

# Analysis and Optimization of the Asian Mobile and Terrestrial Digital Television Systems

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- 2 Analysis and Comparison of DVB-T and DTMB Systems
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- 4 Data-aided Channel Estimation for TDS-OFDM
- 5 Conclusion

## Part I : Digital Television Broadcasting

- Context
- Digital TV broadcasting
- Channel Model
- Orthogonal Frequency-Division Multiplexing

# Milestones



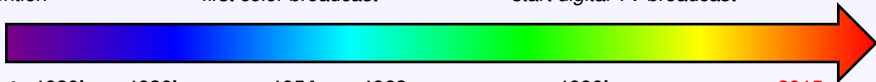
*invention*



*first color broadcast*



*start digital TV broadcast*



late 1920's

1930's

1954

1962

1990's

2015



*first commercial deployment*



*first satellite relay*

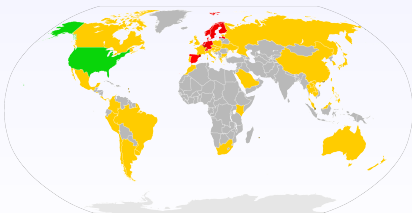


*only DTV in nearly 40 countries*

# Transition to Digital TV

## Motivations :

- Better view quality  $\Rightarrow$  high definition display
- Diverse view interests  $\Rightarrow$  more programs and channels
- Improved spectrum efficiency  $\Rightarrow$  digital dividend
- Higher power efficiency  $\Rightarrow$  less power consumption & better coverage
- Novel viewing behaviors  $\Rightarrow$  interactive TV, 3 dimensional (3D) display etc.



## ■ Transition completed :

- ▶ Germany, Switzerland, Sweden, Norway, Spain, etc.

## ■ Full-power analogue broadcasts ended :

- ▶ the United States

## ■ Transition in progress :

- ▶ France, China, Japan, Canada, Australia, India etc.

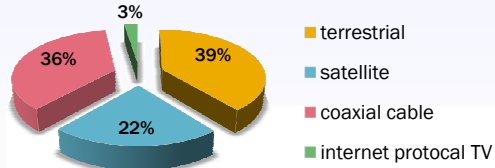
# Transition to Digital TV

## Motivations :

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- Diverse view interests  $\Rightarrow$  more programs and channels
- Improved spectrum efficiency  $\Rightarrow$  digital dividend
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## TV Transmission methods

- **Terrestrial transmission**
- Coaxial cable
- Satellite
- Internet Protocol TV (IPTV)

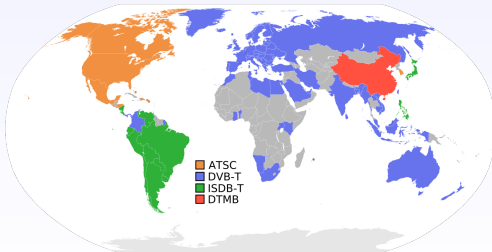


Market share of different reception methods

# Digital Television Terrestrial Broadcast

Main DTTB standards in the world :

- **Advanced Television Standards Committee A/53 (ATSC)**
- **Digital Video Broadcasting–Terrestrial (DVB–T)**
- **Integrated Services Digital Broadcasting–Terrestrial (ISDB–T)**
- **Digital Terrestrial/Television Multimedia Broadcasting (DTMB)**



Export Innovation Bretagne Emploi  
 e-TV Chine USA Export Inno  
 gne Emploi PME Mobile-TV  
 Exp Innovation E... Mobile-TV  
 e-TV Chine USA Export Inno  
 gne Emploi PME Mobile-TV  
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 gne Emploi PME Mobile-TV Chine



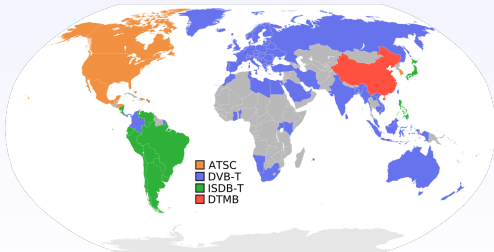
**Mobile  
 TV  
 World**

Objective : comparative  
 study of different DTV  
 standards.

# Digital Television Terrestrial Broadcast

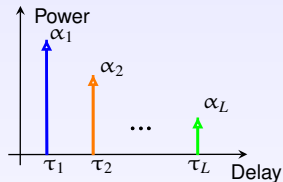
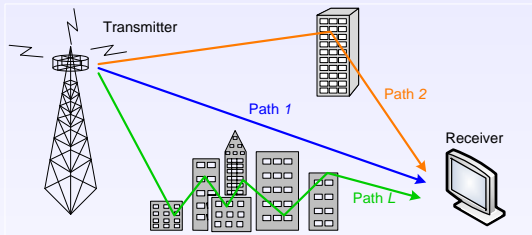
Main DTTB standards in the world :

- Advanced Television Standards Committee A/53 (**ATSC**) ⇒ **ATSC-M/H, MediaFLO**
- Digital Video Broadcasting–Terrestrial (**DVB–T**) ⇒ **DVB–T2**
- Integrated Services Digital Broadcasting–Terrestrial (**ISDB–T**) ⇒ **ISDB–T International**
- Digital Terrestrial/Television Multimedia Broadcasting (**DTMB**)





# Multipath propagation



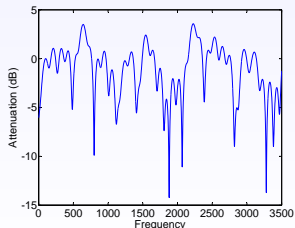
*signal dispersion in the time domain*

- Channel Impulse Response (CIR) :

$$h(\tau) = \sum_l \alpha_l \delta(\tau - \tau_l)$$

- Channel Frequency Response (CFR) :

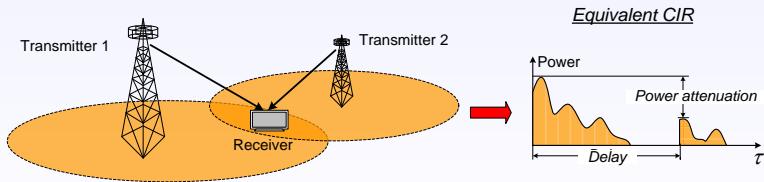
$$H(f) \triangleq \int_{-\infty}^{+\infty} h(\tau) e^{-j2\pi f\tau} d\tau = \sum_l \alpha_l e^{-j2\pi f\tau_l}$$



*selective fading in the frequency domain*

# Single frequency network

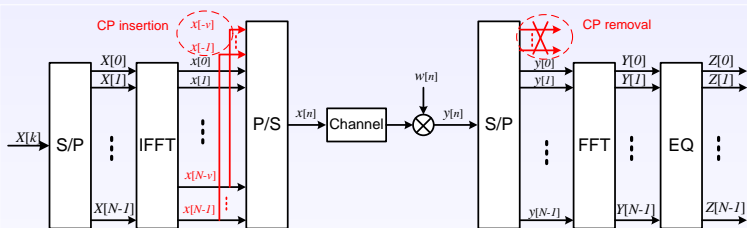
- Single transmitter
- Multiple transmitters in a **M**ulti-**F**requency **N**etwork (MFN)
- Multiple transmitters in a **S**ingle **F**requency **N**etwork (SFN)



# Orthogonal Frequency-Division Multiplexing (OFDM)

## Principle

One high-speed data stream  $\Rightarrow$  many parallel, low-speed data streams



$$\mathbf{y}^{(i)} = \mathbf{H}_{\text{circ}} \mathbf{x}^{(i)} + \mathbf{w}, \text{ where } \mathbf{H}_{\text{circ}} =$$

$$\begin{bmatrix} h_0 & 0 & h_{L-1} & \cdots & h_1 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ h_{L-1} & \cdots & h_{L-1} & \cdots & h_{L-1} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & h_{L-1} & \cdots & 0 \\ & & & & h_0 \end{bmatrix}_{N \times N}$$

Linear convolution

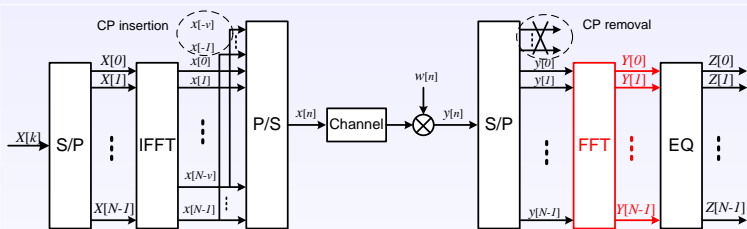


Circular convolution

# Orthogonal Frequency-Division Multiplexing (OFDM)

## Principle

One high-speed data stream  $\Rightarrow$  many parallel, low-speed data streams



$$\mathbf{Y}^{(i)} = \mathbf{F}_N \mathbf{y}^{(i)} = \mathbf{F}_N \mathbf{H}_{\text{circ}} \mathbf{F}_N^H \mathbf{X}^{(i)} + \mathbf{W} = \mathbf{H}_{\text{diag}} \mathbf{X}^{(i)} + \mathbf{W},$$

where  $\mathbf{H}_{\text{diag}} =$

$$\begin{bmatrix} H[0] & & & 0 \\ & \ddots & & \\ & & \ddots & \\ \vdots & & & H[N-1] \end{bmatrix}_{N \times N}$$

