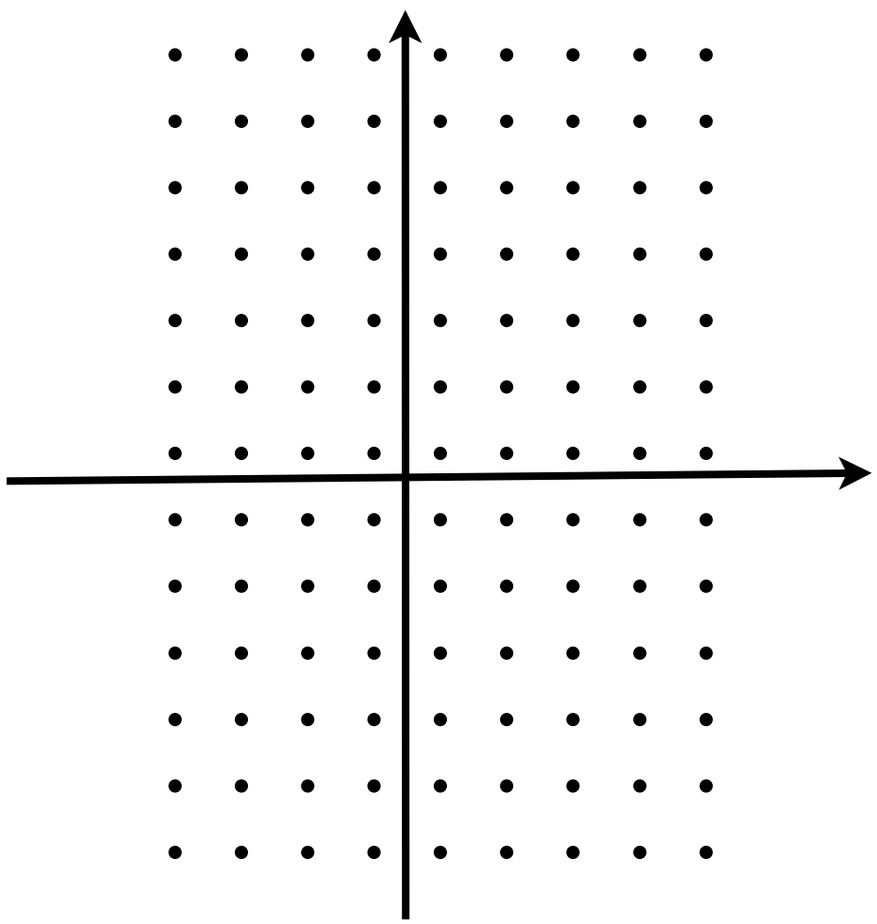
Background

- BPSK?
- Higher order modulation and coding



Background

- Integers on a plane
- Lattice is a subgroup of $\mathbb{R}^2$

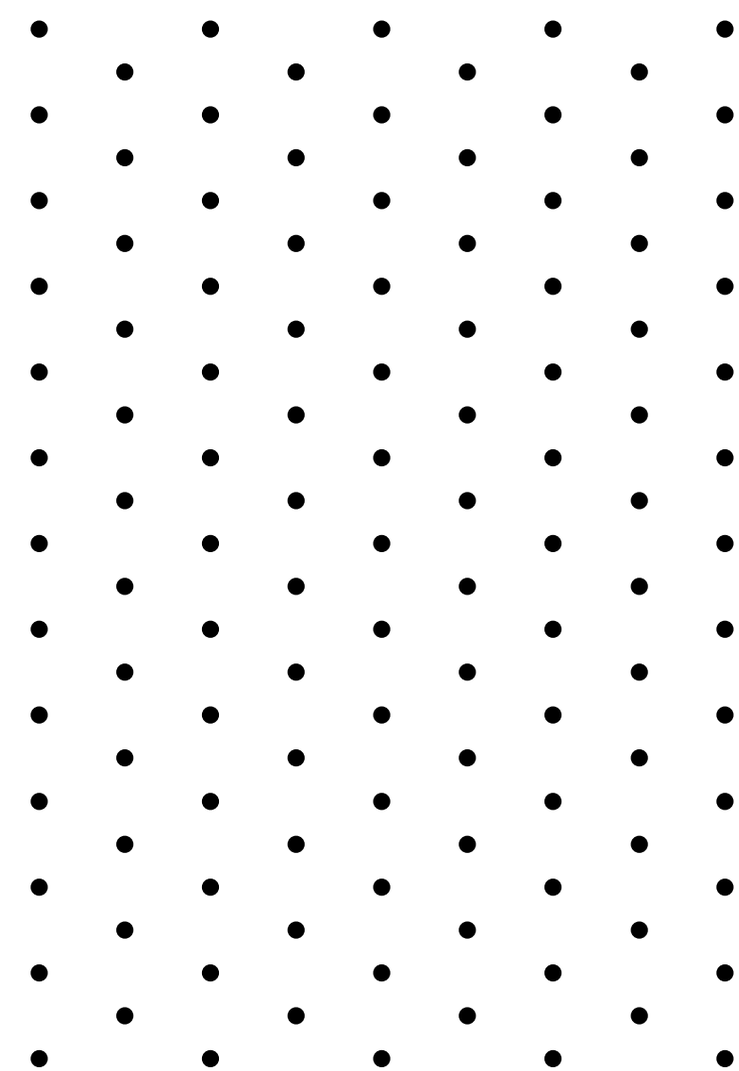


$\mathbb{Z}^n$ is a simple lattice.

Lattices

- An example of $B\mathbb{Z}^2$ in $\mathbb{R}^2$
- Imagine $\mathbb{Z}^n$ and $\mathbb{R}^n$
- Closed under addition
- Symmetric

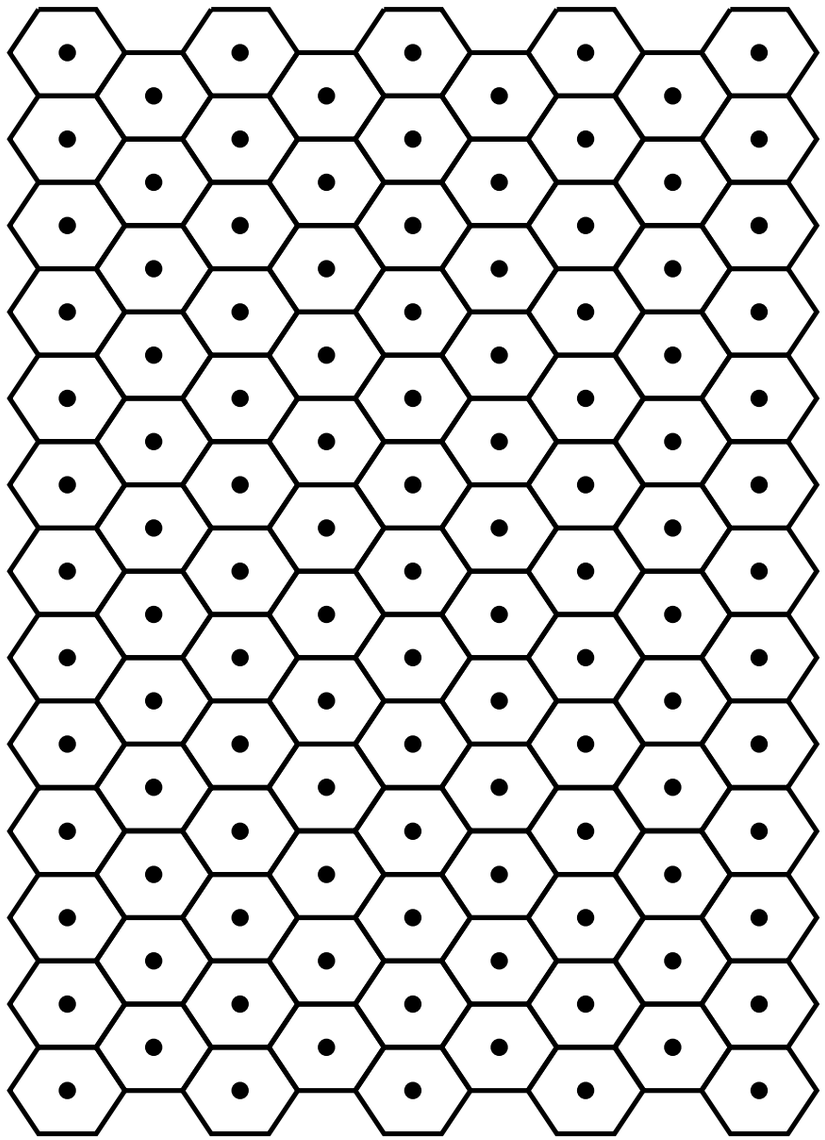
$$\lambda_1, \lambda_2 \in \Lambda \quad \Rightarrow \quad \lambda_1 + \lambda_2 \in \Lambda$$
$$\lambda \in \Lambda \quad \Rightarrow \quad -\lambda \in \Lambda$$



