CDMA Technology

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On line Course on CDMA Technology
CDMA Technology:

- Introduction to spread spectrum technology
- **CDMA / DS: Principle of operation**
  - Generation of PN Spreading Codes
  - Advanced Spreading codes
  - Principles of CDMA/DS decoding
  - Radio Cells & System Capacity
  - Basics of Global Navigation Satellite Systems
  - Galileo / European GNSS
CDMA / DS:
Principle Of Operation

- Introduction: one Channel with a single data stream
- Real case: one channel with many data
- Signal to noise Ratio and Power control
- Conclusion
Part 1: One channel – one data

Data: Binary Random Signal

Bit value:

| Bit Value | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 |

Coding Sequence: Binary pseudo Random Signal

Bit Value:

| Bit Value | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 |
Real time signals

Data: $s_D$

Coding Sequence: PN

Coding Sequence Frame (Period)

$T_D$
Periodicity $\rightarrow$ PSEUDO random signal or Pseudo Noise signal : $pn(t)$ sequence
Part 1: One channel – one data

Data: $s_D(t)$
Time waveform

Data: $s_D(t)$
Power spectrum density $S_{SD}(f)$

First Lobe: 90% of the power

$$SSD(f)$$

$$s_D(t)$$

Time waveform

$$T_D$$

$$(in \ W/Hz)$$

$$(0 \ 1/T_D \ f)$$

Principles of operation
Part 1: One channel – one data

Coding Sequence: PN
Time waveform

Ideal Power spectrum density

Coding PN sequence: Ideal Power spectrum density
$S_{pn}(f)$

(in W/Hz)

$T_{PN}$
Part 1: One channel – one data

Real coding Sequence:

Coding PN sequence:

Real Power spectrum density

\[ S_{pn}(f) \] (in W/Hz)

\[ T_D \]

Data

Real Power spectrum density

\( 0 \)

\( 1/T_{PN} \)

\( f \)
Part 1: One channel – one data

Real coding Sequence:

Data

Discrete Power spectrum density

\[ S_{pn}(f) \]

(in W/Hz)

Due to the periodicity of the PN sequence
Part 1: One channel – one data

Real coding Sequence:

Data

Principles of operation
Part 1: One channel – one data

Real coding

Sequence:

Data

If $T_D \gg T_{PN}$

Discrete spectrum

quasi ideal spectrum

If $T_D >> T_{PN}$

PN Period  PN Period  PN Period
Part 1: One channel – one data

Data

Real coding Sequence:

\[ T_D = 7 \cdot T_{PN} \]

Principles of operation

\[ 1/T_{PN} = 77 \text{ kHz} \]
Data

Real coding Sequence:

\[ T_D = 31 \, T_{PN} \]

\[ 1/T_{PN} = 77 \, \text{kHz} \]
Part 1: One channel – one data

Data

Real coding
Sequence:

\[ T_D = 127 \, T_{PN} \]

\[ 1/T_{PN} = 77 \text{ kHz} \]
Part 1: One channel – one data

In conclusion:

$$S_{SD}(f)$$

$$S_{pn}(f)$$

$$0 \quad 1/T_D \quad 1/T_{PN}$$
Part 1: One channel – one data

Transmitted (coded) signal ‘Tx’ in CDMA/DS

\[ s_S(t) = s_D(t) \times p_n(t) \]

Data: \( s_D(t) \)

\[ +1 \quad \cdots \quad -1 \]

\( p_n(t) \)

\( +1 \quad \cdots \quad -1 \)

\( s_S(t) \) (Tx)

\( +1 \quad \cdots \quad -1 \)

\( s_D(t) \) negative

\[ \text{---> } s_S(t) \text{ opposite to } p_n(t) \]
Part 1: One channel – one data

Transmitted (coded) signal ‘Tx’ in CDMA/DS

Data : $s_D(t)$

$Tx : s_S(t)$

1000110111...

0111001000...