Circular convolution

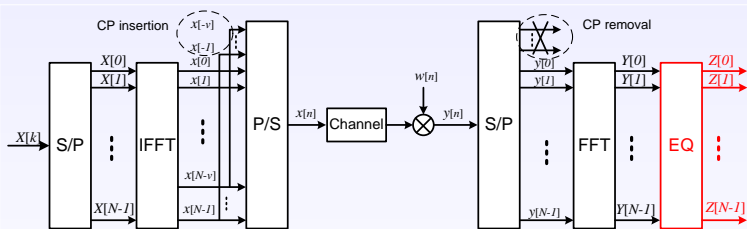
$\Downarrow$  FFT

Element-wise product

# Orthogonal Frequency-Division Multiplexing (OFDM)

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$$\mathbf{Y}^{(i)} = \mathbf{F}_N \mathbf{y}^{(i)} = \mathbf{F}_N \mathbf{H}_{\text{circ}} \mathbf{F}_N^H \mathbf{X}^{(i)} + \mathbf{W} = \mathbf{H}_{\text{diag}} \mathbf{X}^{(i)} + \mathbf{W},$$

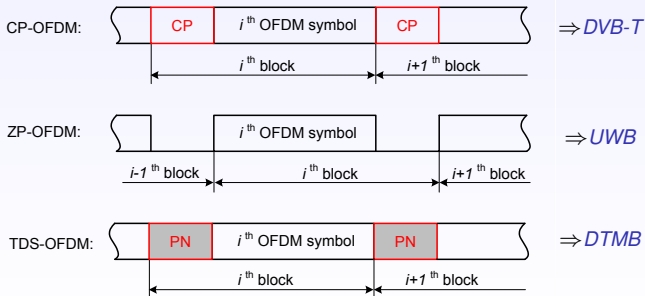
where  $\mathbf{H}_{\text{diag}} =$

$$\begin{bmatrix} H[0] & & & 0 \\ & \ddots & & \\ & & \ddots & \\ 0 & & & H[N-1] \end{bmatrix}_{N \times N}$$

One tap equalizer

## Different types of Guard Intervals (GI)

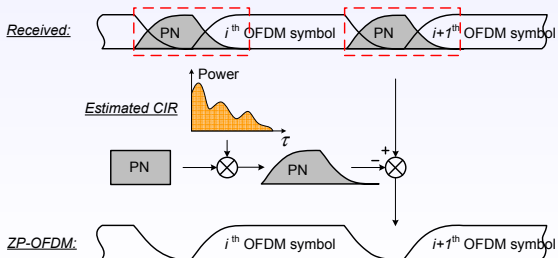
- **C**yclic **P**refix based OFDM (CP-OFDM)
- **Z**ero **P**adding based OFDM (ZP-OFDM)
- **T**ime **D**omain **S**ynchronous OFDM (TDS-OFDM)



# Equalization of TDS-OFDM signal

Remove PN sequence from the received signal

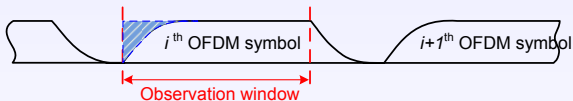
- Generate a perfect PN sequence
- Convolve with an estimated CIR
- Subtract the estimated PN sequence from received signal
- Turn TDS-OFDM signal to ZP-OFDM signal



# Equalization of ZP-OFDM signal

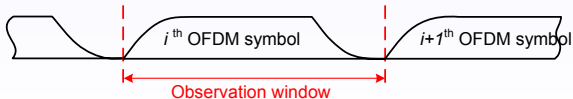
## OverLap-and-Add (OLA)

- ✓ Not require larger FFT operations
- ✓ Same equalizer as CP-OFDM
- ✗ Boost the noise



## Equalize with a longer observation window

- ✓ Equalize within  $N + \nu$  symbols
- ✓ Immune to  $\nu$  channel nulls
- ✗ Require larger FFT size
- ✗ More complex equalization than CP-OFDM





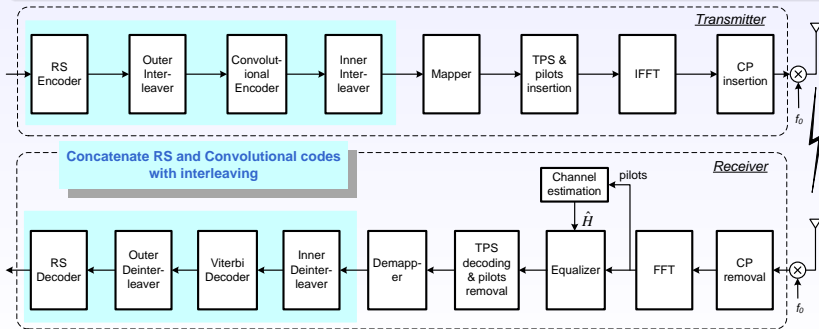
## Part II : Analysis and Comparison of DVB-T and DTMB Systems

- Introduction of the DVB-T and DTMB systems
- Comparisons of the DVB-T and DTMB systems
- BER performance of the DVB-T and DTMB systems

# Introduction on DVB-T and DTMB systems

## DVB-T system

- CP assisted OFDM modulation
- Frequency pilot symbol assisted channel estimation
- Concatenate RS and convolutional codes with interleaving (moderate depth)

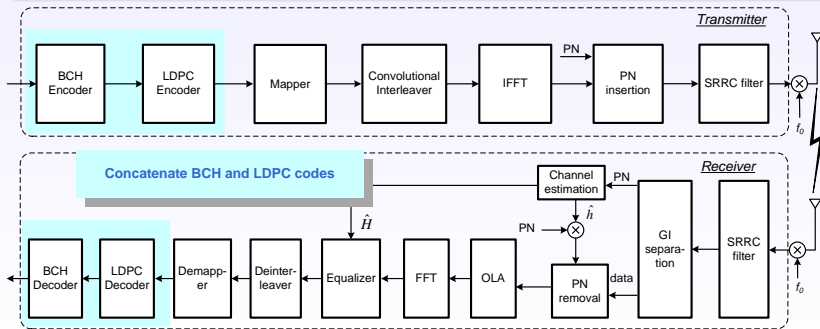


Block diagram of DVB-T system

# Introduction on DVB-T and DTMB systems

## DTMB system

- TDS-OFDM modulation
- PN sequence assisted channel estimation
- Concatenate BCH and LDPC codes with deep convolutional interleaver



Block diagram of DTMB system

## Main parameters of DVB-T and DTMB

|                      |        | DVB-T                   |         | DTMB                                 |                          |
|----------------------|--------|-------------------------|---------|--------------------------------------|--------------------------|
|                      |        | 2K mode                 | 8K mode | Single carrier                       | Multicarrier             |
| Number of subcarrier |        | 2048                    | 8192    | 1                                    | 3780                     |
| GI                   | Length | 1/4, 1/8, 1/16, 1/32    |         | 1/6                                  | 1/4, 1/9                 |
|                      | Power  | non-boost               |         | non-boost                            | boost by 2               |
| Pilot                |        | 176                     | 701     | —                                    |                          |
| Mapping              |        | QPSK, 16QAM, 64QAM      |         | 4QAM-NR,<br>QPSK,<br>16QAM,<br>32QAM | QPSK,<br>16QAM,<br>64QAM |
| Interleaving         | Outer  | convolutional           |         | —                                    |                          |
|                      | Inner  | bitwise + symbol        |         | time domain                          | time & frequency domain  |
| Coding               | Outer  | Reed-Solomon (204, 188) |         | BCH (762, 752)                       |                          |
|                      | Inner  | convolutional code      |         | LDPC                                 |                          |
|                      | Rate   | 1/2, 2/3, 3/4, 5/6, 7/8 |         | 0.4, 0.6, 0.8                        |                          |