$\mathbf{B}\mathbb{Z}^n$

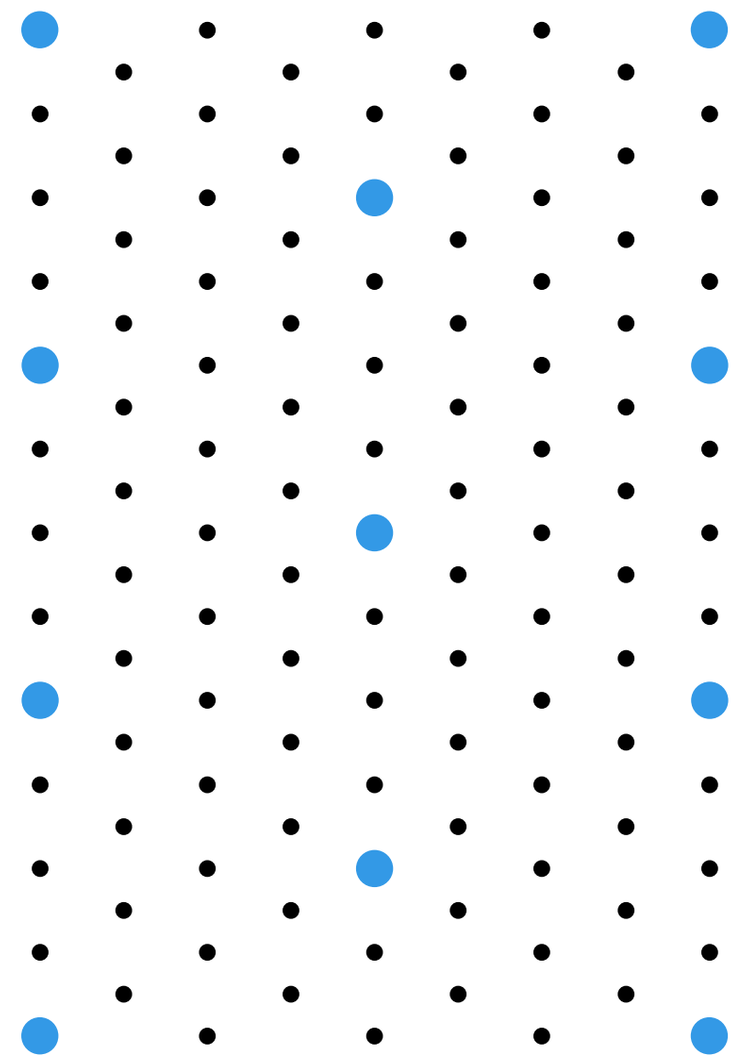
Decoding

- Decision boundary
  - Hexagonal

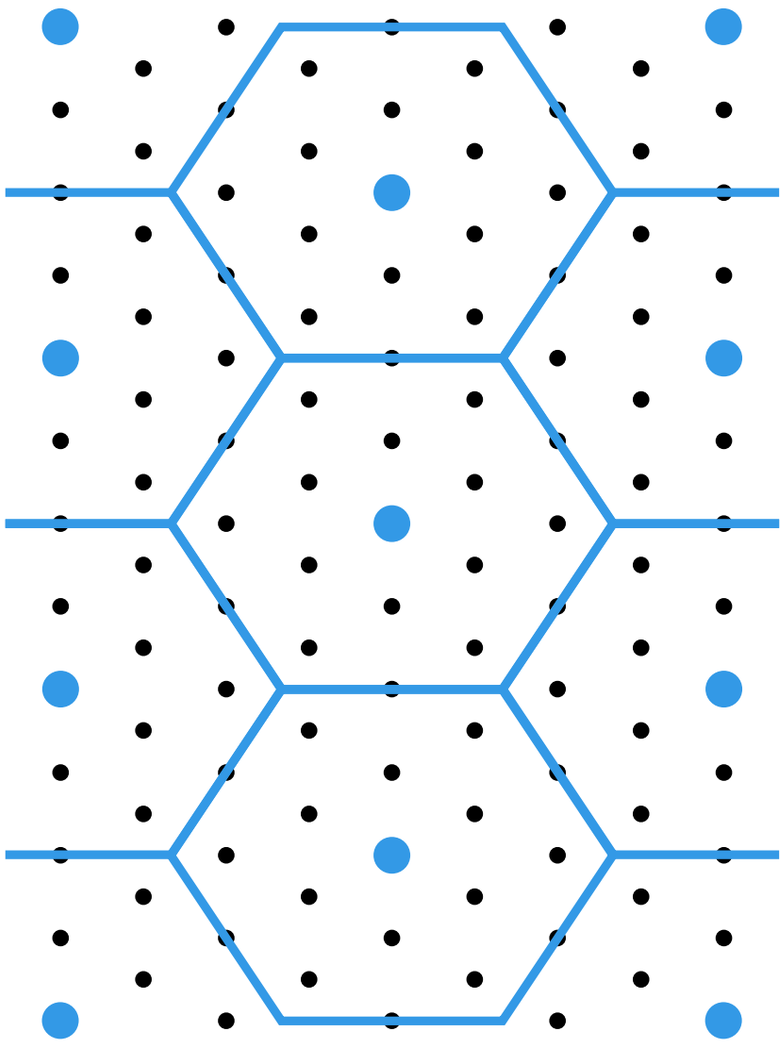


Nested Lattice

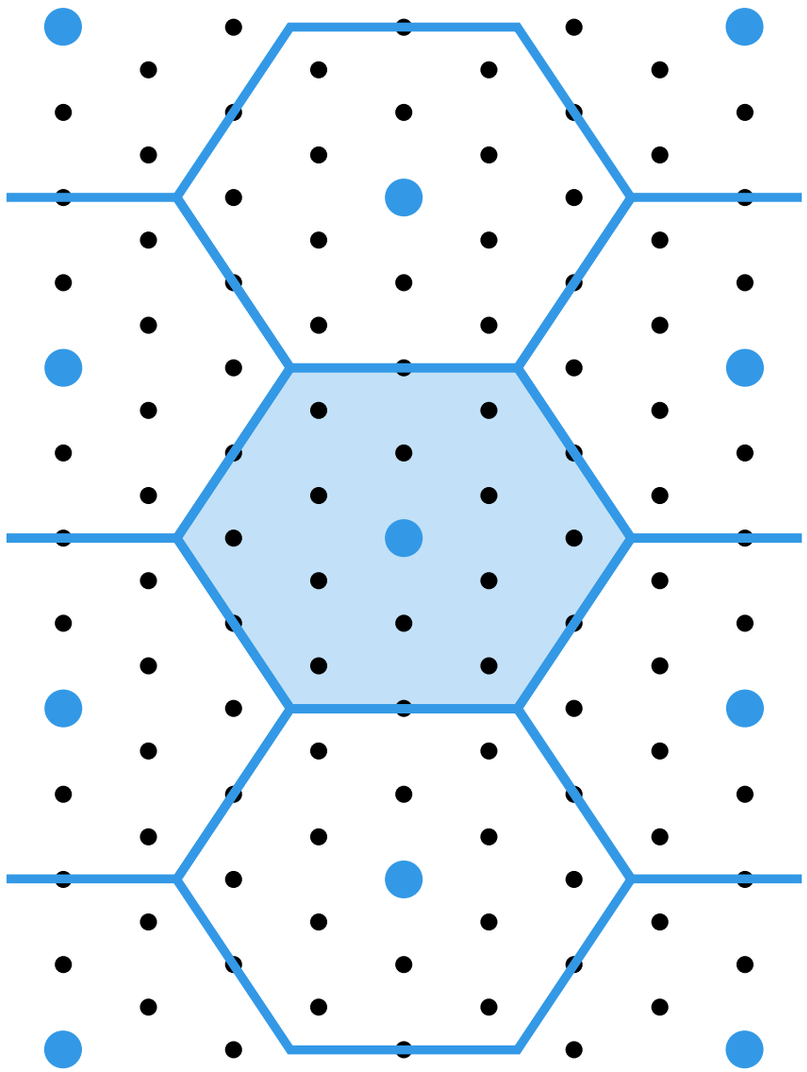
- Lattice and sublattice



Nested Lattice

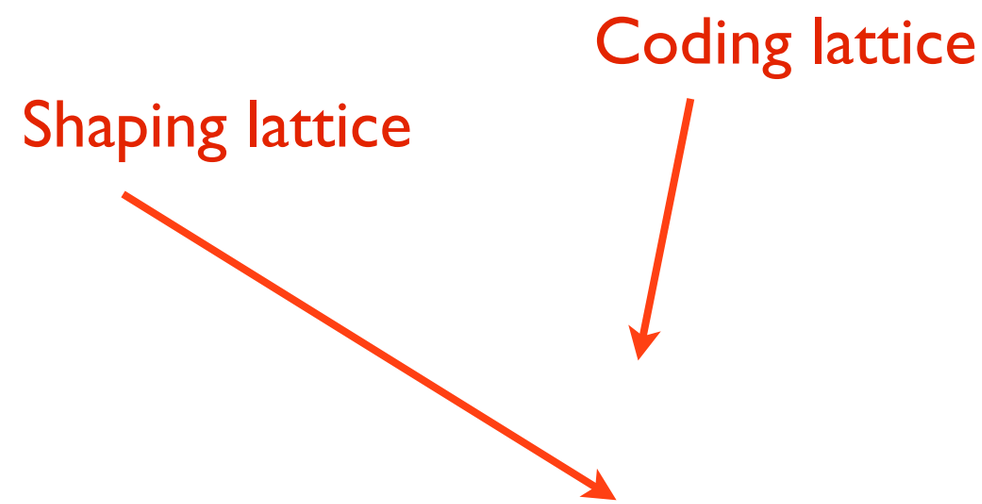


- Power constrained



Lattice Coding

- Large dimensional coded modulation with power constraint



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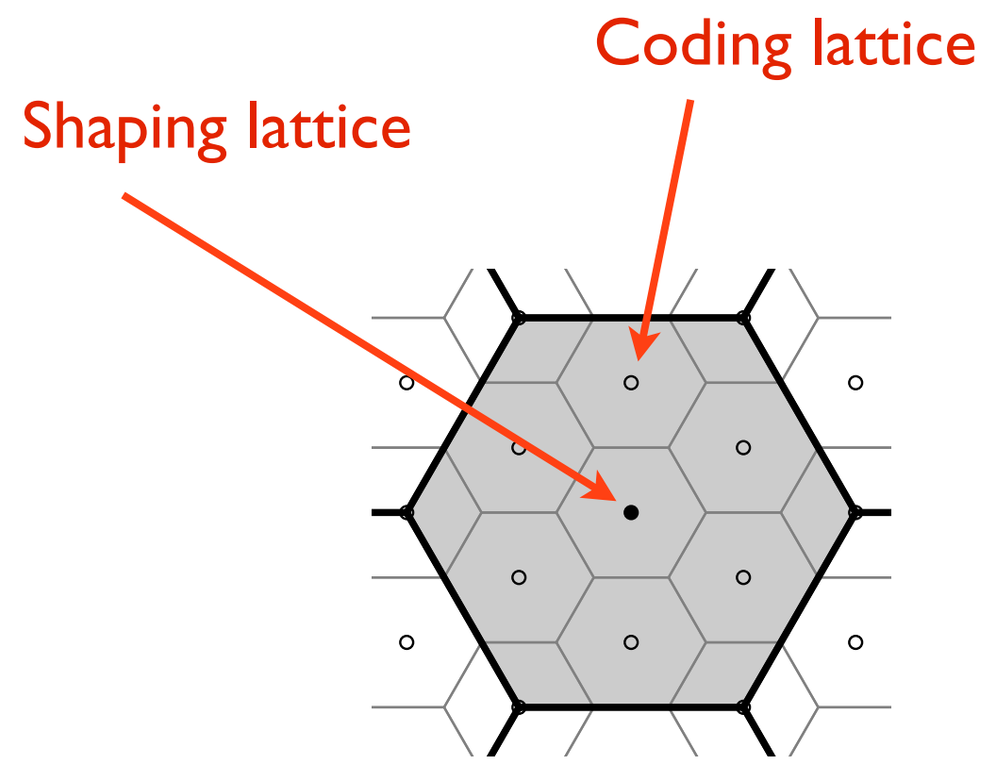
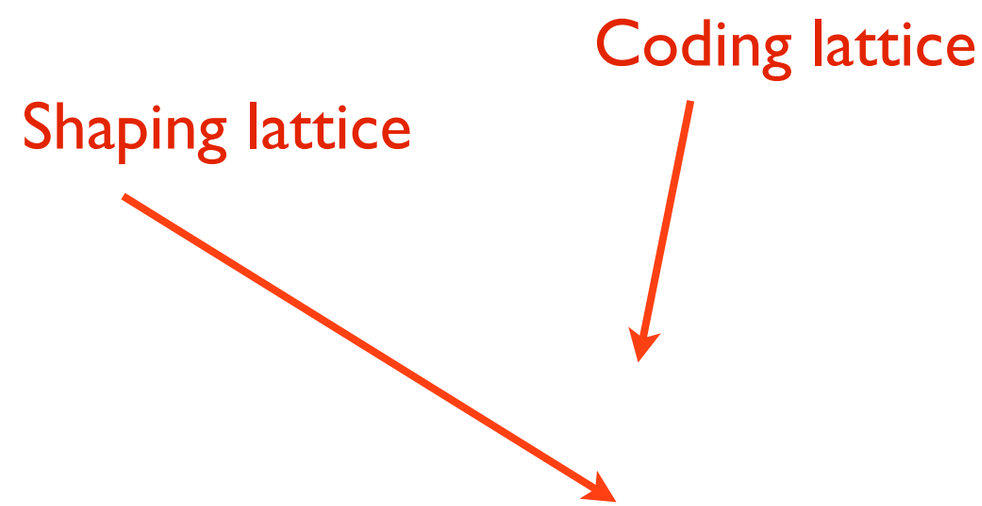