011001000....
Part 1: One channel – one data

Transmitted (coded) signal ‘Tx’ in CDMA/DS

**Time domain**

\[ s_S(t) = s_D(t) \times p_n(t) \]

**Frequency domain**

\[ S_S(f) = S_D(f) \ast S_{pn}(f) \]

Bandwidth: \(1/T_{PN}\)
Transmitted (coded) signal ‘Tx’ in CDMA/DS

Time domain

\[ s_S(t) = s_D(t) \times \text{pn}(t) \]

Frequency domain

\[ S_{ss}(f) = S_{sd}(f) \ast S_{pn}(f) \]

Bandwidth: \(1/\text{TPN}\)

Coding in time domain ➤ Spreading in frequency domain

Coding sequence = Spreading sequence
Part 1: One channel – one data

Data: $s_D(t)$

$T_D = 127 \ T_{PN}$

Data: $S_D(f)$

Emitted signal: $S_{ss}(f)$
Signal decoding at receiver

\[ R_X(t) = s_S \times p_n(t) \]
Signal decoding at receiver

\[ R_X(t) = s_S \times p_n(t) \]

Data: \( s_D(t) \)

\( p_n(t) \) at emitter

Tx: \( s_S(t) \)

\( p_n(t) \) at receiver

Rx(t)
Signal decoding at receiver

\[ R_X(t) = s_S(t) \times pn(t) \]
\[ = s_D(t) \times pn(t) \times pn(t) \]

= 1
Signal decoding at receiver

**Principles of operation**

**Part 1: One channel – one data**

**Signal decoding at receiver**

\[ T_x : S_s(t) \rightarrow \text{correlator/despread.} \rightarrow R_x \]

- **Tx :** \( S_s(t) \)
- **Rx :**
- **Synchron. control loop**
- **Loc. code generator**

\[ p_n(t) \]

**Requirement for spreading code synchronisation**
(see next chapters)
**Part 2 : One channel – many data**

**Data:**

\[ s_{D1} \quad s_{D2} \quad s_{D3} \quad \ldots \quad s_{Dn} \]

**Coding sequence:**

\[ p_{n1} \quad p_{n2} \quad p_{n3} \quad \ldots \quad p_{nn} \]

**bit duration** \( T_D \)

**bit duration** \( T_{PN} \)
Part 2: One channel – many data

**Data:**

$s_{D1}$ $s_{D2}$ $s_{D3}$ $\ldots$ $s_{Dn}$

**Coding sequence:**

$p_{n1}$ $p_{n2}$ $p_{n3}$ $\ldots$ $p_{nn}$

**Spread signal:**

$s_{S}(t) = s_{D1}(t) \times p_{n1}(t) + s_{D2}(t) \times p_{n2}(t) + \cdots + s_{Dn}(t) \times p_{nn}(t)$

**Bit rate:** $1/T_{PN}$
Part 2: One channel – many data

Data:

\[ s_{D1} \quad s_{D2} \quad s_{D3} \quad \ldots \quad s_{Dn} \]

Coding sequence:

\[ p_{n1} \quad p_{n2} \quad p_{n3} \quad \ldots \quad p_{nn} \]

Spread signal:

\[ s_s(t) = s_{D1}(t) \times p_{n1}(t) + s_{D2}(t) \times p_{n2}(t) + \cdots + s_{Dn}(t) \times p_{nn}(t) \]

\[ +/- 1 \quad +/- 1 \quad +/- 1 \]
Part 2: One channel – many data

Data:

\[ s_{D1} \quad s_{D2} \quad s_{D3} \quad \ldots \quad s_{Dn} \]

Coding sequence:

\[ p_{n1} \quad p_{n2} \quad p_{n3} \quad \ldots \quad p_{nn} \]

Spread signal:

\[ s_S(t) = s_{D1}(t) \times p_{n1}(t) + s_{D2}(t) \times p_{n2}(t) + \ldots + s_{Dn}(t) \times p_{nn}(t) \]

\[ \text{non binary signal} \quad \text{/ Bit rate: } 1/ T_{PN} \]
**Part 2: One channel – many data**