# Power efficiency

## Objective

Evaluate the power allocated to the useful data transmission

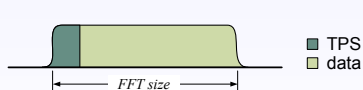
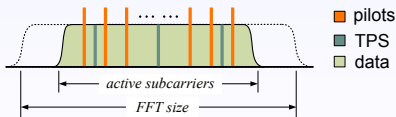
## Factors that affect useful power

### DVB-T :

- Transmission parameter signalling (TPS)
- pilots with power boost
- GI

### DTMB :

- TPS
- **GI with power boost**



## Power efficiency factor

$$\gamma = \frac{P_{data}}{P_{all}} = \frac{N_{data}}{N_{data} + N_{TPS} + N_{pilot} \times \eta_{pilot}} \times \frac{1}{1 + \nu \times \eta_{GI}}$$

- ▶  $N_{data}$  number of data subcarriers → 1512 (6048) → 3744
- ▶  $N_{TPS}$  number of TPS → 17 (68) → 36
- ▶  $N_{pilot}$  number of pilots → 176 (701) → 0
- ▶  $\nu$  fraction of GI over data → 1/4, 1/8, 1/16, 1/32 → 1/4, 1/9
- ▶  $\eta_{pilot}$  boost factor of pilots → 16/9 → 1
- ▶  $\eta_{GI}$  boost factor of GI → 1 → 2

|                         | DVB-T   | DTMB                                   |
|-------------------------|---|--|
| Power efficiency factor | 0.66 ( $\nu=1/4$ ), 0.73 ( $\nu=1/8$ ),<br>0.77 ( $\nu=1/16$ ), 0.79 ( $\nu=1/32$ ) | 0.66 ( $\nu=1/4$ ), 0.81 ( $\nu=1/9$ ) |

# Simulation parameters

## Objective

Evaluate the transmission efficiency in terms of bit error rate (BER)

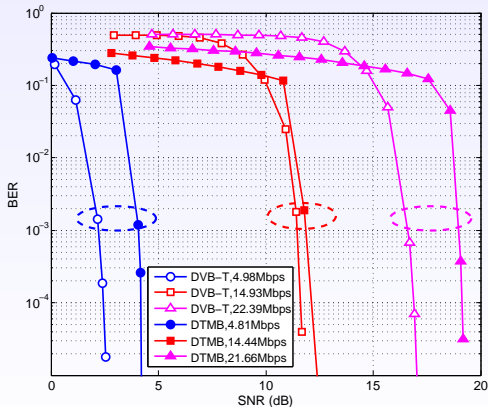
## Simulation setups

- F1 (Ricean) and P1 (Rayleigh) channels
- DVB-T : GI=1/4, 2K mode
- DTMB : GI=1/4, boosted PN, interleaving time delay 170 OFDM symbols
- 3 pairs of working modes from each system

| System | Modulation | Channel Coding                     | Code Rate | Bitrate (Mbps) |
|--------|------------|------------------------------------|-----------|----------------|
| DVB-T  | QPSK       | RS code + Convolutional code R=1/2 | 0.46      | 4.98           |
|        | 16QAM      | RS code + Convolutional code R=3/4 | 0.69      | 14.93          |
|        | 64QAM      | RS code + Convolutional code R=3/4 | 0.69      | 22.39          |
| DTMB   | QPSK       | BCH code + LDPC code (7493, 3048)  | 0.4       | 4.81           |
|        | 16QAM      | BCH code + LDPC code (7493, 4572)  | 0.6       | 14.44          |
|        | 64QAM      | BCH code + LDPC code (7493, 4572)  | 0.6       | 21.66          |

# BER comparison of DVB-T and DTMB systems

## Performance with perfect channel estimation



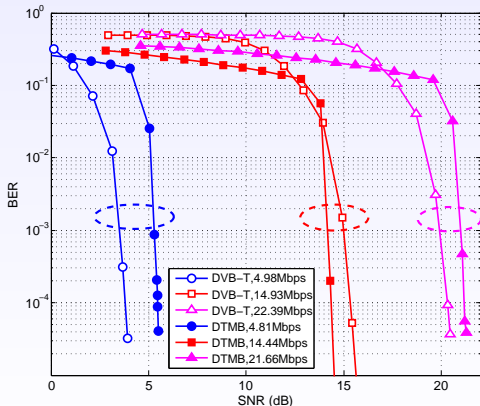
*F1 (Ricean) channel*

- ▶ DVB-T performs better in all cases of F1 channel



# BER comparison of DVB-T and DTMB systems

## Performance with perfect channel estimation



*P1 (Rayleigh) channel*

- ▶ DVB-T performs better in all cases of F1 channel
- ▶ DTMB is robust in worse channel conditions

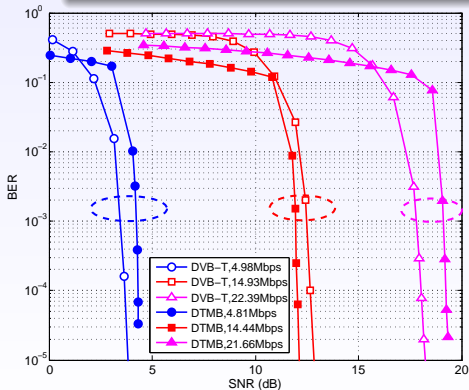
1.0 dB better in 16QAM case

DVB-T is more efficient than DTMB in perfect channel estimation case.

# BER comparison of DVB-T and DTMB systems

## ● Performance with real channel estimation

- ▶ DVB-T : pilot-assisted channel estimation with 1-D Wiener filtering
- ▶ DTMB : PN-correlation-based channel estimation



*F1 (Ricean) channel*

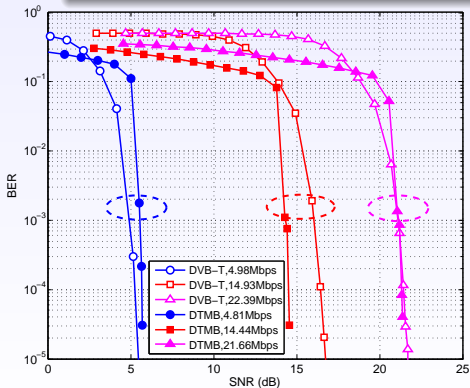
## ▶ Degradation due to channel estimation error :

- ▶ DVB-T :  
1.0 ~ 1.3 dB in F1,
- ▶ DTMB :  
0.2 ~ 0.6 dB in F1,

# BER comparison of DVB-T and DTMB systems

## Performance with real channel estimation

- ▶ DVB-T : pilot-assisted channel estimation with 1-D Wiener filtering
- ▶ DTMB : PN-correlation-based channel estimation



*P1 (Rayleigh) channel*

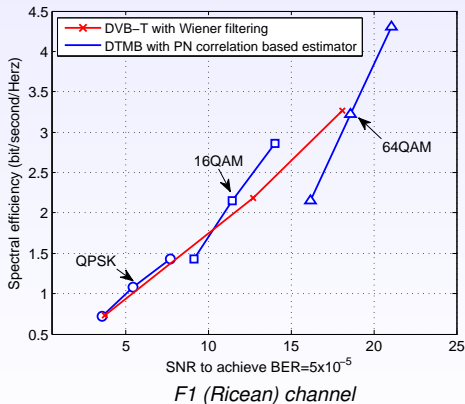
## Degradation due to channel estimation error :

- ▶ DVB-T :  
1.0 ~ 1.3 dB in F1,  
1.1 ~ 1.5 dB in P1
- ▶ DTMB :  
0.2 ~ 0.6 dB in F1,  
0.1 ~ 0.2 dB in P1

DTMB benefits from the power boost of the PN sequence

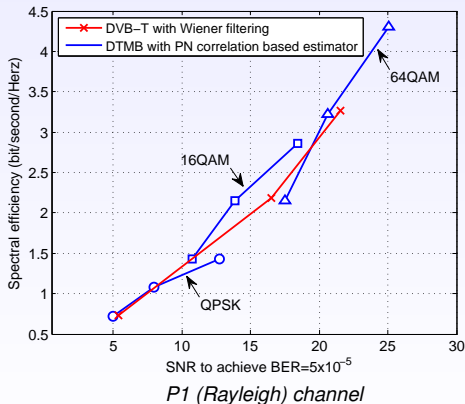
## BER comparison of DVB-T and DTMB systems

- Performance with shorter GI  $\Rightarrow$  DVB-T : 1/8, DTMB : 1/9



## BER comparison of DVB-T and DTMB systems

- Performance with shorter GI  $\Rightarrow$  DVB-T : 1/8, DTMB : 1/9



- DTMB is more efficient with shorter GI
- Difference of the performance is not significant

The spectral efficiencies of the two systems are close.