Lattice Coding

- Large dimensional coded modulation with power constraint
- Coding lattice is fine
- Shaping lattice is coarse



$$\Lambda_s \subset \Lambda_c$$

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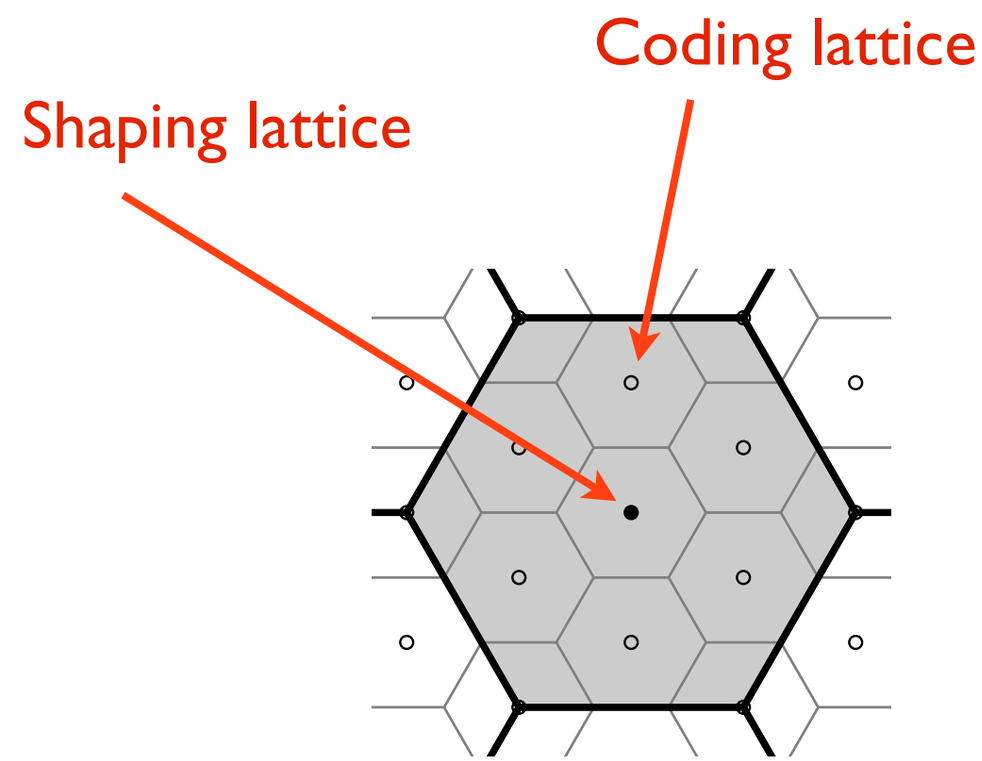

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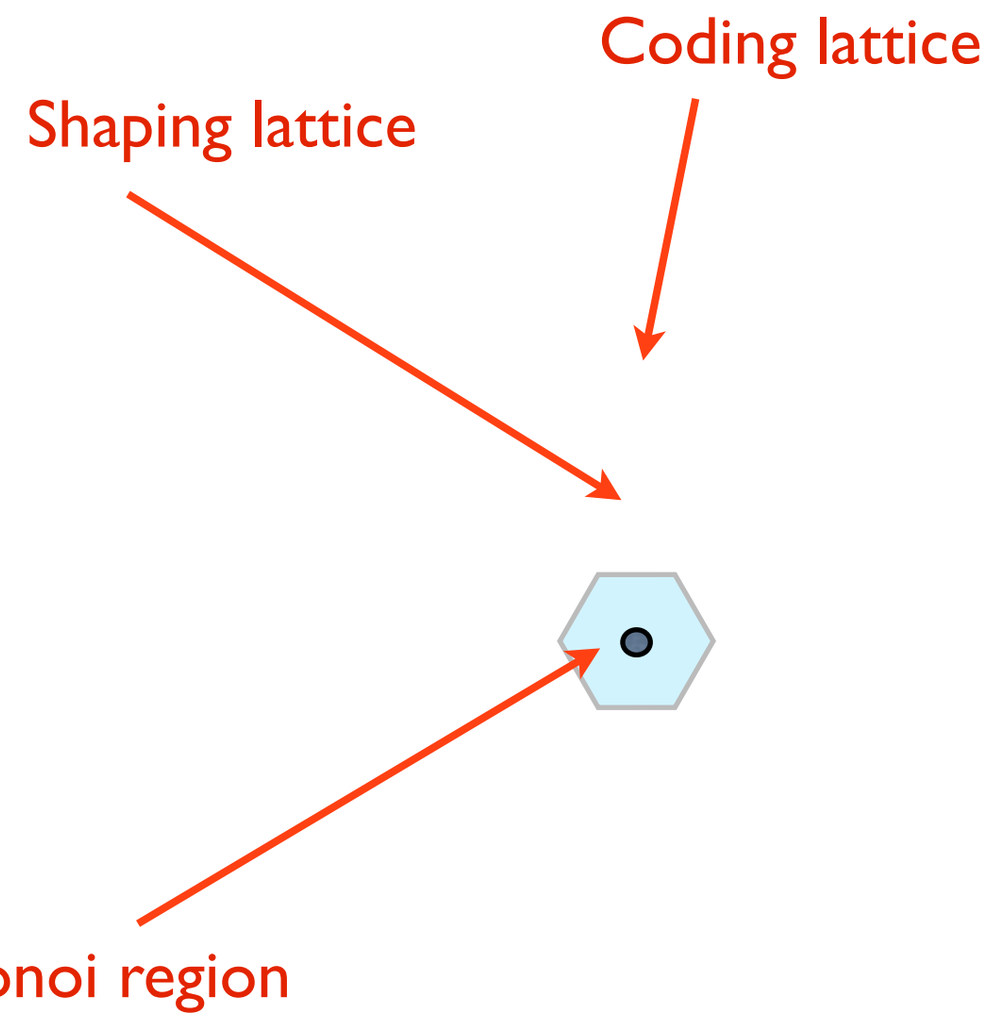

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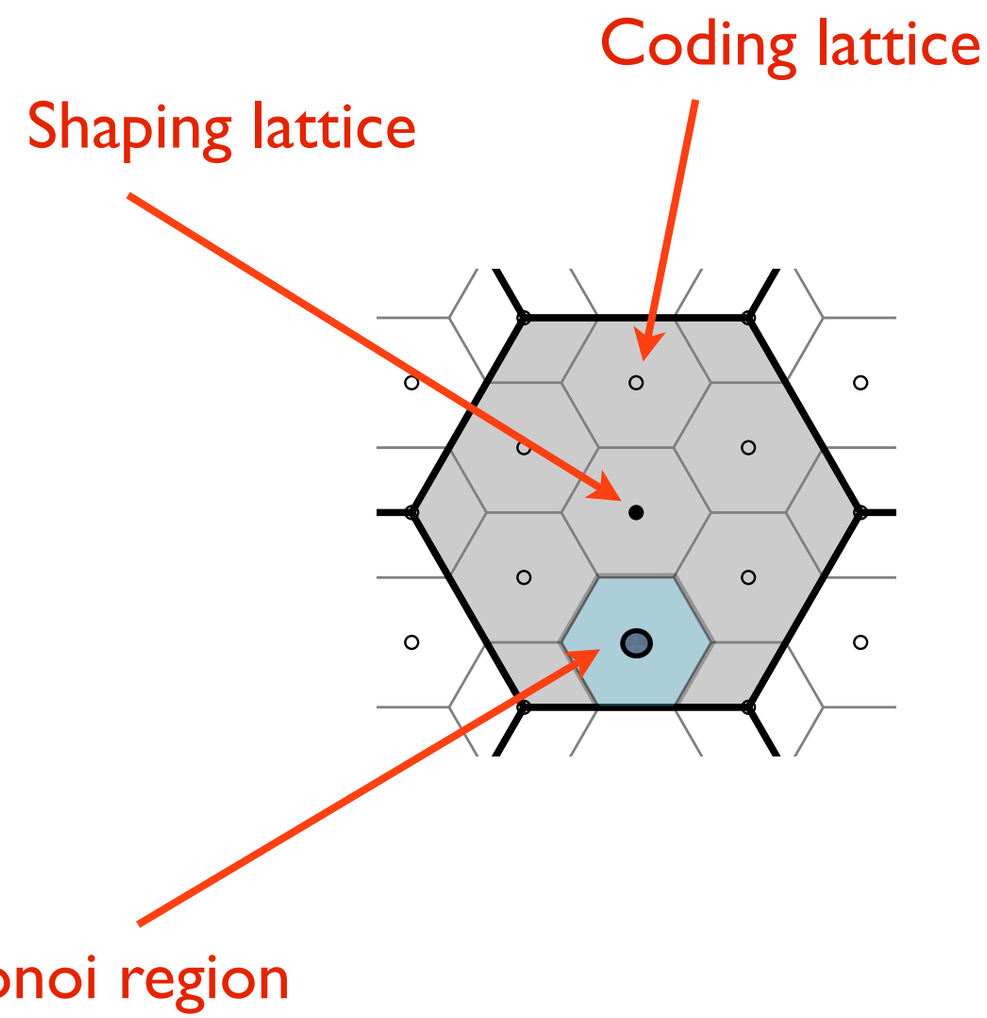

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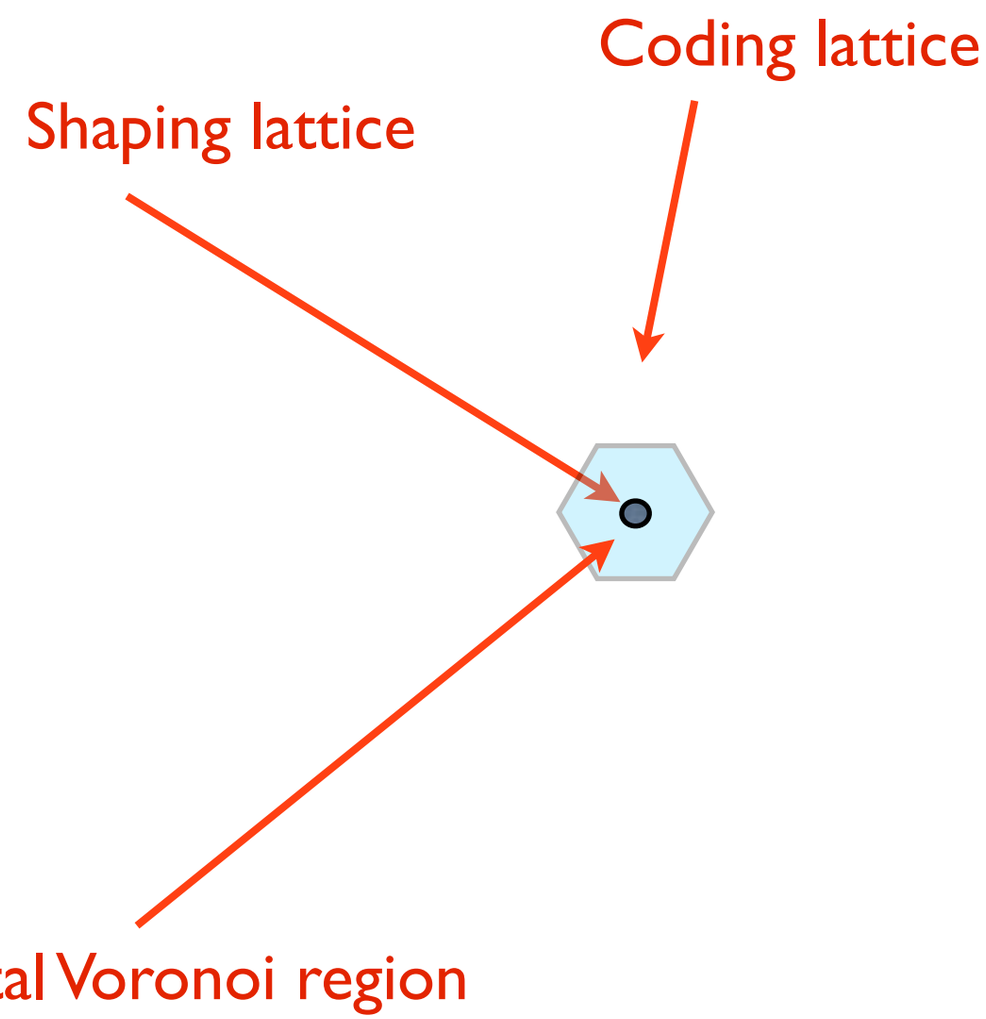

