

# Physical-Layer Network Coding: Design of Constellations over Rings

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# Outline

## 1 Introduction

## 2 Objectives

## 3 What Do We Need in Order to Design?

- Decision Regions
- Probability of Error
- M-QAM
- M-PSK

## 4 Proposed Designs

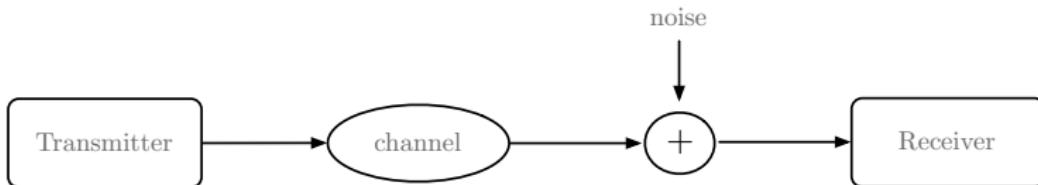
- 1 mod 4 Constellation
- 3 mod 4 Constellation
- Best Performance
- 1 mod 6 Constellation
- 2 mod 3 Constellation
- Best Performance

## 5 Conclusions

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# Introduction



## Note

Intermediate nodes can be added. These nodes would originally have the only function of forwarding the received messages.

# Outline

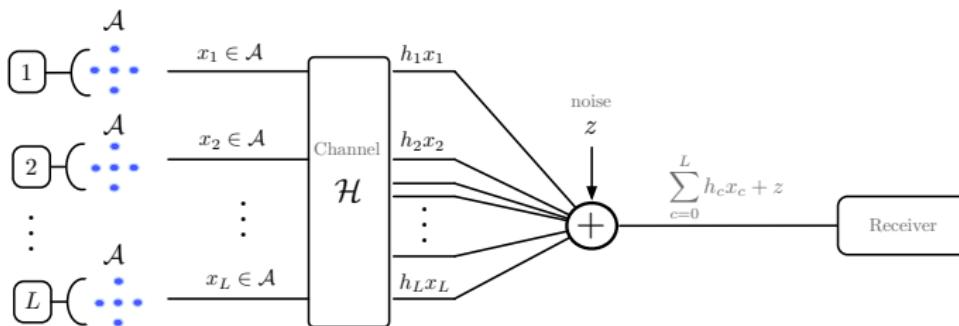
## 1 Introduction

- Physical-Layer Network Coding
- The Role of a Signal Constellation in the System

# Physical-Layer Network Coding

## Network Coding

Allows intermediate nodes to combine messages before forwarding them.



## Physical-Layer Network Coding

Exploits the network coding operation performed by nature.

# Outline

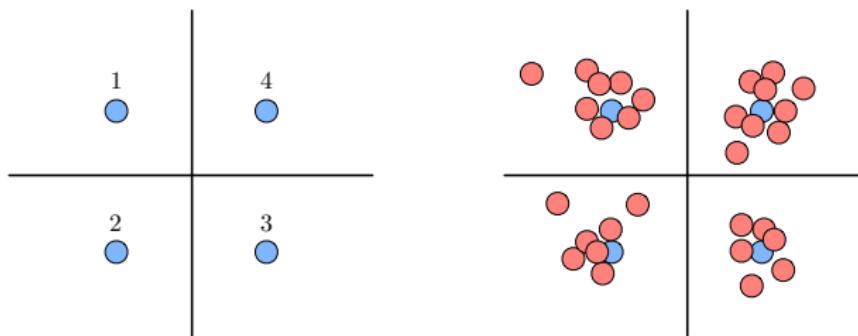
## 1 Introduction

- Physical-Layer Network Coding
- The Role of a Signal Constellation in the System

# The Role of a Signal Constellation

## Definition

A signal constellation is a set of points in the complex plane used to describe all possible symbols used by a system to transmit data.



Transmission and reception points

# Outline

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# Objective

## General Objective

We tackle the design of new signal constellations for Physical-Layer Network Coding. Towards this aim, the appropriate algebraic tools need to be identified.

## Design Objective

We aim at defining a design methodology and propose the best performing constellations. Performance will depend on the algebraically induced geometry.

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# Outline

## 3 What Do We Need in Order to Design?

- Mathematical Theory
- Performance Metrics
- A Reference to Compare
- System Model
- Proposed Methodology

# Introduction

## Commutative Rings

We are going to design constellations carved from the rings  $\mathbb{Z}[i]$  and  $\mathbb{Z}[w]$ .