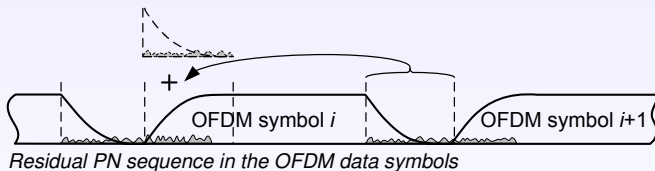
# Summary

- DTMB has more efficient data structure
  - ▶ Higher spectrum utilization
  - ▶ Higher power efficiency
- The overall performances of the two systems are very close in typical channel conditions
  - ▶ DVB-T performs better in perfect channel estimation cases
  - ▶ Channel estimation mechanism of DTMB is more reliable than that of DVB-T
  - ▶ DTMB is more efficient with shorter GI

## Part III : PN Sequence based Channel Estimation for TDS-OFDM

- GI structure of DTMB
- Classical PN-based channel estimators
- Improved time domain channel estimators
- Estimator in the insufficient long CP case

# Motivation





# Motivation

- Residual PN caused by imperfect channel estimation :

$$\xi[n] = \sum_{l=0}^{L-1} \Delta h_l c[n-l]_{\nu}, \quad 0 \leq n < \nu$$

- Interference caused by residual PN for the  $k^{\text{th}}$  subcarrier :

$$I[k] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} \xi[n] e^{-j\frac{2\pi}{N}nk} = \frac{1}{\sqrt{N}} \sum_{l=0}^{L-1} \Delta h_l \sum_{n=0}^{\nu-1} c[n-l]_{\nu} e^{-j\frac{2\pi}{N}nk}$$

- Power of the interference for the  $k^{\text{th}}$  subcarrier :

$$\sigma_I^2[k] = \mathbb{E}[I^*[k]I[k]] = \frac{1}{N} \sum_{l=0}^{L-1} \sigma_{\Delta h_l}^2 \sum_{n_1, n_2=0}^{\nu-1} c_l^*[n_1] c_l[n_2] e^{-j\frac{2\pi}{N}(n_2-n_1)k}$$

Channel estimation accuracy is crucial for TDS-OFDM !

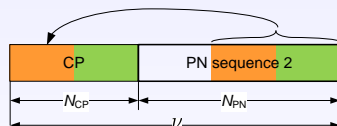
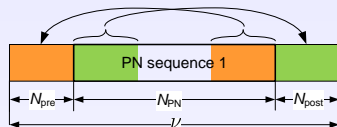
## Structure of the GI in DTMB

### Definition :

- ▶ Maximum length sequence (m-sequence)
- ▶ Prefix & postfix

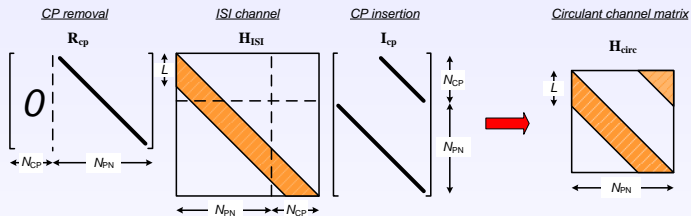
### Equivalent :

- ▶ Shifted m-sequence
- ▶ CP



# Structure of the GI in DTMB

## • Sufficient CP



Channel estimation using m-sequence :

- FFT-based frequency domain estimator
- Correlation-based time domain estimator

## Frequency domain channel estimation method

- Circular convolution in time  $\Rightarrow$  Element-wise product in frequency

$$\mathbf{D} = \mathbf{P}_d \mathbf{H} + \mathbf{W}$$

- Least square (LS) estimator :

$$\hat{\mathbf{H}} = (\mathbf{P}_d^{\mathcal{H}} \mathbf{P}_d)^{-1} \mathbf{P}_d^{\mathcal{H}} \mathbf{D} = \mathbf{H} + \underbrace{(\mathbf{P}_d^{\mathcal{H}} \mathbf{P}_d)^{-1} \mathbf{P}_d^{\mathcal{H}} \mathbf{W}}_{\boldsymbol{\xi}_{\hat{\mathbf{H}}}}$$

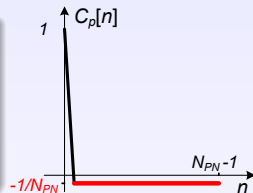
- Mean square error (MSE) :

$$\varepsilon_{\hat{\mathbf{H}}} = \frac{1}{N_{\text{PN}}} \text{Tr} (\mathbb{E} [\boldsymbol{\xi}_{\hat{\mathbf{H}}} \boldsymbol{\xi}_{\hat{\mathbf{H}}}^{\mathcal{H}}]) = \frac{\sigma_W^2}{N_{\text{PN}}^2} \sum_{k=0}^{N_{\text{PN}}-1} \frac{1}{|P[k]|^2} = \frac{2\sigma_W^2}{N_{\text{PN}} + 1}$$

# Time domain channel estimation method

## Correlation property of m-sequence

$$C_p[n] = \frac{1}{N_{PN}} \sum_{m=0}^{N_{PN}-1} p[m] p^*[n+m]_{PN} = \begin{cases} 1 & n=0 \\ -\frac{1}{N_{PN}} & 0 < n < N_{PN} \end{cases}$$



## • PN sequence correlation based estimator :

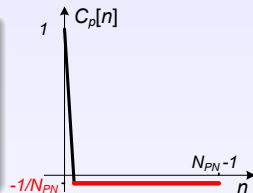
$$\bar{\mathbf{h}} = \frac{1}{N_{PN}} \mathbf{P}_{\text{cor}} \mathbf{d} = \frac{1}{N_{PN}} \mathbf{P}_{\text{cor}} \mathbf{P}_{\text{circ}} \mathbf{h} + \frac{1}{N_{PN}} \mathbf{P}_{\text{cor}} \mathbf{w},$$

$$\text{denote } \mathbf{Q} \triangleq \frac{1}{N_{PN}} \mathbf{P}_{\text{cor}} \mathbf{P}_{\text{circ}} = \begin{bmatrix} 1 & -\frac{1}{N_{PN}} & \cdots & -\frac{1}{N_{PN}} \\ -\frac{1}{N_{PN}} & 1 & \cdots & -\frac{1}{N_{PN}} \\ \vdots & \vdots & \ddots & \vdots \\ -\frac{1}{N_{PN}} & -\frac{1}{N_{PN}} & \cdots & 1 \end{bmatrix}$$

# Time domain channel estimation method

## Correlation property of m-sequence

$$C_p[n] = \frac{1}{N_{\text{PN}}} \sum_{m=0}^{N_{\text{PN}}-1} p[m] p^*[n+m]_{\text{PN}} = \begin{cases} 1 & n = 0 \\ -\frac{1}{N_{\text{PN}}} & 0 < n < N_{\text{PN}} \end{cases}$$

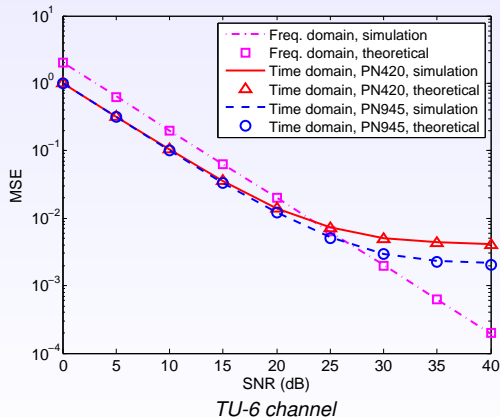


### • MSE :

$$\begin{aligned} \varepsilon_{\bar{h}} &= \frac{1}{N_{\text{PN}}} \text{Tr} \left( \mathbb{E} \left[ \bar{\xi}_{\bar{h}} \bar{\xi}_{\bar{h}}^{\mathcal{H}} \right] \right) = \underbrace{\frac{1}{N_{\text{PN}}} \text{Tr} \left( (\mathbf{Q} - \mathbf{I}_{N_{\text{PN}}}) \wedge (\mathbf{Q} - \mathbf{I}_{N_{\text{PN}}})^{\mathcal{H}} \right)}_{\text{self interference}} + \underbrace{\frac{\sigma_w^2}{N_{\text{PN}}^3} \text{Tr} \left( \mathbf{P}_{\text{cor}} \mathbf{P}_{\text{cor}}^{\mathcal{H}} \right)}_{\text{noise}} \\ &= \frac{N_{\text{PN}} - 1}{N_{\text{PN}}^3} + \frac{1}{N_{\text{PN}}} \sigma_w^2 \end{aligned}$$