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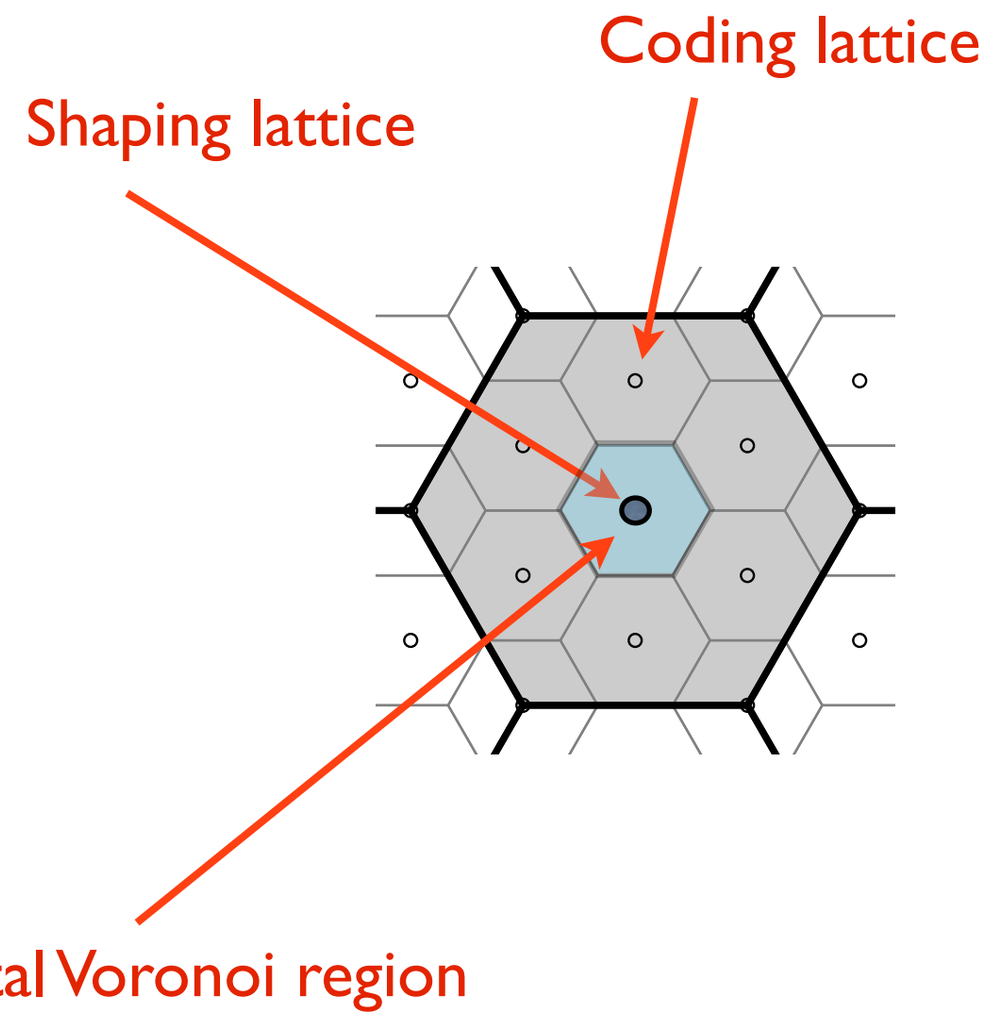
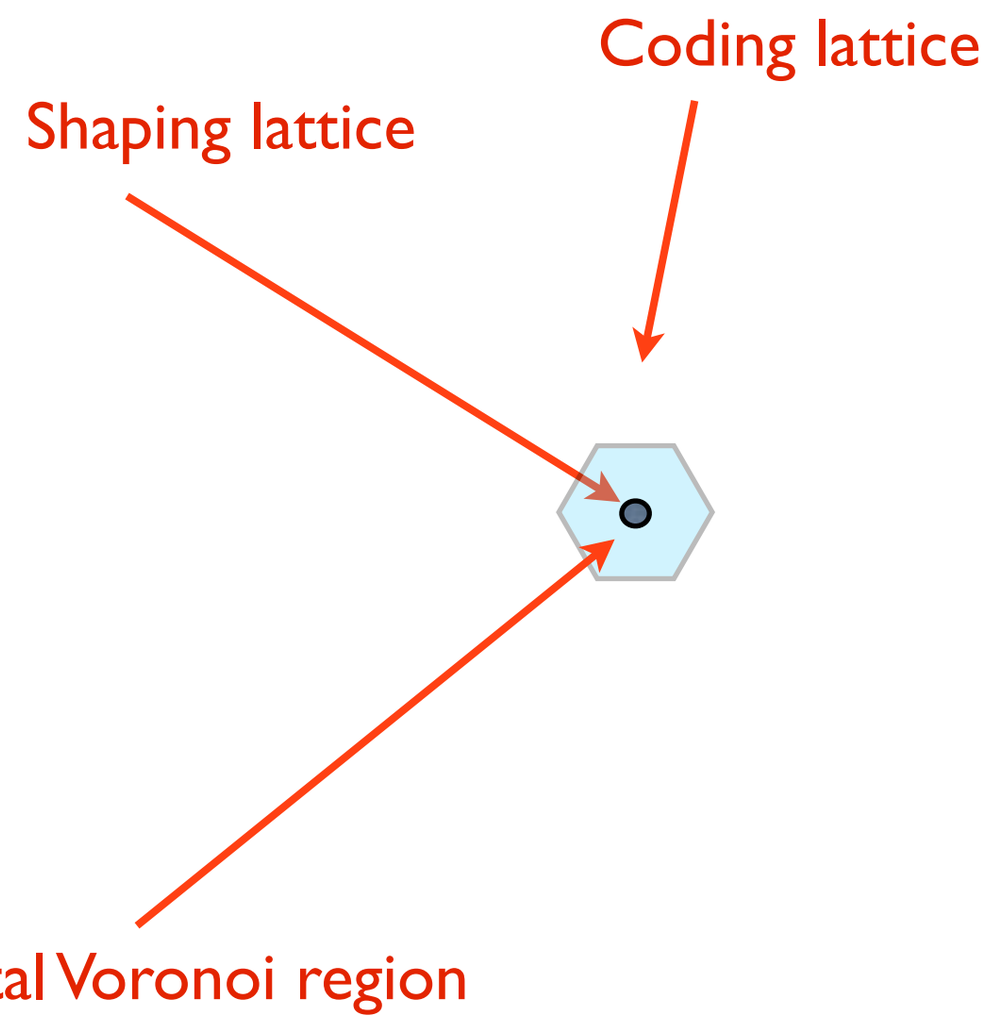


Lattice Coding

- Large dimensional coded modulation with power constraint

$$\begin{aligned} \Lambda_s &\subset \Lambda_c \\ \mathrm{Vol}(\mathcal{V}_s) &> \mathrm{Vol}(\mathcal{V}_c) \end{aligned}$$



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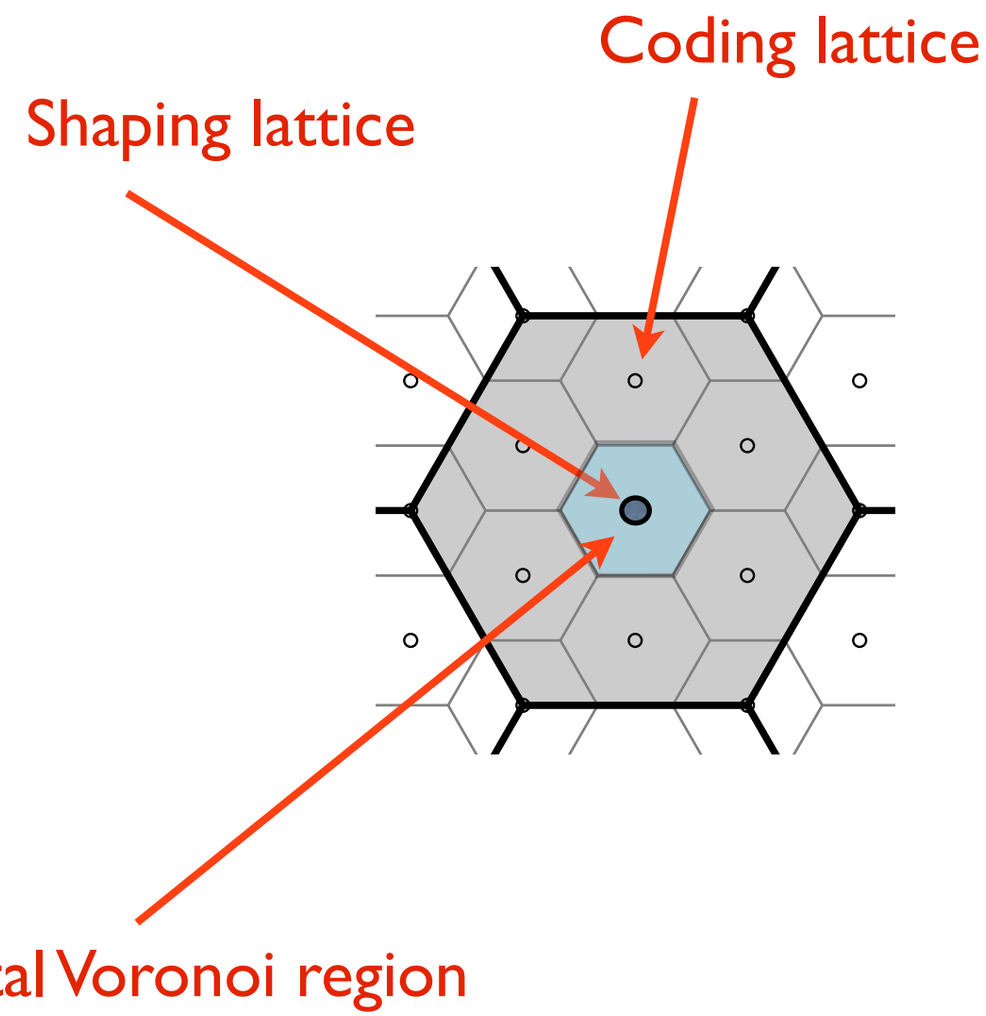
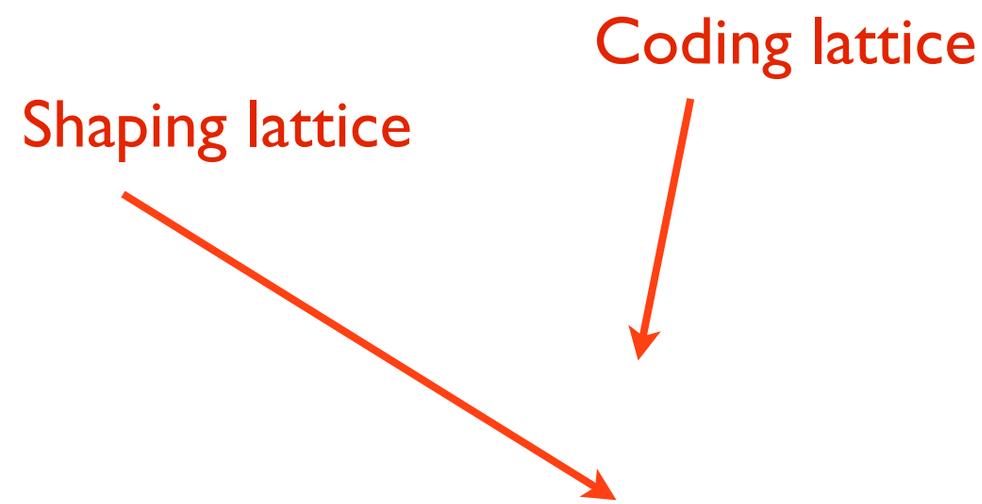


Lattice Coding

- Large dimensional coded modulation with power constraint Lattice codes
- Isomorphism



$$\mathrm{w} \Leftrightarrow \lambda \mod \Lambda_s$$

Lattice Coding

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$$\phi(\mathbf{w}) = \lambda$$