$\{\text{Commutative Rings}\} \supset \{\text{PIDs}\} \supset \{\text{Euclidean Domains}\} \supset \{\text{Fields}\}$

## We Are Looking For

$R/aR$  field,  $R$  PID and  $aR$  ideal.

# The Ring $\mathbb{Z}[i]$

$$\mathbb{Z}[i] = \{a + bi \mid a, b \in \mathbb{Z}\}$$

## Definition

For  $\alpha = a + ib \in \mathbb{Z}[i]$ , its norm is defined as

$$N(\alpha) = \alpha\alpha^* = (a + bi)(a - bi) = a^2 + b^2.$$

## Theorem: Norm Is Multiplicative.

For  $\alpha$  and  $\beta$  in  $\mathbb{Z}[*]$ ,  $N(\alpha\beta) = N(\alpha)N(\beta)$ .

$$N(\alpha\beta) = (\alpha\beta)(\alpha\beta)^* = \alpha\beta\alpha^*\beta^* = (\alpha\alpha^*)(\beta\beta^*) = N(\alpha)N(\beta).$$

# The Ring $\mathbb{Z}[i]$

## Division Theorem

For  $\alpha, \beta \in \mathbb{Z}[i]$  with  $\beta \neq 0$ , there are  $\gamma, \rho \in \mathbb{Z}[i]$  such that

$$\alpha = \beta\gamma + \rho \text{ where } N(\rho) < N(\beta).$$

## Proof.

- Let  $\alpha, \beta \in \mathbb{Z}[i]$  with  $\beta \neq 0$ . Then  $\alpha/\beta \in \mathbb{C} \Rightarrow \alpha/\beta = u + iv$  with  $u, v \in \mathbb{R}$ .
  - $a \in \mathbb{Z}$  close to  $u \Rightarrow |u - a| \leq 1/2$ .
  - $b \in \mathbb{Z}$  close to  $v \Rightarrow |v - b| \leq 1/2$ .
- Set  $\gamma = a + ib \in \mathbb{Z}[i]$ . Set  $\rho = \alpha - \gamma\beta \in \mathbb{Z}[i]$ .
- Remains to prove  $N(\rho) < N(\beta)$ . (Note  $\beta \neq 0 \Rightarrow N(\beta) \neq 0$ ).
  - $N(\rho) = N((\rho/\beta)\beta) = N(\rho/\beta)N(\beta)$ :
  - $N(\rho) < N(\beta) \Leftrightarrow N(\rho/\beta) < 1$
  - $\rho/\beta = (\alpha - \gamma\beta)/\beta = \alpha/\beta - \gamma = (u + iv) - (a + ib) = (u - a) + i(v - b)$ .
  - $N(\rho/\beta) = (u - a)^2 + (v - b)^2 \leq 1/4 + 1/4 = 1/2 < 1$ .

Therefore  $\alpha = \gamma\beta + \rho$  with  $N(\rho) < N(\beta)$ .

# The Ring $\mathbb{Z}[i]$

## $\mathbb{Z}[i]$ as a PID

### Definition

An integral domain  $R$  is said to be an Euclidean domain if there is a function  $N$  from the set of nonzero elements of  $R$  to the set of non-negative integers such that

- (Division Theorem) given  $a, b \in R$  with  $b \neq 0$  there exist  $q, r \in R$  such that  $a = bq + r$  where  $N(r) < N(b)$ , and
- for all non-zero elements  $a$  and  $b$  of  $R$  we have  $N(a) \leq N(ab)$ .

### Theorem

Euclidean domains are PIDs.

### Proof.

Let  $C$  be any non-zero ideal of the Euclidean domain  $R$ , and  $d \in C$  be a nonzero element of minimum norm.

We claim  $(d) = C$ . Certainly,  $(d) \subseteq C$ .