**Data:**

\[ s_{D1} \quad s_{D2} \quad s_{D3} \quad \ldots \quad s_{Dn} \]

**Coding sequence:**

\[ p_{n1} \quad p_{n2} \quad p_{n3} \quad \ldots \quad p_{nn} \]

**Spread signal for 2 data streams**

+2

0

−2

Principles of operation
Part 2: One channel – many data

Signal decoding at receiver: how to recover data 1?

\[ R_X(t) = s_{D1}(t) \times p_{n1}(t) \times p_{n1}(t) + s_{D2}(t) \times p_{n2}(t) \times p_{n1}(t) + \cdots + s_{Dn}(t) \times p_{n}(t) \times p_{n1}(t) = 1 \]
Signal decoding at receiver: how to recover data 1?

\[ R_X(t) = s_{D1}(t) + s_{D2}(t) \times p_{n2}(t) \times p_{n1}(t) + \cdots + s_{Dn}(t) \times p_{n1}(t) \]

**Time signals**

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**Principles of operation**
Signal decoding at receiver: how to recover data 1?

**Part 2: One channel – many data**

\[ R_X(t) = s_{D1}(t) + s_{D2}(t) \times p_{n2}(t) \times p_{n1}(t) + \cdots + s_{Dn}(t) \times p_{n1}(t) \]

**Power Spectrum Density**

**Principles of operation**
Part 2: One channel – many data

Signal decoding at receiver: how to recover data 1?

\[ \mathbf{R}_x(t) = \mathbf{s}_{D1}(t) + \mathbf{s}_{D2}(t) \times \mathbf{p}_{n1}(t) + \cdots + \mathbf{s}_{Dn}(t) \times \mathbf{p}_{n(t)} \times \mathbf{p}_{n1}(t) \]
Signal decoding at receiver: how to recover data 1?

$$\overline{R_X(t)} = s_{D1}(t) + s_{D2}(t) \times pn_2(t) \times pn_1(t) + \cdots + s_{Dn}(t) \times pn_n(t) \times pn_1(t)$$
Signal decoding at receiver: how to recover data 1?

\[ R_X(t) = s_{D1}(t) + s_{D2}(t) \times p_{n2}(t) \times p_{n1}(t) + \cdots + s_{Dn}(t) \times p_{n_n}(t) \times p_{n1}(t) \]

- Data streams \( s_{Di} \) and PN sequences statistically independent

\[ s_{Di}(t) \times p_{ni}(t) \times p_{n1}(t) = s_{Di}(t) \times p_{ni}(t) \times p_{n1}(t) \]
Signal decoding at receiver: how to recover data 1?

\[ R_x(t) = s_{D1}(t) + s_{D2}(t) \times pn_2(t) \times pn_1(t) + \cdots + s_{Dn}(t) \times pn_n(t) \times pn_1(t) \]

Cross-correlation of PN sequences
Signal decoding at receiver: how to recover data 1?

\[ R_x(t) = s_{D1}(t) + s_{D2}(t) \times \frac{p_{n2}(t) \times p_{n1}(t)}{p_{n1}(t)} + \cdots + s_{Dn}(t) \times \frac{p_{nn}(t) \times p_{n1}(t)}{p_{n1}(t)} \]

Proper selection of uncorrelated PN sequences enhances effect of low pass filtering.
Part 2: One channel – many data

Principles of operation
Part 2: One channel – many data

Principles of operation

Data 1

$R_x$

$s_s$

$T_x : s_s(t)$

$X$

$R_x$

Band-Filter $[0 ; 1/T_D]$

$R_x$

Threshold detector

Data 1

recovered

$pn_1$
How many datas on one single channel?

\[ R_X(t) = s_{D1}(t) + s_{D2}(t) \times \frac{p_{n2}(t) \times p_{n1}(t)}{\alpha} + \cdots + s_{Dn}(t) \times \frac{p_{n}(t) \times p_{n1}(t)}{\alpha} \]

Assuming a constant positive value ‘\(\alpha\)’ for PN sequences cross-correlation:

\[ R_X(t) = s_{D1}(t) + s_{D2}(t) \times \alpha + \cdots + s_{Dn}(t) \times \alpha \]
Part 3: Signal to noise ratio / Power control

How many datas on one single channel?