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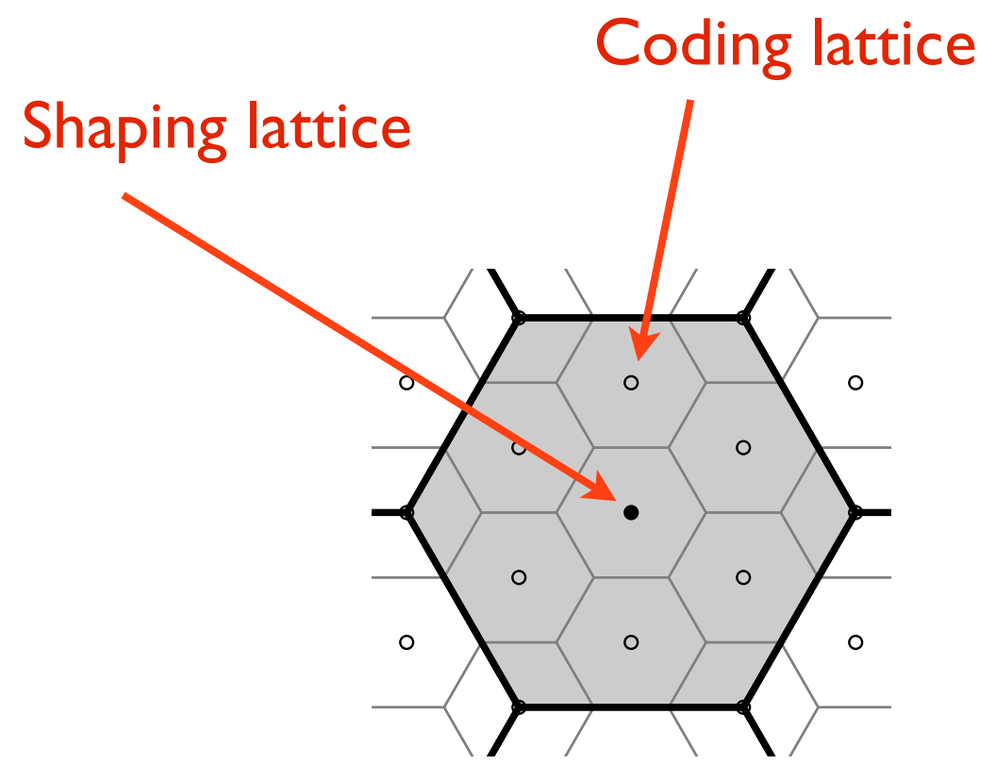
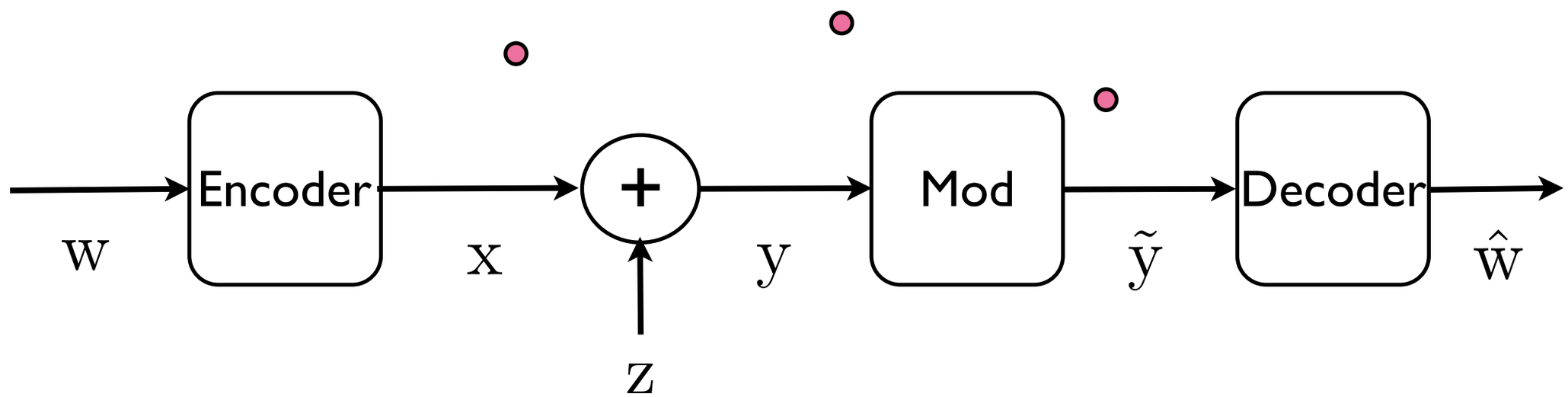


System



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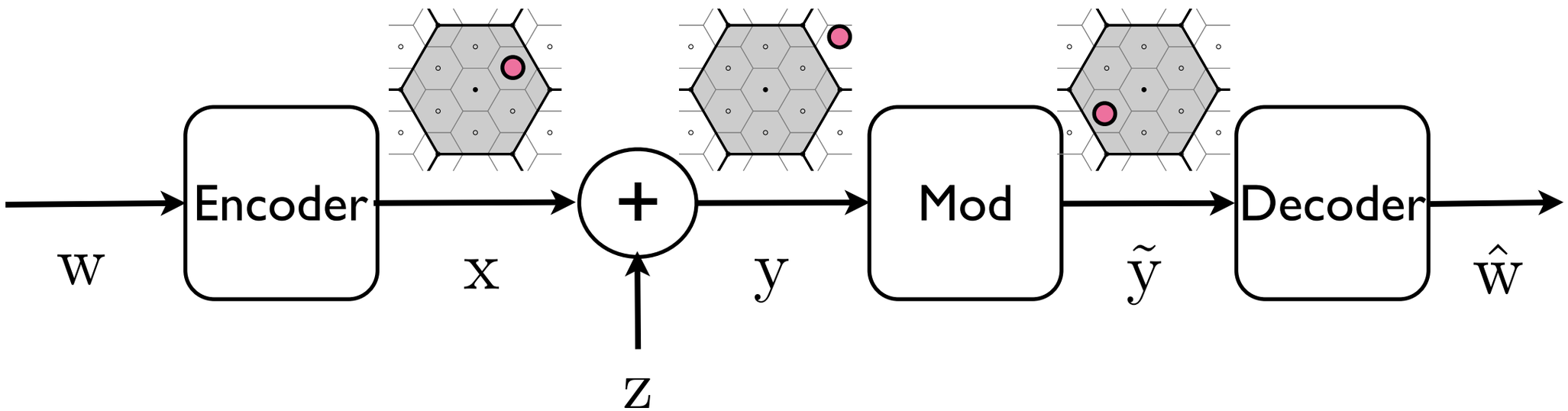
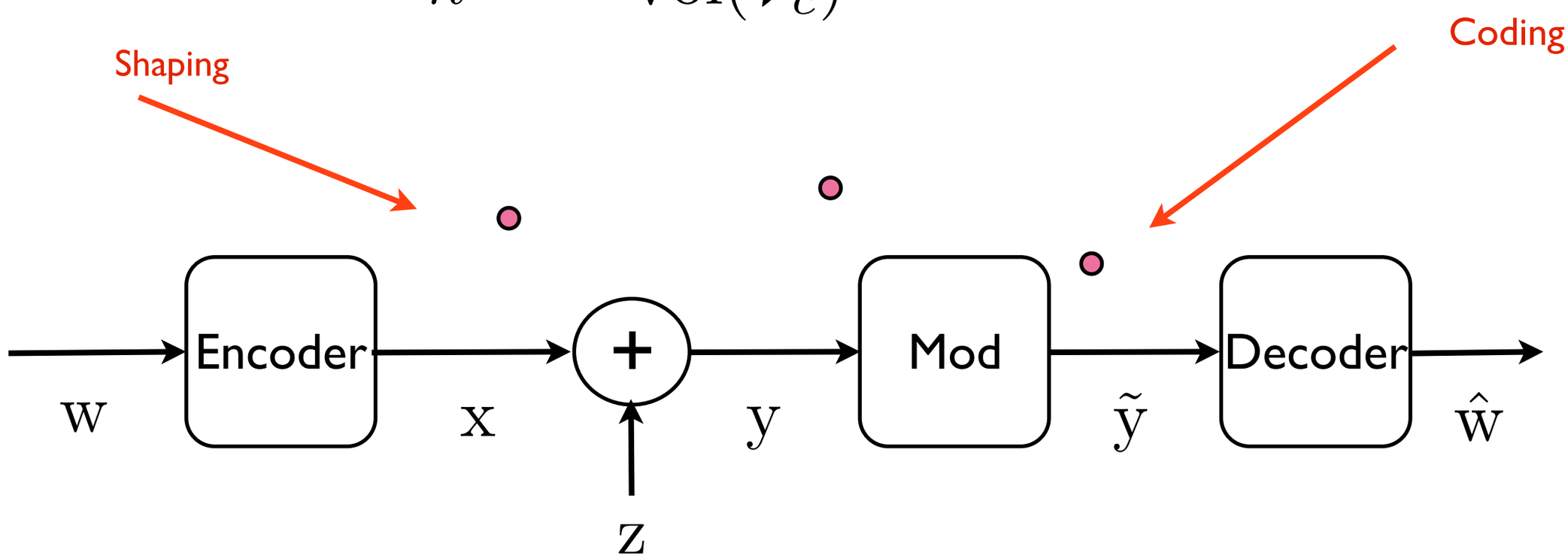


Rate and Error

- The probability of error $\mathbb{P}\{\mathrm{w} \neq \hat{\mathrm{w}}\} \to 0 \quad \text{as} \quad n + \infty$
- The rate

$$\text{Rate} = \frac{1}{n} \log \left(\frac{\text{Vol}(\mathcal{V}_s)}{\text{Vol}(\mathcal{V}_c)} \right)$$