Let  $a \in C$ . By the Division Theorem,  $a = qd + r$ , with  $r = 0$  or  $N(r) < N(d)$ . Since  $a - qd = r \in C$ , by minimality of  $N(d)$  we see  $r = 0$  and  $a = qd \in (d)$ . □

# The Ring $\mathbb{Z}[w]$

$$\mathbb{Z}[w] = \{a + bw \mid a, b \in \mathbb{Z}\}$$

with  $w$  is a primitive cube root of 1:

$$w = e^{2\pi i/3} = \cos\left(\frac{2\pi}{3}\right) + i \sin\left(\frac{2\pi}{3}\right) = \frac{1}{2}(-1 + i\sqrt{3}).$$

## Definition

For  $\alpha = a + wb \in \mathbb{Z}[w]$ , its norm is defined as

$$N(\alpha) = \alpha\alpha^* = a^2 + b^2 - ab.$$

# Outline

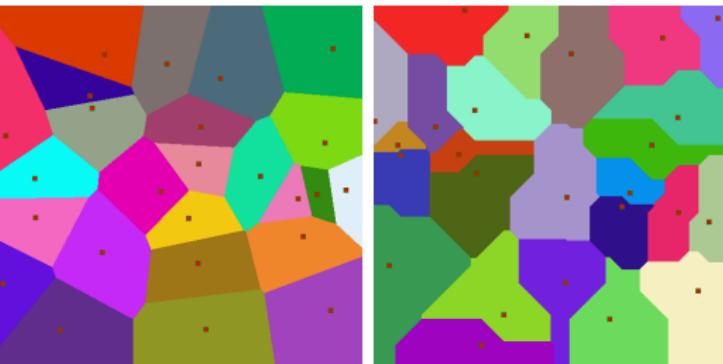
## 3 What Do We Need in Order to Design?

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- Performance Metrics
  - Decision Regions
  - Probability of Error
- A Reference to Compare
- System Model
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# Decision Regions

## Definition

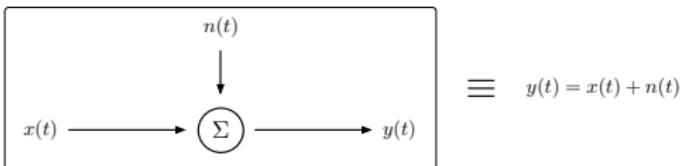
The decision region for a point  $x_c$  in the constellation  $\mathcal{A} = \{x_c\}_{c=0,\dots,M}$ , denoted  $\mathcal{R}_{x_c}$ , is the set of points of the complex plane that are closer to  $x_c$  than to any other point of the signal constellation.



# Probability of Error

## Hypothesis

We assume an AWGN (Additive White Gaussian Noise) channel.



The noise  $n(t)$  is a 1 dimensional random signal Gaussian with zero mean, variance  $\sigma^2$  and probability distribution:

$$P_n(u) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2\sigma^2} u^2}.$$

## Assumption

The computation of  $P_e$  assumes the inputs  $x_c$  equally likely:  $p_x(c) = \frac{1}{M} \forall c$ .

# Probability of Error

## ML Detector Is the Optimum Detector

Which has decision rule of taking the point of the constellation the detected point is nearest to.

### The Exact $P_e$

Corresponds to the sum of probabilities of having an error when transmitting a given symbol

$$P_e = \sum_{c=0}^{M-1} P_{e|c} \cdot P(c) = \frac{1}{M} \sum_{c=0}^{M-1} P_{e|c} = 1 - \frac{1}{M} \sum_{c=0}^{M-1} P_{r|c}.$$

# Probability of Error

## Union Bound

The probability of error for the ML detector on the AWGN channel, with an  $M$ -point signal constellation with minimum distance  $d_{min}$  is bounded by

$$P_e \leq (M - 1)Q\left[\frac{d_{min}}{2\sigma}\right].$$

## The Nearest Neighbor Union Bound

The probability of error for the ML detector on the AWGN channel, with an  $M$ -point constellation with minimum distance  $d_{min}$  is bounded by

$$P_e \leq N_e Q\left[\frac{d_{min}}{2\sigma}\right].$$

# Outline

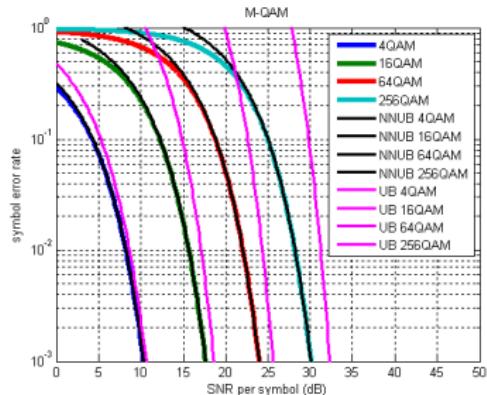
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# M-QAM Constellation