Assuming a constant positive value ‘$\alpha$‘ for PN sequences cross-correlation:

$$\overline{R_X(t)} = s_{D_1}(t) + s_{D_2}(t) \times \alpha + \cdots + s_{D_n}(t) \times \alpha$$

Worst case:

$$\begin{cases} 
  s_{D_1} = +1 \quad \text{and} \quad s_{D_2} = s_{D_3} = \ldots = s_{D_n} = -1 \\
  \overline{R_X(t)} = 1 - (n-1) \times \alpha 
\end{cases}$$
Part 3: Signal to noise ratio / Power control

How many datas on one single channel?

Assuming a constant positive value ‘$\alpha$‘ for PN sequences cross-correlation:

$$R_X(t) = s_{D1}(t) + s_{D2}(t) \times \alpha + \cdots + s_{Dn}(t) \times \alpha$$

Worst case:

$$\begin{cases} 
    s_{D1} = +1 \quad \text{and} \quad s_{D2} = s_{D3} = \ldots = s_{Dn} = -1 \\
    R_X(t) = 1 - (n-1) \times \alpha 
\end{cases}$$

If $$|n \times \alpha| > 1$$ then the sign of $$R_X(t)$$ is different from the sign of $$s_{D1}$$

Error: system capacity is fixed by the sequences cross-correlation value
How many datas on one single channel?

Assuming a constant positive value ‘α’ for PN sequences cross-correlation:

\[
\overline{R_X(t)} = s_{D1}(t) + s_{D2}(t) \times \alpha + \cdots + s_{Dn}(t) \times \alpha
\]

Worst case:

\[
\begin{cases}
  s_{D1} = +1 \quad \text{and} \quad s_{D2} = s_{D3} = \ldots = s_{Dn} = -1 \\
  \overline{R_X(t)} = 1 - (n - 1) \times \alpha
\end{cases}
\]

→ the smaller is \( \alpha \) the larger \( n \) can be
Signal to noise ratio

Assuming a constant positive value ‘$\alpha$’ for PN sequences cross-correlation:

$$R_X(t) = s_{D1}(t) + s_{D2}(t) \times \alpha + \cdots + s_{Dn}(t) \times \alpha$$

Power \(P\)
Signal to noise ratio

Assuming a constant positive value ‘$\alpha$’ for PN sequences cross-correlation:

$$R_X(t) = s_{D1}(t) + s_{D2}(t) \times \alpha + \cdots + s_{Dn}(t) \times \alpha$$

‘Signal’  ‘Noise’
Assuming a constant positive value ‘$\alpha$’ for PN sequences cross-correlation:

$$R_X(t) = s_{D1}(t) + s_{D2}(t) \times \alpha + \cdots + s_{Dn}(t) \times \alpha + \text{Johnson Noise}$$

\(\text{‘Signal’}\)

\(\text{‘Johnson White noise’}\)

White noise power spectrum density

Noise equivalent bandwidth of bandfilter
Part 3: Signal to noise ratio / Power control

Signal to noise ratio

Assuming a constant positive value \( \alpha \) for PN sequences cross-correlation:

\[
R_X(t) = s_{D1}(t) + s_{D2}(t) \times \alpha + \cdots + s_{Dn}(t) \times \alpha + \text{Johnson Noise}
\]

\[
\begin{align*}
\text{‘Signal’} & \\
\text{‘Noise’} &
\end{align*}
\]

Signal to Noise ratio including white noise:

\[
\frac{S}{N} = \frac{P}{(n-1) \cdot P \times \alpha + N_o \times B_{eq}}
\]
What happens in case of non-uniform power of data streams?