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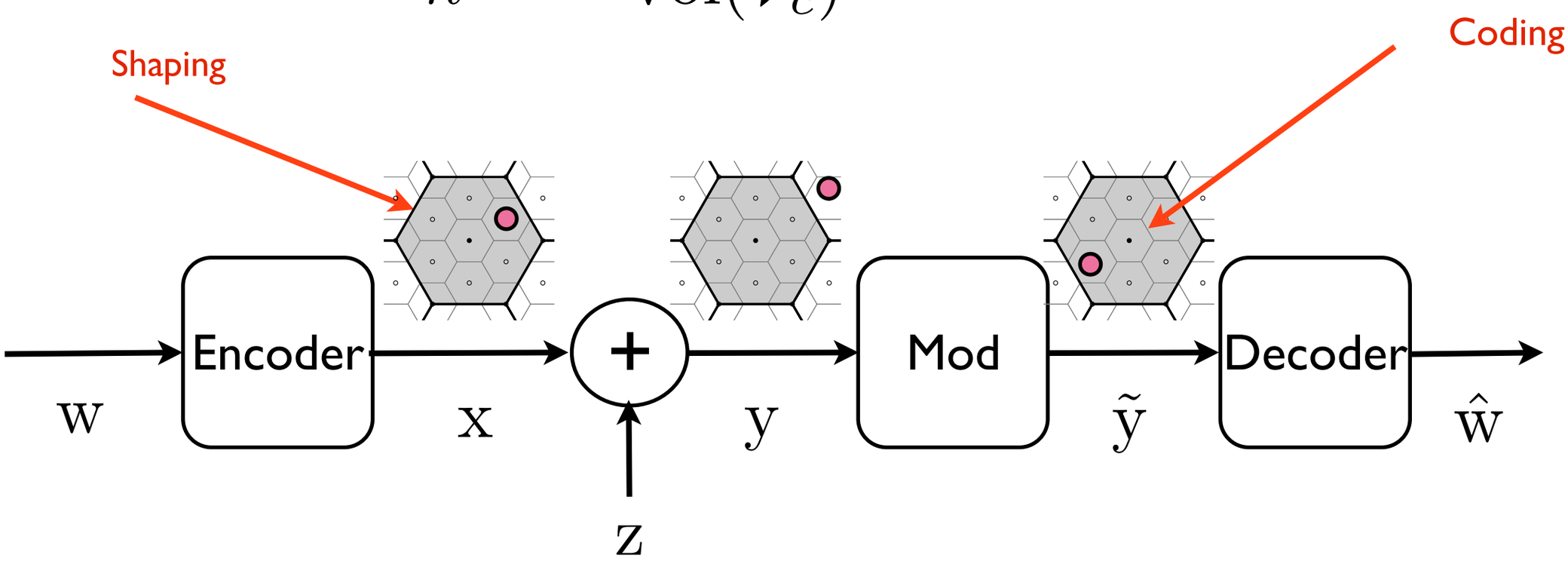
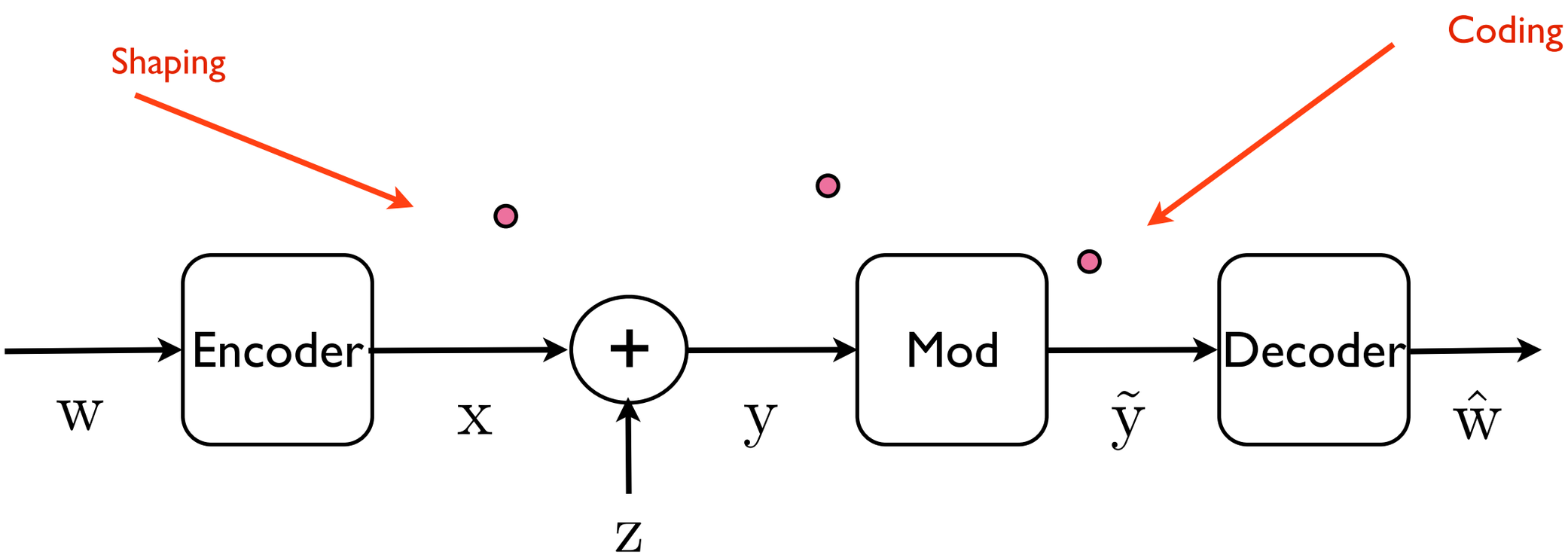


Encoding

- Mapping from p-ary to integers
- Isomorphism $\mathrm{x} = G\lambda \mod \Lambda_s$



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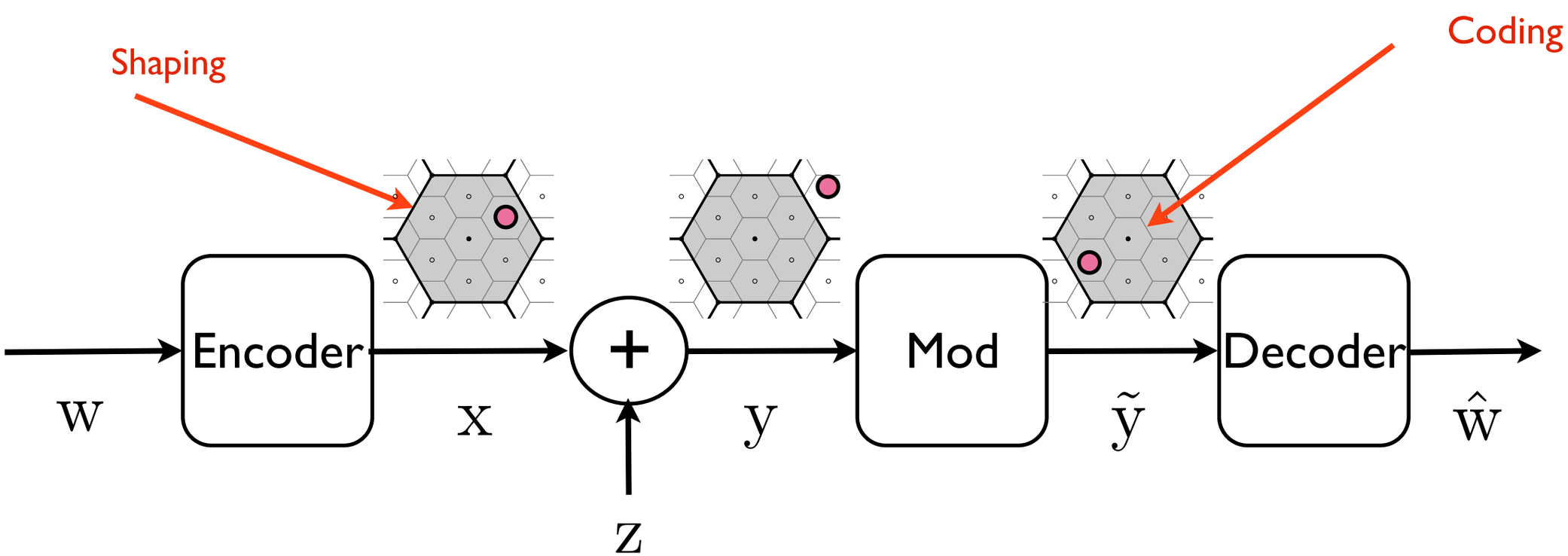


Linear Coding

- The generator matrix $G \in \mathbb{R}^{n \times n}$
- The parity check matrix $H = G^{-1} \in \mathbb{R}^{n \times n}$
  - Sparse H

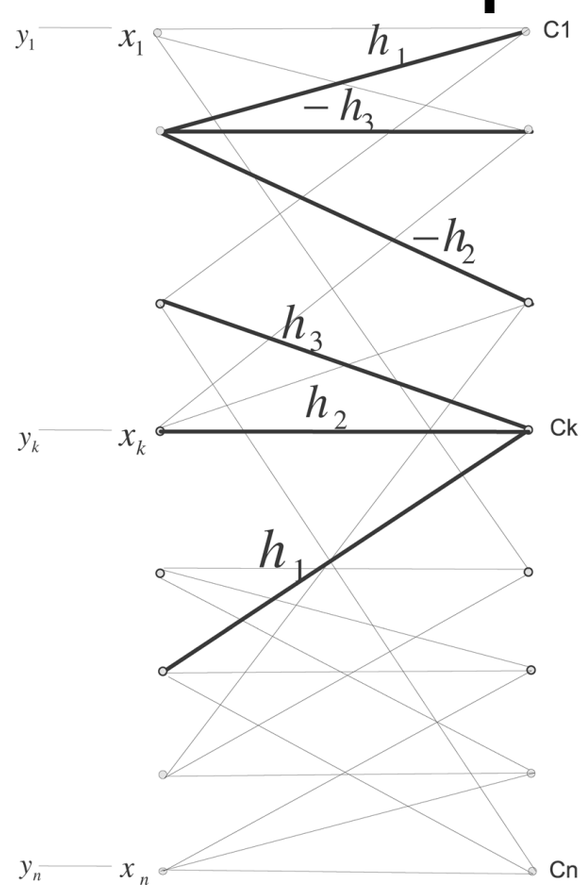
Low Density Lattice Codes (LDLC)

- Sparse non-binary parity check matrix
- Example [Sommer, Feder, Shalvi-2008]
  - Regular latin square with degree 3

$$H = \begin{pmatrix} 0 & -0.8 & 0 & -0.5 & 1 & 0 \\ 0.8 & 0 & 0 & 1 & 0 & -0.5 \\ 0 & 0.5 & 1 & 0 & 0.8 & 0 \\ 0 & 0 & -0.5 & -0.8 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0.5 & 0.8 \\ 0.5 & -1 & -0.8 & 0 & 0 & 0 \end{pmatrix}$$

LDLC

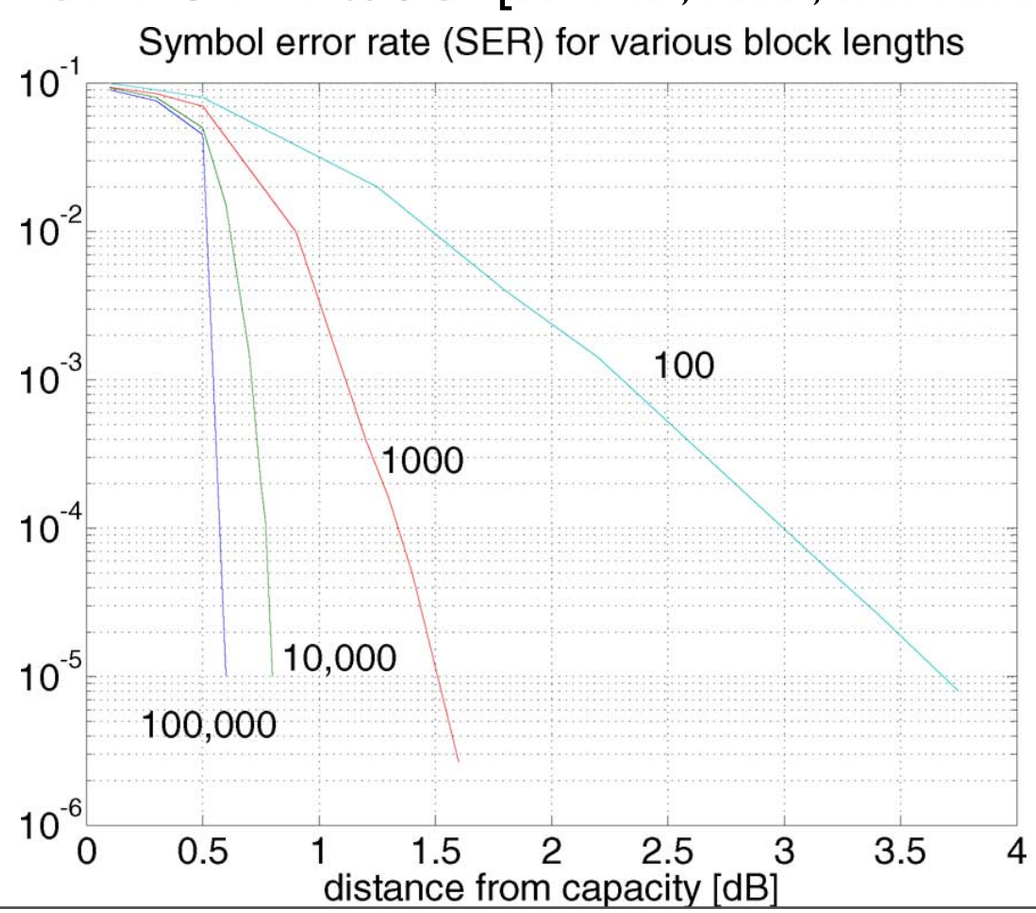
- Encoding complexity linear in n
- Iterative decoding with complexity linear in n
  - Bipartite graphical decoding [Sommer, Feder, Shalvi-2008]



$$
\begin{aligned}
H\mathrm{x} &= HG\lambda \\
\sum_k h_k x_{i_k} &= \text{integer}
\end{aligned}
$$

LDLC

- Degree 5 for n=100 and 7 for others
- Iterations <200
- Symbol error rate [Sommer, Feder, Shalvi-2008]