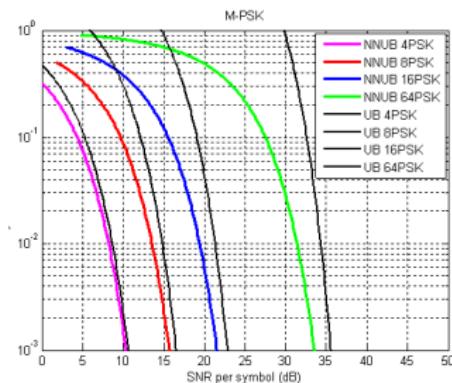
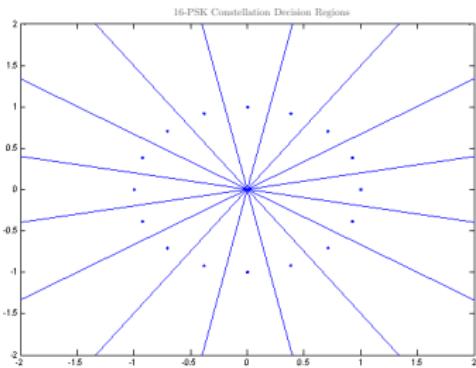
$$\mathcal{A} = \{a[n]\} = \{A(a_r[n] + ia_c[n])\},$$

with  $a_*[n]$  odd integers around zero.



# M-PSK Constellation

$$\mathcal{A} = \{Ae^{j2k\pi/M}\}, \quad k = 1, 2, \dots, M.$$



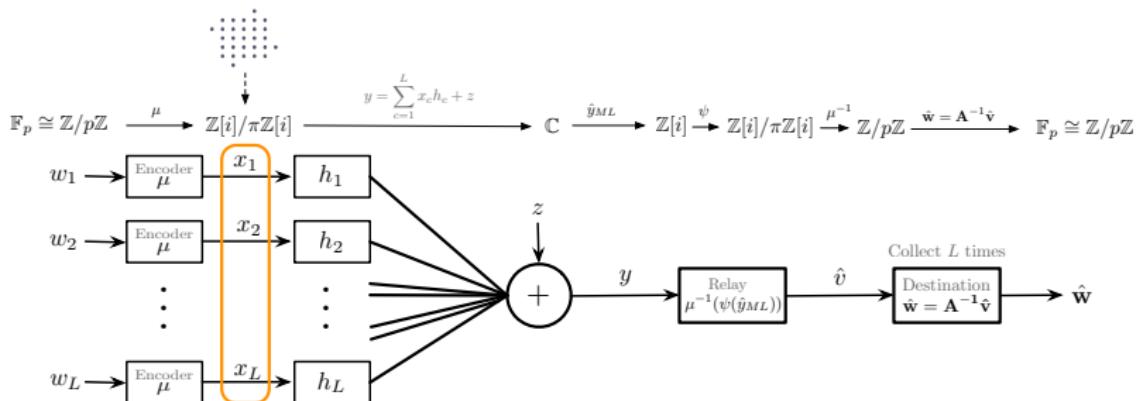
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# System Model

Points of the Constellation



# Outline

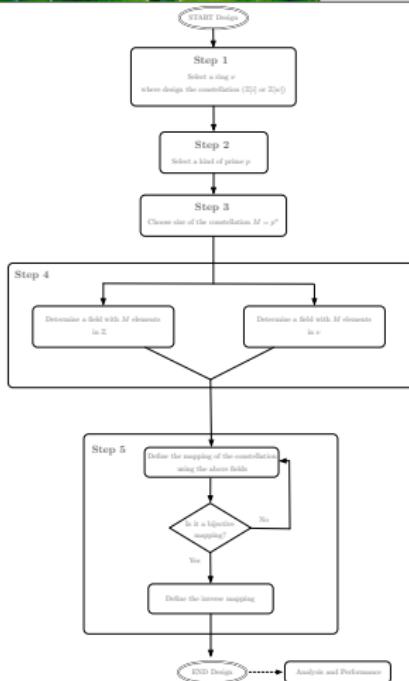
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# Proposed Methodology

## Methodology

- Step 1: select a ring  $\nu$ .
- Step 2: select a type of prime  $p$ .
- Step 3: choose size of the constellation  $M = p^n$ .
- Step 4: determine a field in  $\mathbb{Z}$  and  $\nu$ .
- Step 5: define the mapping of the constellation and its inverse.