⇒ **Estimation error floor @**  $\frac{N_{\text{PN}} - 1}{N_{\text{PN}}^3}$

# Frequency and time domain estimators



- ▶ Time domain estimator performs better in low SNR
- ▶ Time domain estimator suffers error floor in high SNR
- ▶ Better performance using longer PN sequence

## Reduce estimation error floor, Method 1

- Idea 1 : Use a linear transformation  $\mathbf{\Omega}$  such that  $\mathbf{\Omega}\mathbf{Q} = \mathbf{I}_{N_{PN}} \Rightarrow \mathbf{\Omega} = \mathbf{Q}^{-1}$

- Improved estimator 1 :

$$\hat{\mathbf{h}}_1 = \mathbf{Q}^{-1}\bar{\mathbf{h}} = \mathbf{h} + \frac{1}{N_{PN}}\mathbf{Q}^{-1}\mathbf{P}_{\text{cor}}\mathbf{w}$$

compute  $\mathbf{Q}^{-1}$  in advance

$$\mathbf{Q}^{-1} = \begin{bmatrix} \frac{2N_{PN}}{N_{PN}+1} & \frac{N_{PN}}{N_{PN}+1} & \cdots & \frac{N_{PN}}{N_{PN}+1} \\ \frac{N_{PN}}{N_{PN}+1} & \frac{2N_{PN}}{N_{PN}+1} & \cdots & \frac{N_{PN}}{N_{PN}+1} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{N_{PN}}{N_{PN}+1} & \frac{N_{PN}}{N_{PN}+1} & \cdots & \frac{2N_{PN}}{N_{PN}+1} \end{bmatrix}$$

- MSE :

$$\varepsilon_{\hat{\mathbf{h}}_1} = \frac{\sigma_w^2}{N_{PN}^2} \text{Tr}(\mathbf{Q}^{-1}) = \frac{2\sigma_w^2}{N_{PN} + 1}$$

⇒ No estimation error floor

⇒ Noise component power boosted by 2



## Reduce estimation error floor, Method 1 with truncation

- Truncate the estimate to real channel length  $L$  :

$$\tilde{\mathbf{h}} = \mathbf{I}_{L \times N_{\text{PN}}} \tilde{\mathbf{h}} = \tilde{\mathbf{Q}} \mathbf{h} + \frac{1}{N_{\text{PN}}} \mathbf{I}_{L \times N_{\text{PN}}} \mathbf{P}_{\text{cor}} \mathbf{w}$$

- Improved estimator 1 with truncation :

$$\hat{\mathbf{h}}'_1 = \tilde{\mathbf{Q}}^{-1} \tilde{\mathbf{h}} = \mathbf{h} + \frac{1}{N_{\text{PN}}} \tilde{\mathbf{Q}}^{-1} \mathbf{I}_{L \times N_{\text{PN}}} \mathbf{P}_{\text{cor}} \mathbf{w}$$

$$\tilde{\mathbf{Q}}^{-1} = \begin{bmatrix} a & b & \cdots & b \\ b & a & \cdots & b \\ \vdots & \vdots & \ddots & \vdots \\ b & b & \cdots & a \end{bmatrix}$$

$$\begin{cases} a = 1 + \frac{L-1}{N_{\text{PN}}^2 + 2N_{\text{PN}} - N_{\text{PN}} L - L + 1} \\ b = \frac{N_{\text{PN}}}{N_{\text{PN}}^2 + 2N_{\text{PN}} - N_{\text{PN}} L - L + 1} \end{cases}$$

- MSE :

$$\varepsilon_{\hat{\mathbf{h}}'_1} = \frac{\sigma_w^2}{LN_{\text{PN}}} \text{Tr}(\tilde{\mathbf{Q}}^{-1}) = \frac{\frac{1}{N_{\text{PN}}}}{1 + \frac{1-L}{N_{\text{PN}}(N_{\text{PN}} - L + 2)}} \sigma_w^2$$

⇒ No estimation error floor

⇒  $\text{MSE} \approx \frac{\sigma_w^2}{N_{\text{PN}}}$ , when  $N_{\text{PN}} \gg L$

## Reduce estimation error floor, Method 2

- Idea 2 : Subtract interference using channel estimate

- Improved estimator 2 :

$$\hat{\mathbf{h}}_2 = \tilde{\mathbf{h}} - \tilde{\Delta} \tilde{\mathbf{h}}$$

$$\tilde{\Delta} = \begin{bmatrix} 0 & -\frac{1}{N_{\text{PN}}} & \cdots & -\frac{1}{N_{\text{PN}}} \\ -\frac{1}{N_{\text{PN}}} & 0 & \cdots & -\frac{1}{N_{\text{PN}}} \\ \vdots & \vdots & \ddots & \vdots \\ -\frac{1}{N_{\text{PN}}} & -\frac{1}{N_{\text{PN}}} & \cdots & 0 \end{bmatrix}$$

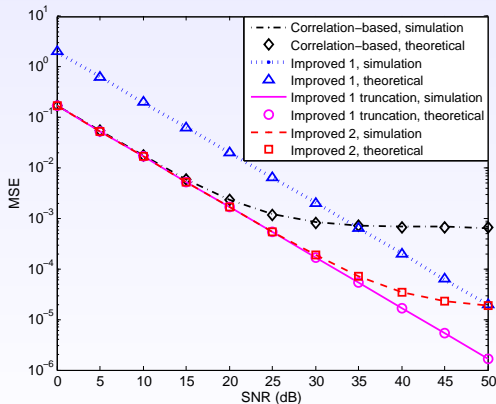
- MSE :

$$\varepsilon_{\hat{h}_2} = \frac{(L-1)(L^2-3L+3)}{N_{\text{PN}}^4 L} + \left( \frac{1}{N_{\text{PN}}} + \frac{(L-1)(2-L-N_{\text{PN}})}{N_{\text{PN}}^4} \right) \sigma_w^2.$$

⇒ Estimation error floor reduced by approximately  $\left(\frac{L}{N_{\text{PN}}}\right)^2$

⇒  $\text{MSE} \approx \frac{\sigma_w^2}{N_{\text{PN}}}$ , when  $N_{\text{PN}} \gg L$

# Improved time domain estimators



PN420,  $L = 43$

## ► Method 1 :

- ✓ No error floor
- ✗ Boosted noise

## ► Method 1 with truncation :

- ✓ No error floor
- ✓ Without boosting noise

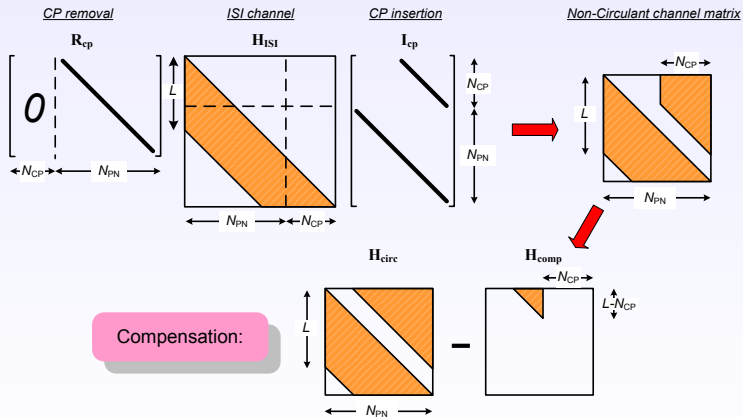
## ► Method 2 :

- ✓ Without boosting noise
- ✓ Reduce error floor when  $N_{PN} \gg L$

**Method 1 with truncation is the best choice.**

# Improved estimator in the insufficient CP case

## Insufficient CP



## Improved estimator in the insufficient CP case

- Received PN sequence :

$$\mathbf{d}^{(i)} = \mathbf{H}_{\text{circ}}\mathbf{p}^{(i)} - \underbrace{\mathbf{H}_{\text{comp}}\mathbf{p}^{(i)}}_{\text{loss of cyclicity}} + \underbrace{\mathbf{R}_{\text{cp}}\mathbf{H}_{\text{IBI}}\mathbf{x}^{(i-1)}}_{\text{IBI}} + \mathbf{w}$$

- Improved methods :

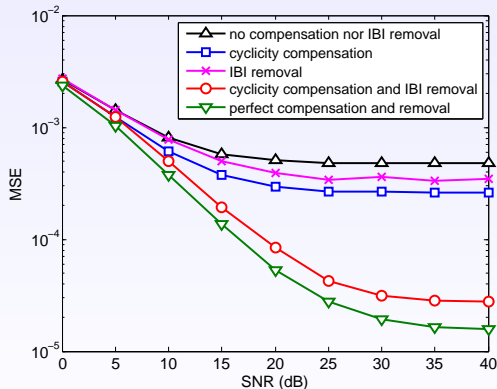
- ▶ Compensate cyclicity :

$$\tilde{\mathbf{d}}^{(i)} = \mathbf{d}^{(i)} + \hat{\mathbf{H}}_{\text{comp}}\mathbf{p}^{(i)} \approx \mathbf{H}_{\text{circ}}\mathbf{p}^{(i)} + \mathbf{R}_{\text{cp}}\mathbf{H}_{\text{IBI}}\mathbf{x}^{(i-1)} + \mathbf{w}$$