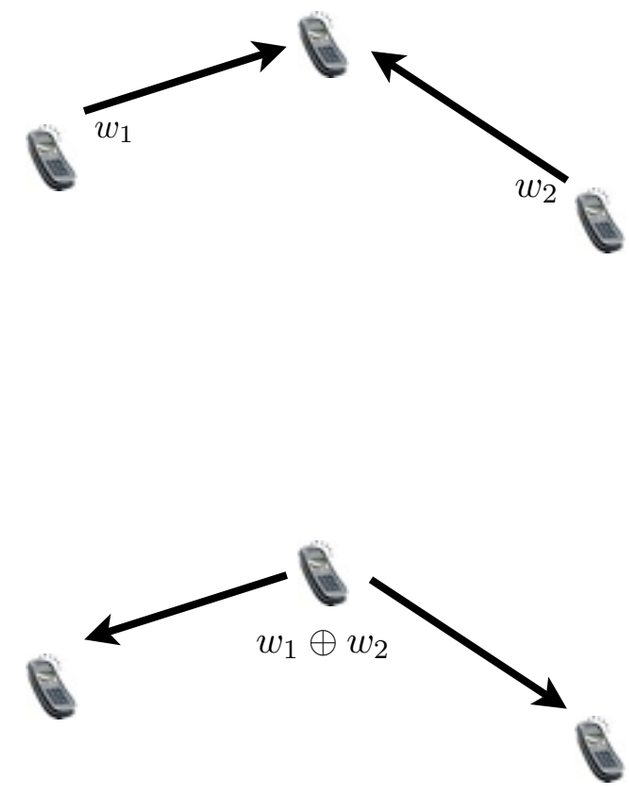


LDLC

- Effective in medium to high SNR
- Relatively simple encoding and decoding
- Linear structure
- Superposition
- Decomposable
- Amenable to side information

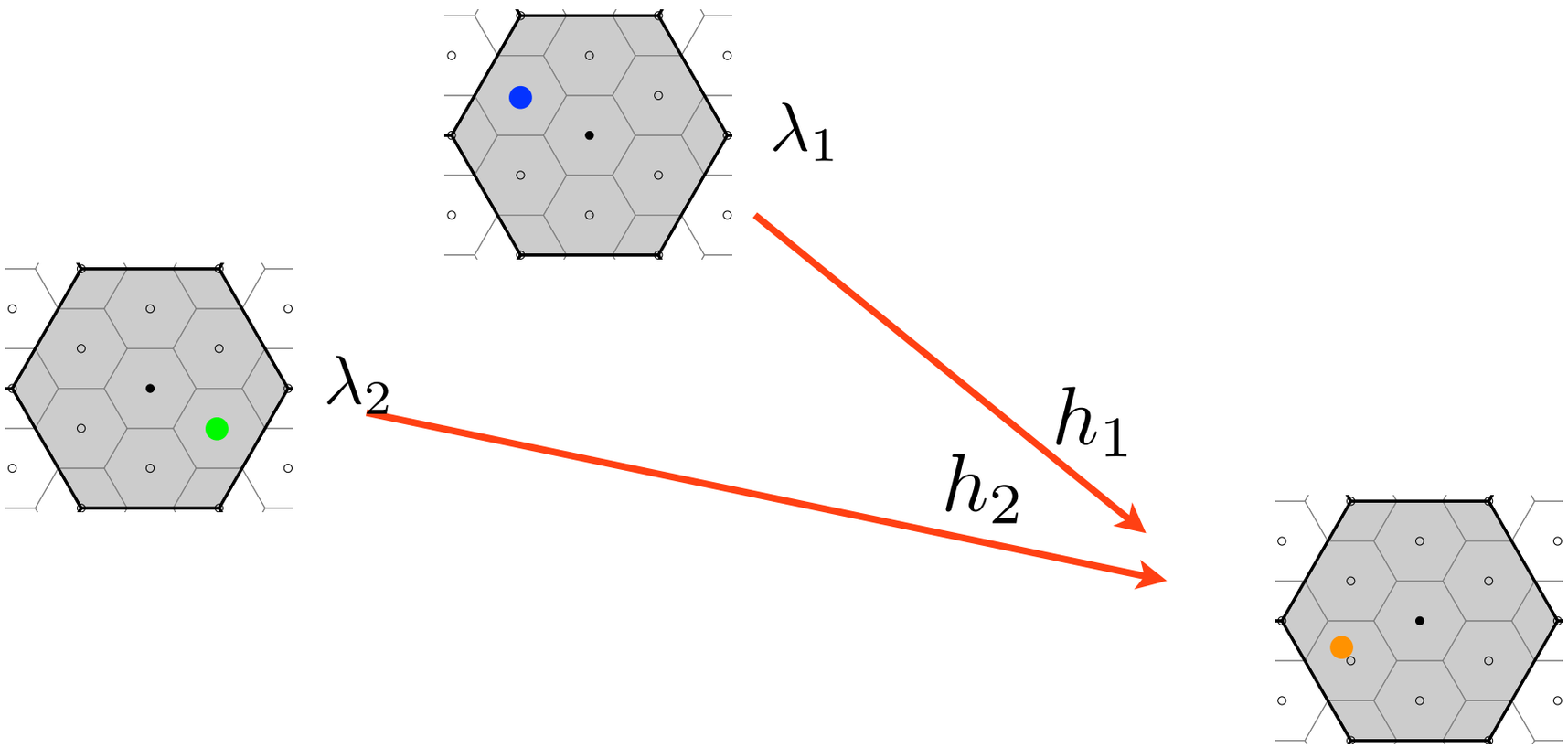
LDLC in Networks

- Network coding
  - Superposition [Nazer,Gasptar-2011]

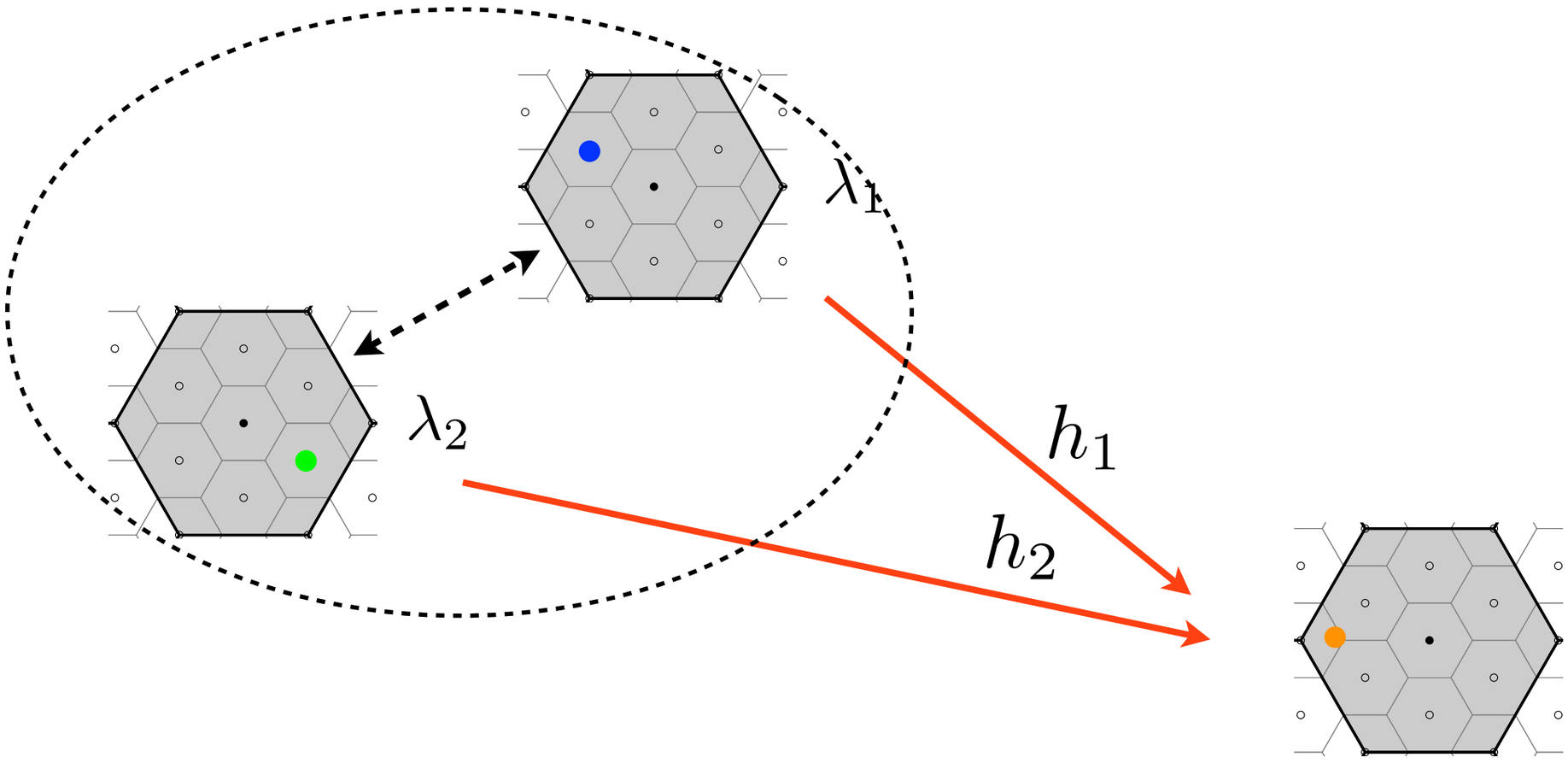


$$\lambda_i \bmod \Lambda_s \Longleftrightarrow \mathrm{w}_i$$

$$\lambda_1 + \lambda_2 \quad \bmod \Lambda_s \Longleftrightarrow \mathrm{w}_1 \bigoplus \mathrm{w}_2$$



$$[\sum_{i=1}^{N} a_i \lambda_i] \bmod \Lambda_s$$



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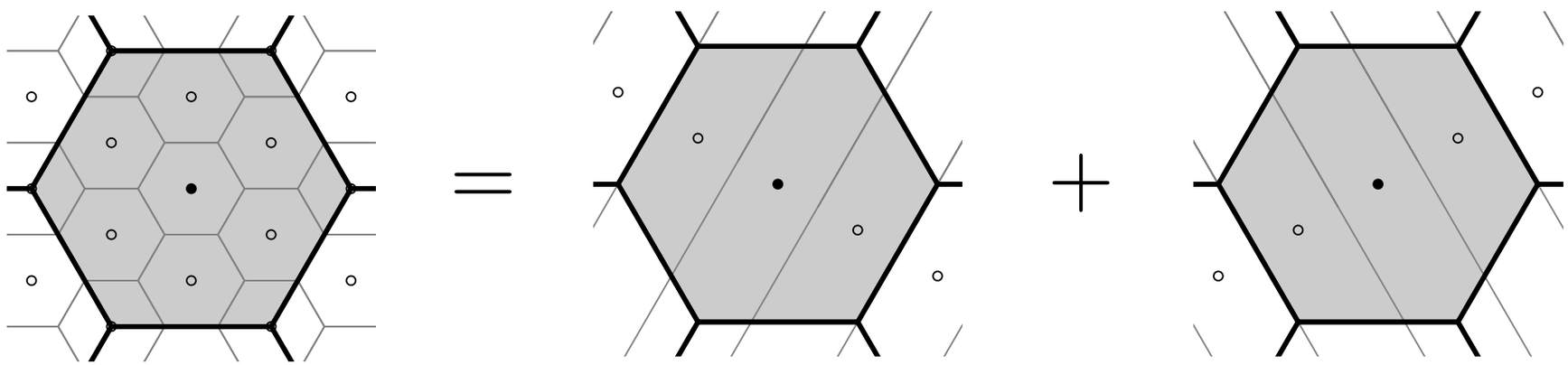
LDLC