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# Outline

## 4 Proposed Designs

- Designs in  $\mathbb{Z}[i]$ 
  - 1 mod 4 Constellation
  - 3 mod 4 Constellation
  - Best Performance
- Designs in  $\mathbb{Z}[w]$

# 1 mod 4 Constellation

## Design 1

- Step 1: ring  $\mathbb{Z}[i]$ .
- Step 2: primes  $p \in \mathbb{Z}^+$ ,  $p \equiv 1 \pmod{4}$  in  $\mathbb{Z}[i]$  ( $p = \pi\pi^*$ ).
- Step 3:  $M = p$ .
- Step 4: field with  $M = p$  elements in  $\mathbb{Z}$  and  $\mathbb{Z}[i]$ .
  - $\mathbb{Z}/p\mathbb{Z}$ ,  $\#(\mathbb{Z}/p\mathbb{Z}) = |p| = p$ .
  - $\mathbb{Z}[i]/\pi\mathbb{Z}[i]$ ,  $\#(\mathbb{Z}[i]/\pi\mathbb{Z}[i]) = N(\pi) = \pi\pi^* = p$ .

## Theorem

If  $R$  is a PID and  $a \in R$  is irreducible, then  $R/aR$  is a field.

# 1 mod 4 Constellation

## Design 1

- Step 5: we are looking for  $\mathbb{F}_p \cong \mathbb{Z}[i]/\pi\mathbb{Z}[i]$ .

The first mapping from  $\mathbb{F}_p$  to  $\mathbb{Z}[i]/\pi\mathbb{Z}[i]$  is defined as follows:  
We first state the division theorem in  $\mathbb{Z}[i]$

$$x = \lambda\pi + \gamma,$$

with  $N(\gamma) < N(\pi)$ ,

$$\text{where } \lambda = \left[ \frac{x}{\pi} \right] = \left[ \frac{x\pi^*}{\pi\pi^*} \right].$$

If we solve for the residue

$$\gamma = x - \left[ \frac{x\pi^*}{\pi\pi^*} \right] \pi.$$

# 1 mod 4 Constellation

The mapping of the constellation is defined as:

$$\begin{aligned}\mu : \mathbb{F}_p &\xrightarrow{\hspace{2cm}} \mathbb{Z}[i]/\pi\mathbb{Z}[i] \\ x &\longmapsto \mu(x) = x - \left[ \frac{x\pi^*}{\pi\pi^*} \right] \pi\end{aligned}$$

The inverse mapping is defined as:

$$\begin{aligned}\mu^{-1} : \mathbb{Z}[i]/\pi\mathbb{Z}[i] &\xrightarrow{\hspace{2cm}} \mathbb{F}_p \\ a &\longmapsto \mu^{-1}(a) = (a(v\pi^*) + a^*(u\pi^*)) \bmod p\end{aligned}$$

with  $u\pi + v\pi^* = 1$ .

# 3 mod 4 Constellation

## Design 2

- Step 1: ring  $\mathbb{Z}[i]$ .
- Step 2: primes  $p \in \mathbb{Z}^+$ ,  $p \equiv 3 \pmod{4}$  in  $\mathbb{Z}[i]$ .
- Step 3:  $M = p^2$ .
- Step 4:
  - $\mathbb{Z}[i]/p\mathbb{Z}[i]$ ,  $\#(\mathbb{Z}[i]/p\mathbb{Z}[i]) = N(p) = p^2$ .
  - $\mathbb{F}_p[X]/(x^2 + 1)$ ,  $\#(\mathbb{F}_p[X]/(x^2 + 1)) = p^2$ .

## Theorem

If  $R$  is a PID and  $a \in R$  is irreducible, then  $R/aR$  is a field.

# 3 mod 4 Constellation

## Design 2

- Step 5: we are looking for  $\mathbb{F}_p[X]/(x^2 + 1) \cong \mathbb{Z}[i]/p\mathbb{Z}[i]$  ( $X$  corresponding  $i$ ).

We are going to see that the two fields are isomorphic to  $\mathbb{Z}[X]/(p, x^2 + 1)$ .