- ▶ Remove IBI :

$$\check{\mathbf{d}}^{(i)} = \tilde{\mathbf{d}}^{(i)} - \mathbf{R}_{\text{cp}}\hat{\mathbf{H}}_{\text{IBI}}\hat{\mathbf{x}}^{(i-1)} \approx \mathbf{H}_{\text{circ}}\mathbf{p}^{(i)} + \mathbf{w}$$

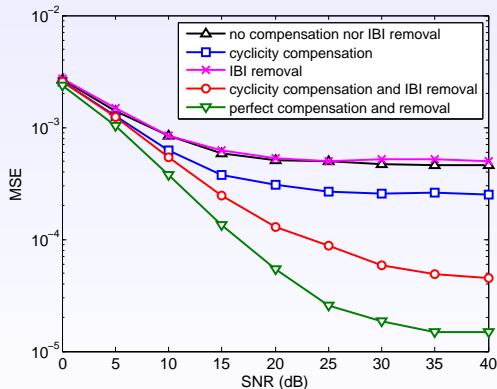
# Insufficient CP



$PN420, N_{PN} = 255, N_{CP} = 165, L = 244, QPSK$

- ▶ Cyclicity compensation is more efficient than IBI removal.
- ▶ Combination of cyclicity compensation and IBI removal approaches the performance of perfect compensation and IBI removal.

# Insufficient CP



$PN420, N_{PN} = 255, N_{CP} = 165, L = 244, 64QAM$

- ▶ Cyclicity compensation is more efficient than IBI removal.
- ▶ Combination of cyclicity compensation and IBI removal approaches the performance of perfect compensation and IBI removal.
- ▶ Performance of IBI removal degrades with high order constellation

# Summary

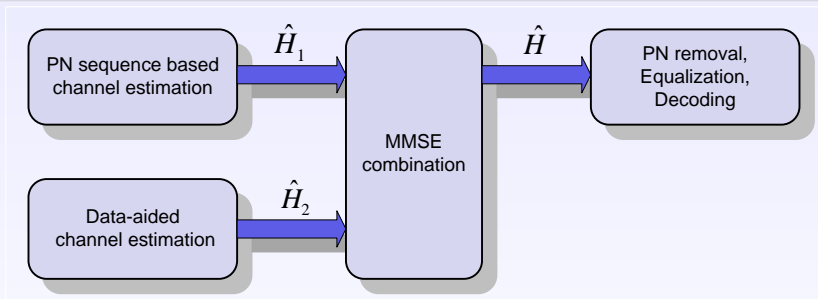
- GI specified in DTMB is seen as a shifted m-sequence and a CP
- Time domain correlation-based estimator performs better but suffers an estimation error floor
- Improved time domain estimators with reduced estimation error floor
  - ▶ Method 1 : left multiplying by  $\mathbf{Q}^{-1}$
  - ▶ Method 1 with truncation : left multiplying by  $\bar{\mathbf{Q}}^{-1}$
  - ▶ Method 2 : subtracting the interference caused by imperfect correlation property
- Improved estimator when CP is insufficient
  - ▶ Cyclicity compensation
  - ▶ IBI removal



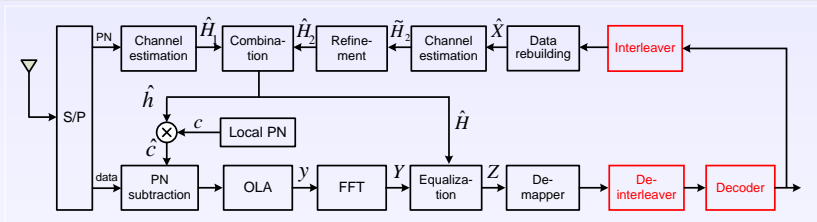
## Part IV : Data-aided Channel Estimation for TDS-OFDM

- Interference caused by imperfect PN removal
- Data-aided channel estimation
- Data-aided channel estimate refinement
- MMSE combination

# Data-aided channel estimation

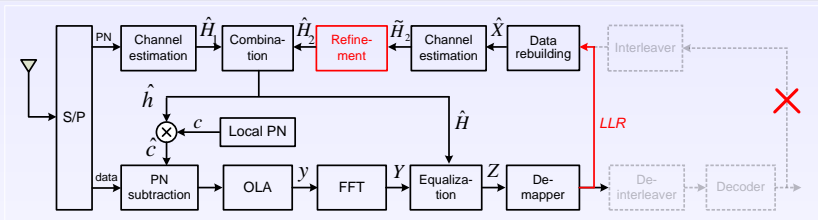


# Data-aided channel estimation



- Turbo channel estimation
- Deep interleaver & complicated decoder e.g. in DTMB :
  - ▶ Convolutional interleaver with a delay of 170 or 510 OFDM symbols
  - ▶ Iterative LDPC decoder

# Data-aided channel estimation



- Objective : low-complexity, low-time-delay channel estimation
- Proposed method :
  - ▶ Exclude interleaver, deinterleaver & decoder from the feedback loop
  - ▶ Feedback information from **soft-output demapper**
  - ▶ Refine the data-aided channel estimate

## Soft data rebuilding

- Log-likelihood ratio (LLR) from soft-output demapper :

$$\lambda_l[i, k] \triangleq \log \frac{P(b[i, k, l]=1|Z[i, k])}{P(b[i, k, l]=0|Z[i, k])} \Rightarrow \begin{cases} P(b[i, k, l] = 1 | Z[i, k]) = \frac{e^{\lambda_l[i, k]}}{1 + e^{\lambda_l[i, k]}} \\ P(b[i, k, l] = 0 | Z[i, k]) = \frac{1}{1 + e^{\lambda_l[i, k]}} \end{cases}$$

- a priori* probability of each constellation point :

$$P(X[i, k] = \alpha_j | Z[i, k]) = \prod_{l=1}^{\log_2 \mu} P(b[i, k, l] = \kappa_l(\alpha_j) | Z[i, k])$$

- Soft data rebuilding :

$$\hat{X}[i, k] = \sum_{\alpha_j \in \Psi} \alpha_j \cdot P(X[i, k] = \alpha_j | Z[i, k])$$

$$\Rightarrow \begin{cases} \hat{X}[i, k] = \tanh\left(\frac{\lambda_1[i, k]}{2}\right) & \text{BPSK} \\ \hat{X}[i, k] = \frac{1}{\sqrt{2}} \left[ \tanh\left(\frac{\lambda_1[i, k]}{2}\right) + j \tanh\left(\frac{\lambda_2[i, k]}{2}\right) \right] & \text{QPSK} \end{cases}$$

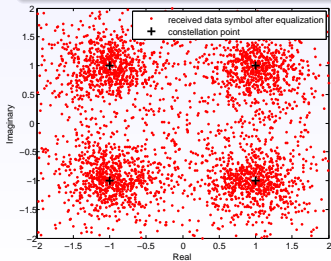
# Soft data rebuilding

- Log-likelihood ratio (LLR) from soft-output demapper :

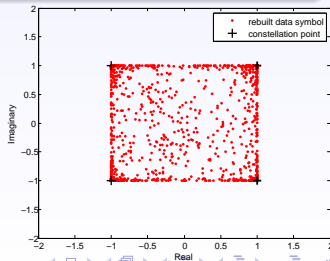
$$\lambda_l[i, k] \triangleq \log \frac{P(b[i, k, l]=1|Z[i, k])}{P(b[i, k, l]=0|Z[i, k])} \Rightarrow \begin{cases} P(b[i, k, l] = 1 | Z[i, k]) = \frac{e^{\lambda_l[i, k]}}{1 + e^{\lambda_l[i, k]}} \\ P(b[i, k, l] = 0 | Z[i, k]) = \frac{1}{1 + e^{\lambda_l[i, k]}} \end{cases}$$

- a priori* probability of each constellation point :

$$P(X[i, k] = \alpha_j | Z[i, k]) = \prod_{l=1}^{\log_2 \mu} P(b[i, k, l] = \kappa_l(\alpha_j) | Z[i, k])$$



soft decision



# Instantaneous channel estimation

- Received frequency domain data symbol :

$$\mathbf{Y} = \mathbf{X}\mathbf{H} + \mathbf{W}$$

- LS estimator :

$$\hat{\mathbf{H}}^{\text{LS}} = \arg \min_H \mathbb{E}[\|\mathbf{Y} - \mathbf{X}\mathbf{H}\|^2 | \mathbf{Z}]$$