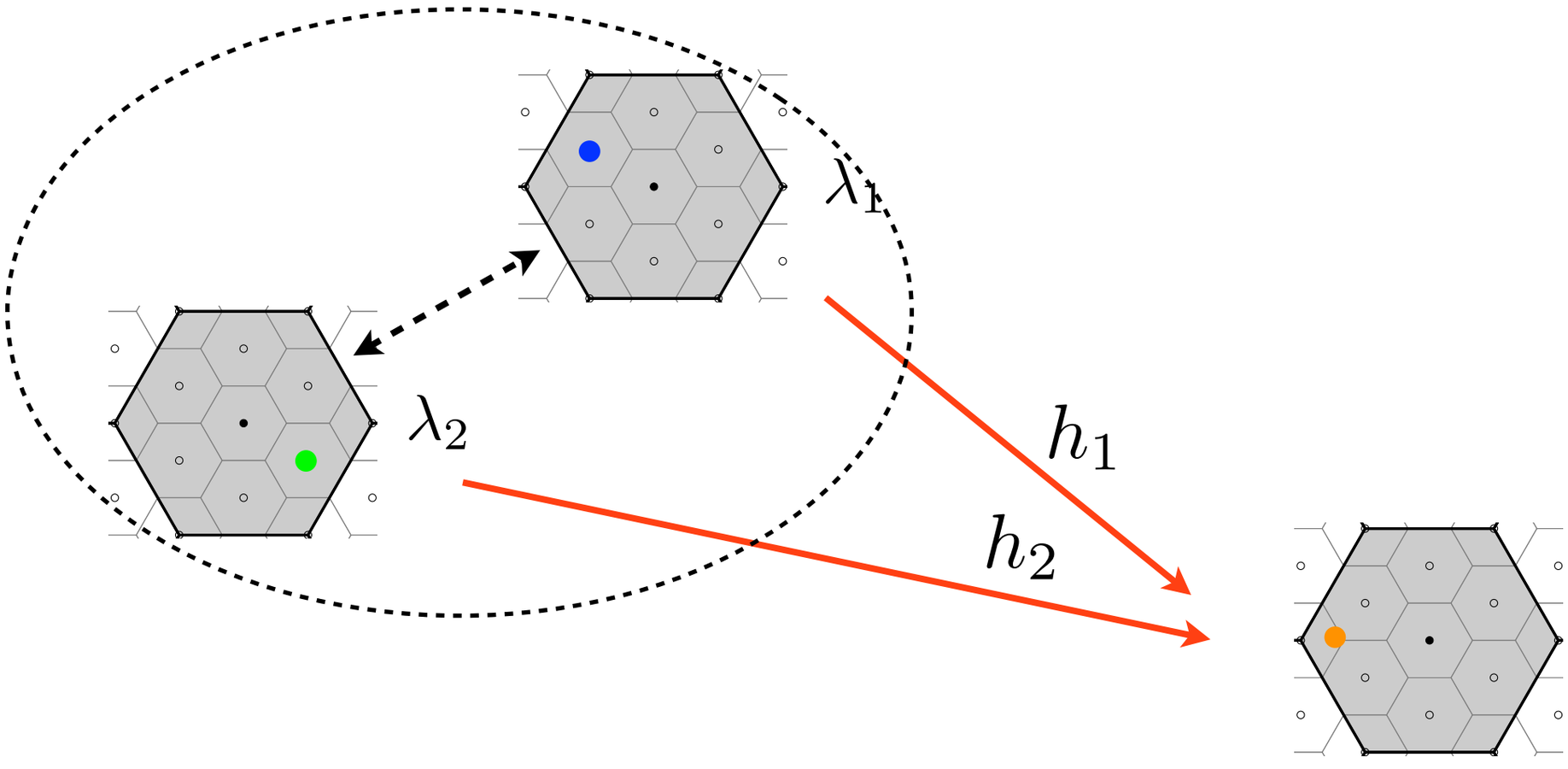
- Decomposable [Nokleby-Aazhang-2012]



Complete
$\mathcal{C} = \Lambda_c \cap \mathcal{V}_s$

Resolution
$\mathcal{C}_r = \Lambda_r \cap \mathcal{V}_s$

"Leftover"
$\mathcal{C}_l = \Lambda_l \cap \mathcal{V}_s$



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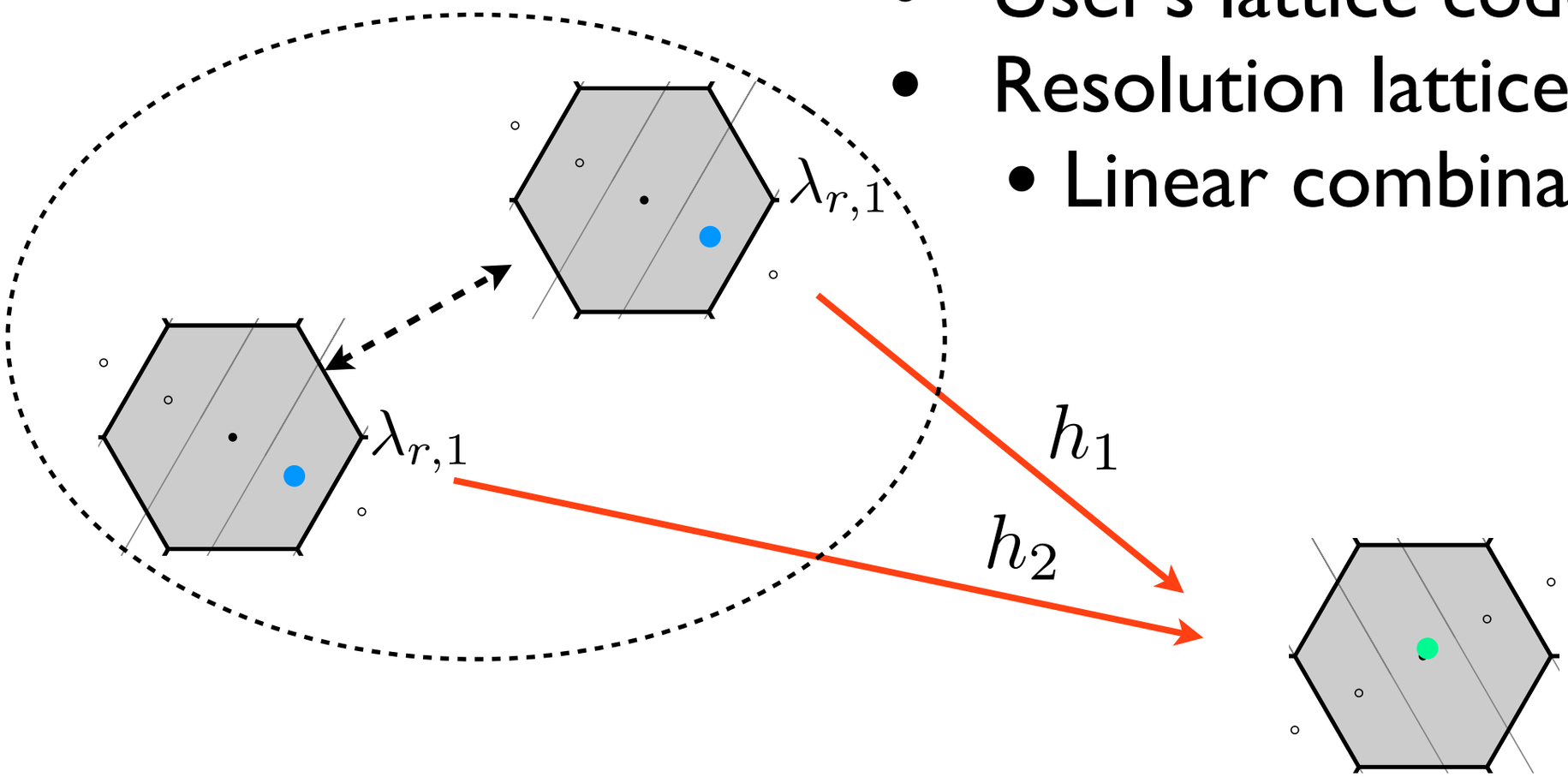
- Transmit in two stages
  - User's lattice code
  - Resolution lattice code
    - Linear combination



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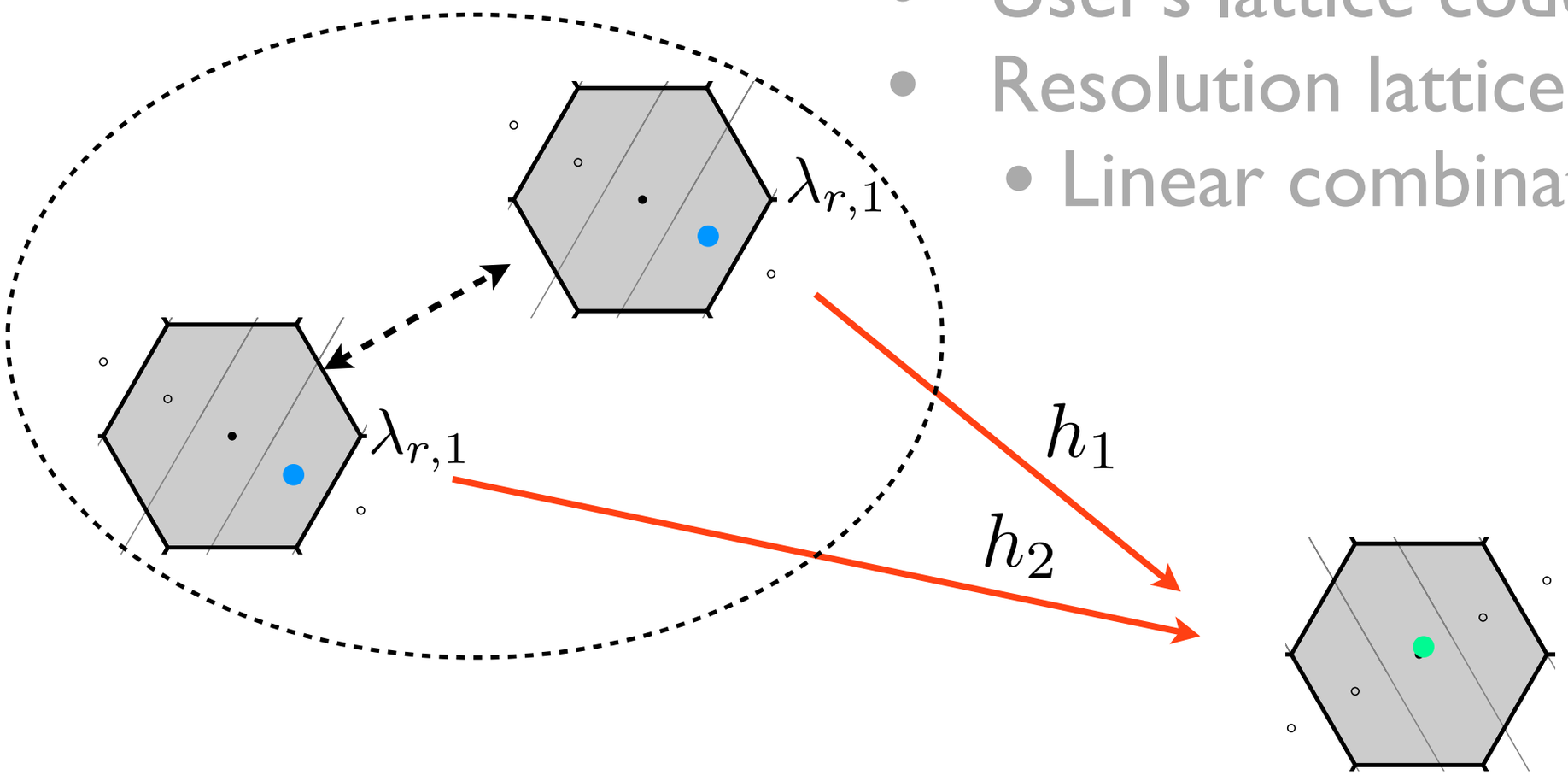

- Decode in stages
  - Resolution
  - Subtract
  - Leftover

LDLC in Networks

- Side information
- Interference
  - Full duplex
  - Successive interference cancelation
  - Layered coding

Final Thoughts

- Multi-flow networks
  - Granularities
    - Session, packet, symbol, signal
  - Applications
  - Implementation on WARP