- First,  $\mathbb{Z}[X]/(x^2 + 1) \cong \mathbb{Z}[i]$  with  $X \rightarrow i$ .

$$\psi : \mathbb{Z}[X] \longrightarrow \mathbb{Z}[i]$$

$$P(X) \longmapsto P(i)$$

Surjective with kernel  $(1 + x^2)$ .

# 3 mod 4 Constellation

By the NOETHER First Isomorphism Theorem:

$$\text{Image}(\psi) \cong \mathbb{Z}[X]/\text{Kernel}(\psi)$$

$$\begin{array}{ccc} \mathbb{Z}[X] & \xrightarrow{\psi} & \mathbb{Z}[i] = \text{Image}(\psi) \\ \pi \downarrow & & \swarrow \cong \hat{\psi} \\ \mathbb{Z}[X]/\text{Kernel}(\psi) & = & \mathbb{Z}[X]/(x^2 + 1) \end{array}$$

We can assert  $\psi^{-1}(p\mathbb{Z}[i]) = (p, x^2 + 1)$ . Hence,  
 $\mathbb{Z}[i]/p\mathbb{Z}[i] \cong \mathbb{Z}[X]/(p, x^2 + 1)$ .

# 3 mod 4 Constellation

- Since  $\mathbb{F}_p \cong \mathbb{Z}/p\mathbb{Z}$  we have

$$\begin{aligned}\mathbb{F}_p[X]/(x^2 + 1) &\cong (\mathbb{Z}/p\mathbb{Z})[X]/(x^2 + 1) \\ &\cong (\mathbb{Z}[X]/(p)) / (x^2 + 1) \cong \mathbb{Z}[X]/(p, x^2 + 1).\end{aligned}$$

# 3 mod 4 Constellation

The mapping of the constellation is defined as:

$$\gamma : \mathbb{F}_p[X]/(x^2 + 1) \longrightarrow \mathbb{Z}[i]/p\mathbb{Z}[i]$$

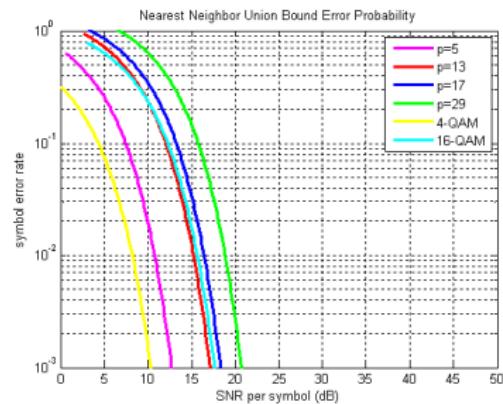
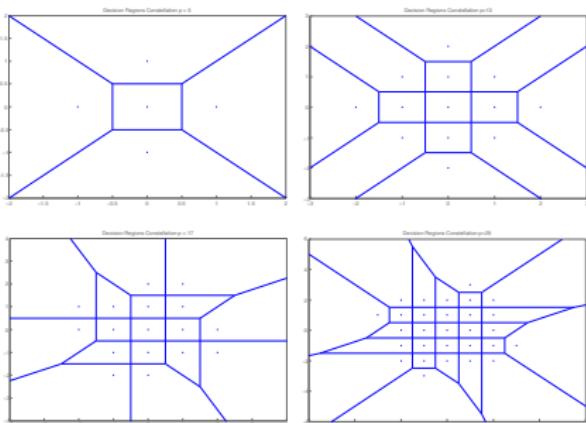
$$x \longmapsto i$$

The inverse mapping is defined as:

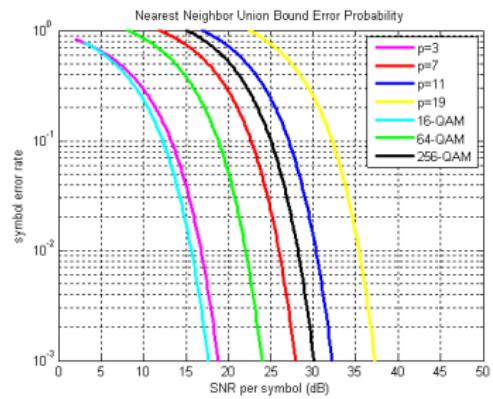
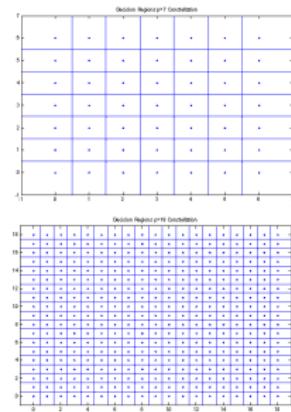
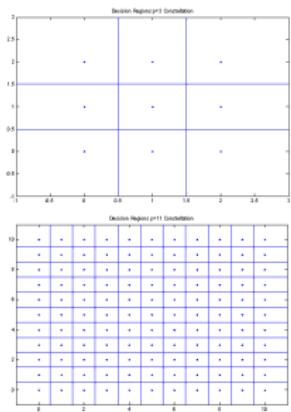
$$\gamma^{-1} : \mathbb{Z}[i]/p\mathbb{Z}[i] \longrightarrow \mathbb{F}_p[X]/(x^2 + 1)$$

$$i \longmapsto x$$

# 1 mod 4 Constellation



# 3 mod 4 Constellation



# Outline

## 4 Proposed Designs

- Designs in  $\mathbb{Z}[i]$
- Designs in  $\mathbb{Z}[w]$ 
  - 1 mod 6 Constellation
  - 2 mod 3 Constellation
  - Best Performance

# 1 mod 6 Constellation

## Design 3

- Step 1: ring  $\mathbb{Z}[w]$ .
- Step 2: primes  $p \in \mathbb{Z}^+$ ,  $p \equiv 1 \pmod{6}$  in  $\mathbb{Z}[w]$  ( $p = \pi\pi^*$ ).
- Step 3:  $M = p$ .
- Step 4:
  - $\mathbb{Z}/p\mathbb{Z}$ ,  $\#(\mathbb{Z}/p\mathbb{Z}) = |p| = p$ .
  - $\mathbb{Z}[w]/\pi\mathbb{Z}[w]$ ,  $\#(\mathbb{Z}[w]/\pi\mathbb{Z}[w]) = N(\pi) = \pi\pi^* = p$ .

## Theorem

If  $R$  is a PID and  $a \in R$  is irreducible, then  $R/aR$  is a field.

# 1 mod 6 Constellation

## Design 3

- Step 5: we are looking for  $\mathbb{Z}/p\mathbb{Z} \cong \mathbb{Z}[w]/\pi\mathbb{Z}[w]$ .

The mapping of the constellation is defined as:

$$\begin{aligned}\tilde{\mu} : \mathbb{F}_p &\longrightarrow \mathbb{Z}[w]/\pi\mathbb{Z}[w] \\ x &\longmapsto \tilde{\mu}(x) = x - \left[ \frac{x\pi^*}{\pi\pi^*} \right] \pi\end{aligned}$$

The inverse mapping is defined as:

$$\begin{aligned}\mu^{-1} : \mathbb{Z}[w]/\pi\mathbb{Z}[w] &\longrightarrow \mathbb{F}_p \\ a &\longmapsto \mu^{-1}(a) = (a(v\pi^*) + a^*(u\pi^*)) \text{mod } p\end{aligned}$$

with  $u\pi + v\pi^* = 1$ .

# 2 mod 3 Constellation

## Design 4

- Step 1: ring  $\mathbb{Z}[w]$ .
- Step 2: primes  $p \in \mathbb{Z}^+$ ,  $p \equiv 2 \pmod{3}$  in  $\mathbb{Z}[w]$ .
- Step 3:  $M = p^2$ .
- Step 4:
  - $\mathbb{Z}[w]/p\mathbb{Z}[w]$ ,  $\#(\mathbb{Z}[w]/p\mathbb{Z}[w]) = N(p) = p^2$ .
  - $\mathbb{F}_p[X]/(x^2 + x + 1)$ ,  $\#(\mathbb{F}_p[X]/(x^2 + x + 1)) = p^2$ .

## Theorem

If  $R$  is a PID and  $a \in R$  is irreducible, then  $R/aR$  is a field.

# 2 mod 3 Constellation

## Design 4

- Step 5: we are looking for  $\mathbb{Z}[w]/p\mathbb{Z}[w] \cong \mathbb{F}_p[X]/(x^2 + x + 1)$  with  $X$  corresponding  $w$ .

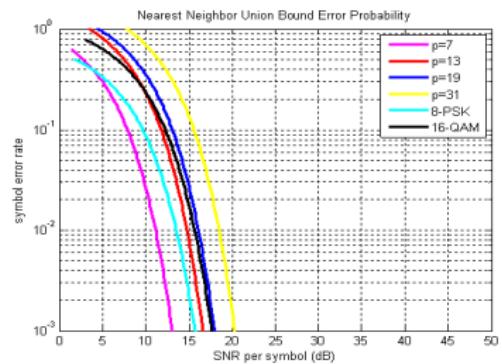
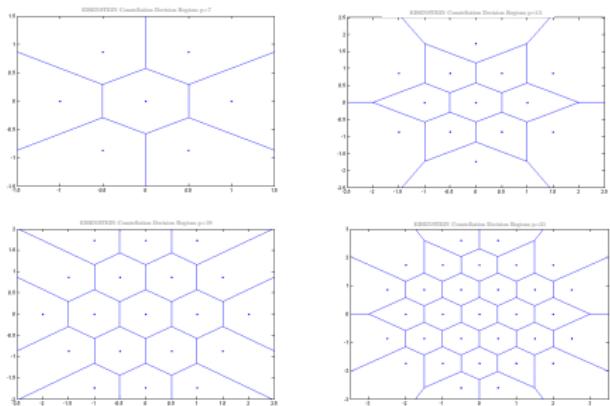
The mapping of the constellation is defined as:

$$\tilde{\gamma} : \mathbb{F}_p[X]/(x^2 + x + 1) \longrightarrow \mathbb{Z}[w]/p\mathbb{Z}[w]$$
$$x \longmapsto w$$

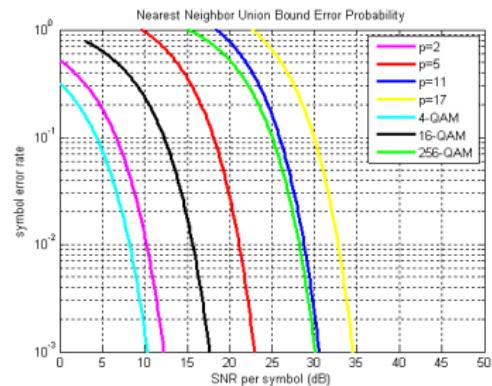
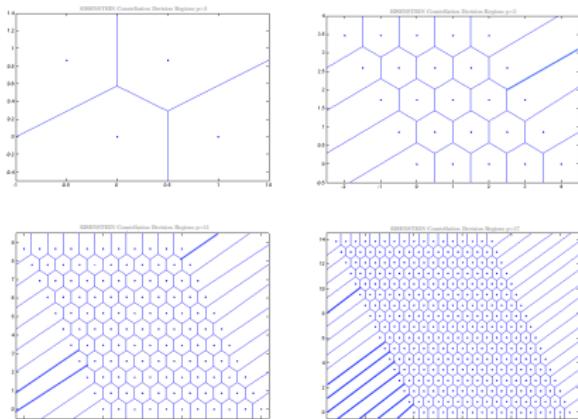
The inverse mapping is defined as:

$$\tilde{\gamma}^{-1} : \mathbb{Z}[w]/p\mathbb{Z}[w] \longrightarrow \mathbb{F}_p[X]/(x^2 + x + 1)$$
$$w \longmapsto x$$

# 1 mod 6 Constellation



# 2 mod 3 Constellation



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# Conclusions

- Algebraic theory identification:
  - PID. ✓
  - Euclidean domain. ✓
  - Fields. ✓
- Performance metrics identification:
  - Decision regions. ✓
  - Nearest Neighbor Union Bound. ✓
- MATLAB parameters computation:
  - $d_{\min}$ . ✓
  - $N_e$ . ✓
- System model know how:
  - MATLAB implementation proposed. ✓

# Conclusions

- Design and performance of the constellations:
  - $\mathbb{Z}[i]$ :
    - 1 mod 4. ✓
    - 3 mod 4. ✓
  - $\mathbb{Z}[w]$ :
    - 1 mod 6. ✓
    - 2 mod 3. ✓

# Conclusions

## And Finally the Best Constellations Are

- 1 mod 6 constellation in  $\mathbb{Z}[w]$  is the best performing constellation.
- 1 mod 4 constellations in  $\mathbb{Z}[i]$  appear as a good QAM alternative.
- QAM constellations have better performance than 3 mod 4 in  $\mathbb{Z}[i]$  and 2 mod 3 in  $\mathbb{Z}[w]$ .

# Thank You

DE ZARZA I CUBERO Irene  
Thank you