⇒

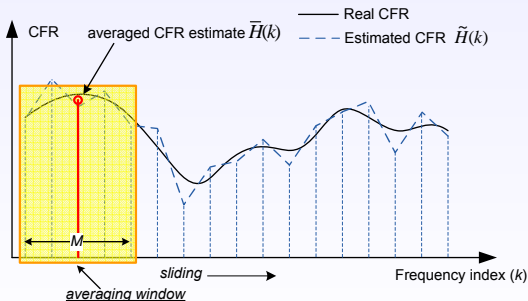
$$\hat{\mathbf{H}}^{\text{LS}} = \mathbb{E}[\mathbf{X}^{\text{H}}\mathbf{X} | \mathbf{Z}]^{-1} \mathbb{E}[\mathbf{X}^{\text{H}} | \mathbf{Z}] \mathbf{Y}$$

- Channel estimate for the  $k^{\text{th}}$  subcarrier :

$$\tilde{H}_2^{\text{LS}}[i, k] = \frac{\hat{X}[i, k]}{\mathbb{E}[|X[i, k]|^2 | Z[i, k]]} Y[i, k]$$

# One-Dimensional (1-D) Moving average

- Average the instantaneous channel estimates within a “window”
- Obtain a more accurate estimate for the central frequency of this window
- Slide the window to the adjacent subcarrier



- ▶ Refined estimate :

$$\begin{aligned}\tilde{H}_2[k] &= \frac{1}{M} \sum_{m \in \Theta_k} \tilde{H}_2[m] \\ &\approx H[k] + \frac{1}{M} \sum_{m \in \Theta_k} \frac{\hat{X}[m]^* W''[m]}{E_{\hat{X}}[m]}\end{aligned}$$

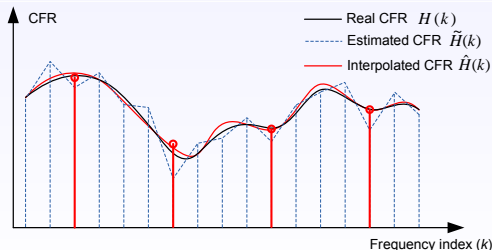
- ▶ MSE :

$$\varepsilon_{H_2} = \frac{\sigma_{W''}^2}{M^2 N} \sum_{k=0}^{N-1} \sum_{m \in \Theta_k} \frac{1}{E_{\hat{X}}[m]}$$



# 1-D Wiener filtering

- Select a bunch of subcarriers as “virtual pilots”
- Average instantaneous channel estimates over an averaging window
- Reliable estimate for virtual pilot position
- Repeat averaging over all virtual pilot positions
- Interpolate the estimates in virtual pilot positions



- ▶ Wiener filtering based interpolation :

$$\hat{H}_2[k] = \sum_{k_p \in \Xi} \omega_f[k, k_p] \tilde{H}_2[k_p]$$

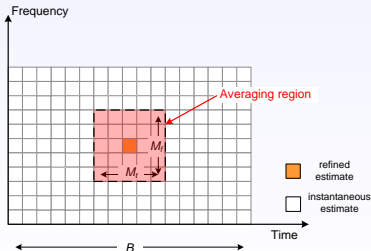
- ▶ Weighting coefficients :

$$\omega_f = \arg \min_{\omega_f} \mathbb{E}\{\|\mathbf{H} - \omega_f^T \tilde{\mathbf{H}}_2\|^2\}$$

## Two-Dimensional (2-D) refinements

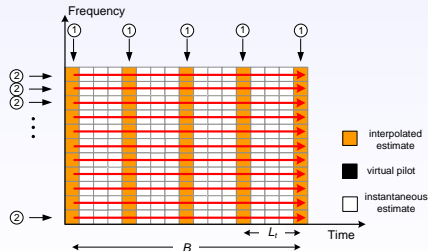
### 2-D Moving average

- Expand the averaging region across several OFDM symbols



### 2-D Wiener filtering

- 2-D virtual pilot grid
- Expanded the averaging region
- Wiener filtering in frequency
- Wiener filtering in time



# MMSE combination

- Linear combination of PN-based & data-aided channel estimates :

$$\hat{H} = \beta \hat{H}_1 + (1 - \beta) \hat{H}_2$$

- Minimum mean square error (MMSE) weighting factor :

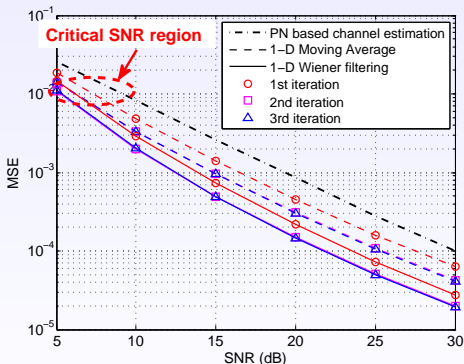
$$\beta_{opt} = \arg \min_{\beta} \{E\{|H - \hat{H}|^2\}\} = \arg \min_{\beta} \{\beta^2 \varepsilon_{\hat{H}_1} + (1 - \beta)^2 \varepsilon_{\hat{H}_2}\}$$

$$\Rightarrow \beta_{opt} = \frac{\varepsilon_{\hat{H}_2}}{\varepsilon_{\hat{H}_1} + \varepsilon_{\hat{H}_2}}$$

- Combined channel estimate is used for :
  - ▶ initial channel estimate of the next iteration
  - ▶ channel estimate for equalization

# MSE performance

## Time domain initial estimation with 1-D refinement methods



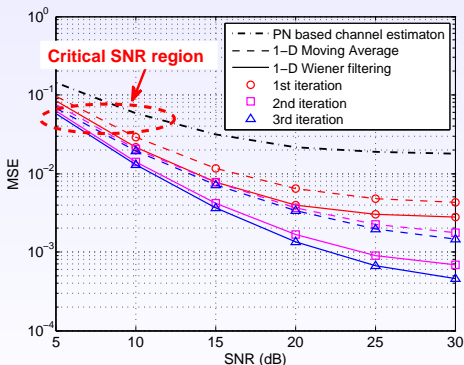
*QPSK, TU-6 channel,  $L = 43, M = L_f = 9$*

- ▶ Converge after 3 iterations
- ▶ Wiener filtering is more effective
- ▶ Improvement to the initial channel estimate :

1-D Moving average : 3.0 dB } @  $10^{-2}$   
 1-D Wiener filtering : 4.0 dB

# MSE performance

## Time domain initial estimation with 1-D refinement methods



QPSK, SFN channel,  $L = 219$ ,  $M = L_f = 3$

- ▶ Converge after 3 iterations
- ▶ Wiener filtering is more effective
- ▶ Improvement to the initial channel estimate :

1-D Moving average : 3.0 dB } @  $10^{-2}$   
 1-D Wiener filtering : 4.0 dB }

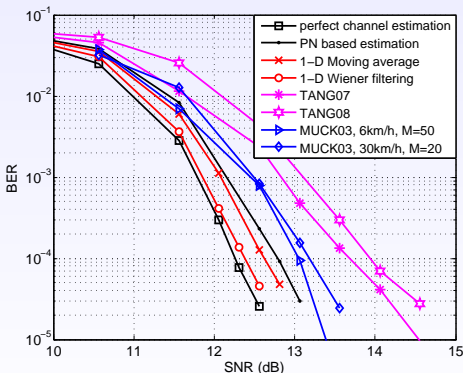
- ▶ Improvement in severe SFN channel :

1-D Moving average : 4.9 dB } @  $5 \times 10^{-2}$   
 1-D Wiener filtering : 5.7 dB }

Data-aided method significantly improves the PN-based estimate

# BER performance

## Time domain initial estimation with 1-D refinement methods

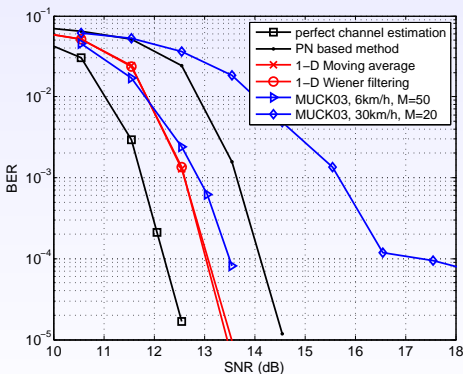


QPSK, TU-6 channel with a velocity of 30 km/h  
 $L = 43, M = L_f = 9$

- ▶ Gaps to the perfect channel estimation :
  - 1-D Moving average : **0.4 dB**
  - 1-D Wiener filtering : **0.2 dB**
- ▶ Improvements over PN-based channel estimation :
  - 1-D Moving average : **0.2 dB**
  - 1-D Wiener filtering : **0.4 dB**
- ▶ Better than methods in literatures

# BER performance

## Time domain initial estimation with 1-D refinement methods



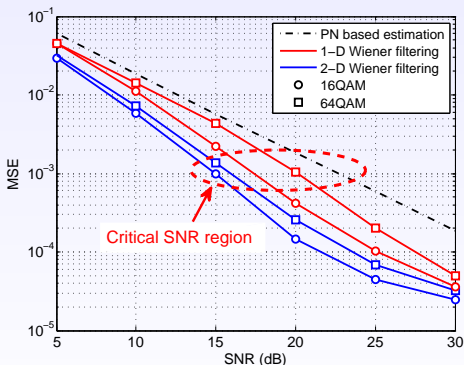
QPSK, SFN channel with a velocity of 30 km/h  
 $L = 219, M = L_f = 3$

- ▶ Gaps to the perfect channel estimation :
  - 1-D Moving average : **0.8 dB**
  - 1-D Wiener filtering : **0.8 dB**
- ▶ Improvements over PN-based channel estimation :
  - 1-D Moving average : **1.0 dB**
  - 1-D Wiener filtering : **1.1 dB**
- ▶ Better than methods in literatures

Data-aided methods acquire gains  
 over PN-based method

# MSE performance

## 1-D vs 2-D refinement methods



► Gains @MSE =  $10^{-3}$  in TU-6 :

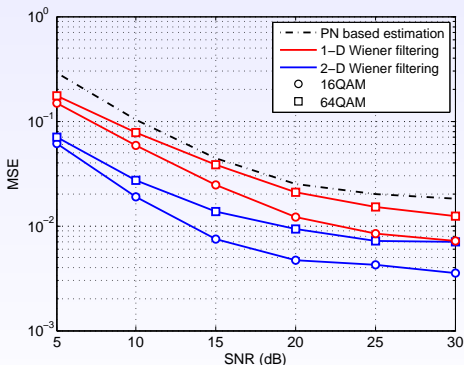
$\left\{ \begin{array}{l} 16\text{QAM} : 2.4 \text{ dB} \\ 64\text{QAM} : 4.2 \text{ dB} \end{array} \right.$

TU-6 channel with a velocity of 30 km/h  
 $M_f = L_f = 9, M_t = L_t = 2$



# MSE performance

## 1-D vs 2-D refinement methods



SFN channel with a velocity of 30 km/h  
 $M_f = L_f = 3, M_t = L_t = 2$

- ▶ Gains @MSE =  $10^{-3}$  in TU-6 :

$$\left\{ \begin{array}{l} 16\text{QAM} : 2.4 \text{ dB} \\ 64\text{QAM} : 4.2 \text{ dB} \end{array} \right.$$

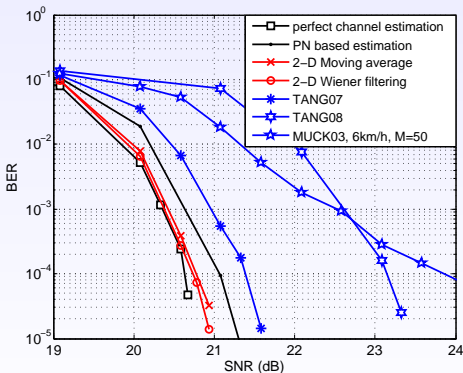
- ▶ Improvement @SNR = 20 dB in SFN :

$$\left\{ \begin{array}{l} 16\text{QAM} : 1.1 \times 10^{-2} \Rightarrow 4.9 \times 10^{-3} \\ 64\text{QAM} : 2.0 \times 10^{-2} \Rightarrow 9.0 \times 10^{-3} \end{array} \right.$$

2-D refinement methods are more effective than 1-D methods for higher order constellations

# BER performance

## Time domain initial estimation with 2-D refinement methods

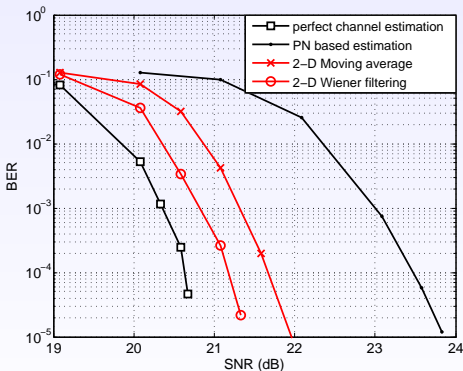


64QAM, TU-6 channel with a velocity of 30 km/h  
 $M_f = L_f = 9, M_t = L_t = 2$

- ▶ Gaps to the perfect channel estimation :
  - 2-D Moving average : **0.2 dB**
  - 2-D Wiener filtering : **0.2 dB**
- ▶ Improvements over PN-based channel estimation :
  - 2-D Moving average : **0.3 dB**
  - 2-D Wiener filtering : **0.3 dB**

# BER performance

## Time domain initial estimation with 2-D refinement methods



64QAM, SFN channel with a velocity of 30 km/h  
 $M_f = L_f = 3, M_t = L_t = 2$

- ▶ Gaps to the perfect channel estimation :
  - 2-D Moving average : **1.1 dB**
  - 2-D Wiener filtering : **0.6 dB**
- ▶ Improvements over PN-based channel estimation :
  - 2-D Moving average : **1.8 dB**
  - 2-D Wiener filtering : **2.3 dB**

2-D data-aided channel estimation is effective for higher order constellations

# Summary

- Proposition of an iterative data-aided channel estimation with low complexity & time delay
  - ▶ Exclusion of deinterleaving, interleaving & decoding from feedback loop
  - ▶ Rebuilding soft data symbols from demapper
  - ▶ Refining the channel estimate using channel correlation property
- 1-D & 2-D approaches for channel estimation refinement
  - ▶ Moving average
  - ▶ Wiener filtering
- Improved channel estimation performance
  - ▶ Better performance than PN-based method and reference methods
  - ▶ Robust in severe channel conditions

## Conclusions and Prospects

# Main contributions

## Analysis and Optimization of the Asian DTTB Systems

### Analysis and Comparison of DVB-T and DTMB

- DTMB has more efficient data structure
  - ▶ Higher spectrum utilization
  - ▶ Higher power efficiency
- The overall performance of the two systems is very close in typical channel conditions
  - ▶ DVB-T performs better in perfect channel estimation cases
  - ▶ Channel estimation mechanism of DTMB is more reliable than that of DVB-T
  - ▶ DTMB is more efficient with shorter GI

# Main contributions

## Analysis and Optimization of the Asian DTTB Systems

### PN sequence based channel estimation

- Time domain correlation-based estimator performs better but suffers an estimation error floor
- Improved time domain estimators with reduced estimation error floor
  - ▶ Method 1 : left multiplying by  $\mathbf{Q}^{-1}$
  - ▶ Method 1 with truncation : left multiplying by  $\bar{\mathbf{Q}}^{-1}$
  - ▶ Method 2 : subtracting the interference
- Improved estimator in insufficient CP case
  - ▶ Cyclicity compensation
  - ▶ IBI removal

# Main contributions

## Analysis and Optimization of the Asian DTTB Systems

### A low-complexity data-aided channel estimation

- Proposal of an iterative data-aided channel estimation with low complexity & time delay
  - ▶ Exclusion of deinterleaving, interleaving & decoding from feedback loop
  - ▶ Rebuilding soft data symbols from demapper
  - ▶ Refining the channel estimate using channel correlation property
    - ◇ 1-D or 2-D
    - ◇ Moving average or Wiener filtering
- Improved channel estimation performance
  - ▶ Better performance than PN-based method and reference methods
  - ▶ Robust in severe channel conditions



# Prospects

## TDS-OFDM waveform

- Study of TDS-OFDM waveform in Multiple-Input Multiple-Output (MIMO) case
  - ▶ Optimal TDS-OFDM waveform design for MIMO transmission
  - ▶ Effective channel estimation algorithms for MIMO transmission
- Global comparisons between pilot-assisted CP-OFDM based systems and TDS-OFDM based ones
  - ▶ Transmission overhead
  - ▶ Power allocation
  - ▶ Accuracy of channel estimation and synchronization

## DTMB system

- Enhanced reception algorithms in mobile reception scenarios
  - ▶ Mobile reception in urban areas
  - ▶ Reception in extremely high speed scenarios

Thank you !