**Situation 1:**
- $n_{\text{max}}$ datas of power $P$ --> minimum S/N leading to error free transmission

\[
\frac{S}{N}_{\text{min}} = \frac{P}{(n_{\text{max}} - 1) \cdot P \times \alpha}
\]

*(White noise neglected)*

**Situation 2:**
- $n_{\text{max}}$ datas
- Data 1 to $(n-1)$ of power $P$ and $n^{\text{th}}$ Data of power $(\beta \cdot P) > P$

\[
R_X(t) = s_{D1}(t) + s_{D2}(t) \times \alpha + \ldots + s_{Dn}(t) \times \alpha
\]

Principles of operation
What happens in case of non-uniform power of data streams?

**Situation 1:**
- $n_{\text{max}}$ datas of power $P$ --> minimum S/N leading to error free transmission

\[
\frac{S}{N}_{\text{min}} = \frac{P}{(n_{\text{max}} - 1) \cdot P \times \alpha}
\]

*(White noise neglected)*

**Situation 2:**
- $n_{\text{max}}$ datas
- Data 1 to (n-1) of power $P$ and $n^{th}$ Data of power $(\beta \cdot P) > P$

\[
\frac{S}{N} = \frac{P}{(n_{\text{max}} - 1 + \beta) \cdot P \times \alpha} < \frac{S}{N}_{\text{Min}}
\]
What happens in case of non-uniform power of data streams?

**Situation 1:**
- \( n_{\text{max}} \) datas of power \( P \) --> minimum S/N leading to error free transmission

\[
\frac{S}{N}_{\text{min}} = \frac{P}{(n_{\text{max}} - 1) \cdot P \times \alpha}
\]

(White noise neglected)

**Situation 2:**
- \( n_{\text{max}} \) datas
- Data 1 to (n-1) of power \( P \) and \( n^{th} \) Data of power \( (\beta \cdot P) > P \)

\[
\frac{S}{N}\left|_{\text{Data 1 to (n-1)}}\right. = \frac{P}{(n_{\text{max}} - 1 + \beta) \cdot P \times \alpha} < \frac{S}{N}\left|_{\text{Min}}\right.
\]

Data 1 to (n-1) lost
What happens in case of non-uniform power of data streams?

**Situation 1:**
- $n_{\text{max}}$ datas of power $P$ --> minimum $S/N$ leading to error free transmission

$$\frac{S}{N}_{\text{min}} = \frac{P}{(n_{\text{max}} - 1) \cdot P \times \alpha}$$  
(White noise neglected)

**Situation 2:**
- $n_{\text{max}}$ datas
- Data 1 to $(n-1)$ of power $P$ and $n^{\text{th}}$ Data of power $(\beta \cdot P) > P$

$$\frac{S}{N}_{n^{\text{th}} \text{Data}} = \frac{\beta \cdot P}{(n_{\text{max}} - 1 + \beta) \cdot P \times \alpha} \approx \beta \cdot \frac{S}{N}_{\text{Min}} > \frac{S}{N}_{\text{Min}}$$

Only data $n$ is detected
-CDMA/DS allow transmission of many data on one single channel

-Data are coded using binary pseudo random sequences with a bit rate much larger than the bit rate of Data

-Coding causes the spreading of all data over the same band

-Recovering of data at receiver requires:
  -pseudo random sequences at receiver identical to pseudo sequences at emitter
  -pseudo sequences at receiver synchronized with pseudo sequences at emitter
  -pseudo sequences as low correlated as possible
  -all coded Data to be transmitted with the same power
Blockdiagram of a CDMA/DS System

signals:  
\[ s_D \equiv \text{data signal} \]  
\[ s_S \equiv \text{spread signal (baseband)} \]  
\[ s_S' \equiv \text{spread signal (rf carrier)} \]

bandwidths:  
\[ B_D \equiv \frac{1}{T_D} \]  
\[ B_S \equiv \frac{1}{T_{PN}} \text{ (baseband)} \]  
\[ B_{S'} \equiv \text{transmission bandwidth (spread rf bandwidth)} \]
- If needed, a few related to spread spectrum systems: