Coordination in Distributed Multi-User High-Performance Dense Networks (5G Synchronization: October Update)

Outline

- **Recap**
  - Proposed phase noise estimation and cancellation methods
    : compleixty analysis
- **Initial Implementation results of the algorithm**
  - Key function blocks
  - Synthesis results and comparision
- **System-hardware co-design**
  - Phase noise in distributed massiv MIMO
- **Discussion on post-silicon verification and future plan**

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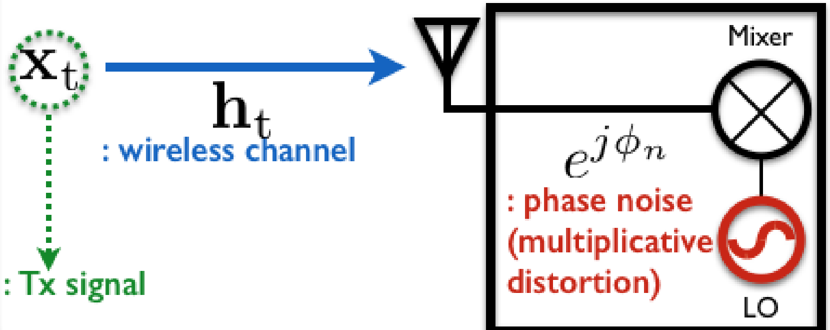
Recap

Background: System Model with Phase Noise (PN)

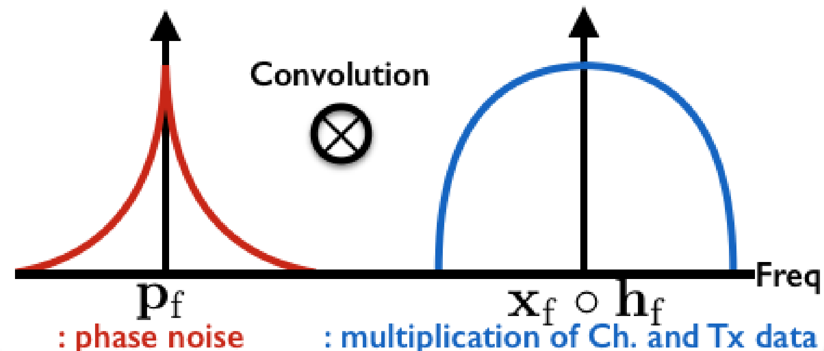
System Model in Time Domain

Rx signal: $\mathbf{y}_t = \mathbf{\Phi}_t(\mathbf{x}_t \otimes \mathbf{h}_t)$



System Model in Freq. Domain

Rx signal: $\mathbf{y}_f = \mathbf{p}_f \otimes (\mathbf{x}_f \circ \mathbf{h}_f)$



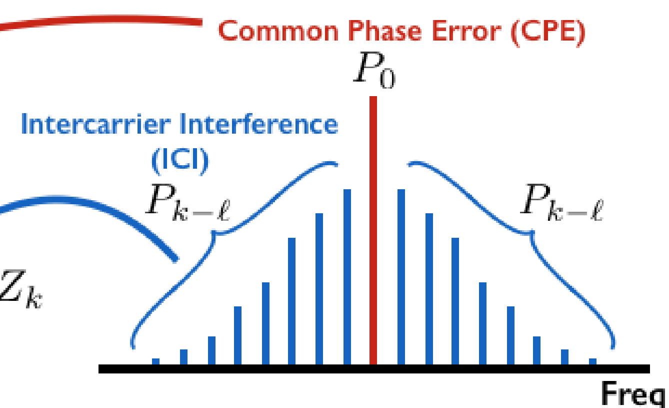
Phase Noise Components in Freq. Domain

Phase Noise (Freq): $P_i = \frac{1}{N}\sum_{n=0}^{N-1} e^{j\phi_n} e^{-j2\pi ni/N}$

FFT size (N); PN (time domain) ($e^{j\phi_n}$)

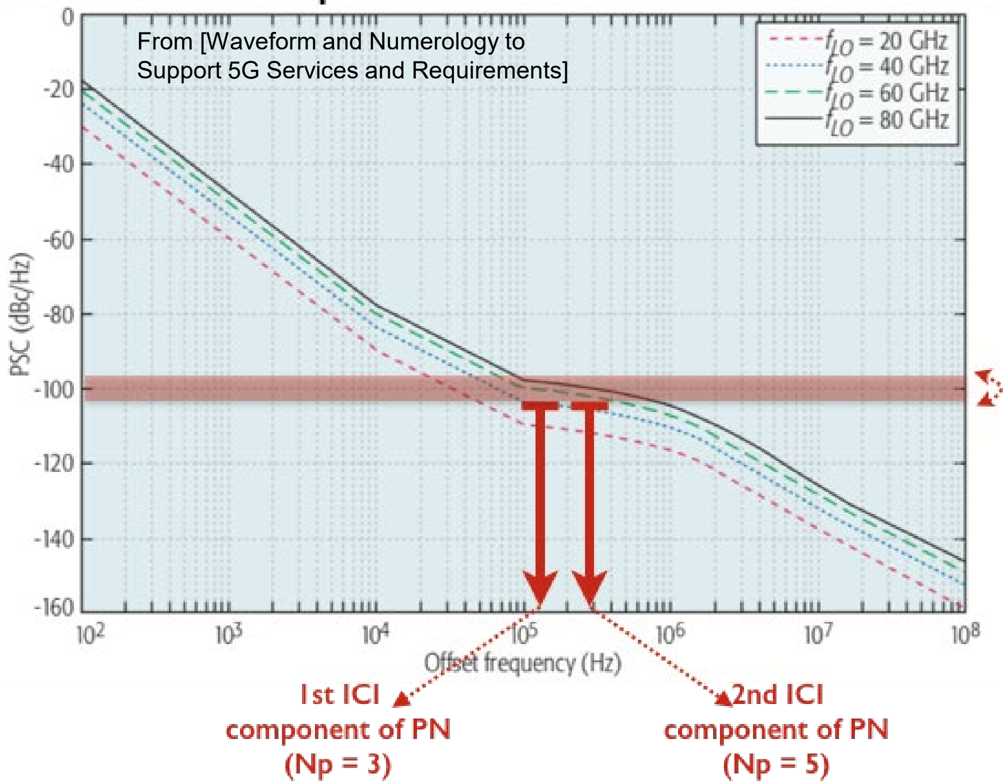
Rx signal (Freq):

$$Y_k = X_k H_k \underbrace{\boxed{P_0}}_{\text{CPE}} + \underbrace{\sum_{l=0,\ell\neq k}^{N-1} X_\ell H_\ell \boxed{P_{k-\ell}}}_{\text{ICI}} + Z_k$$



5G NR with Phase Noise

Phase Noise Power Spectral Densities at mmWave Osc. Freq.



- Output power of mmWave LO
  : 10 ~ 15 dBm
- Noise floor for 400 MHz
  : -85~ -90 dBm
- Subcarrier spacing (60-80 GHz) for 5G NR
  : 120, 240 kHz
- Minimum # of PN-dedicated pilots to estimate *Np* of dominant PN components:

$$\frac{3N_\mathrm{p}-1}{2}$$

Takeaway

PN Cancellation OH: $\frac{3N_\mathrm{p}-1}{2N}$: 0.1 - 0.17 % (approx.)

(Np = 3 ~ 5, FFT size: 4096)

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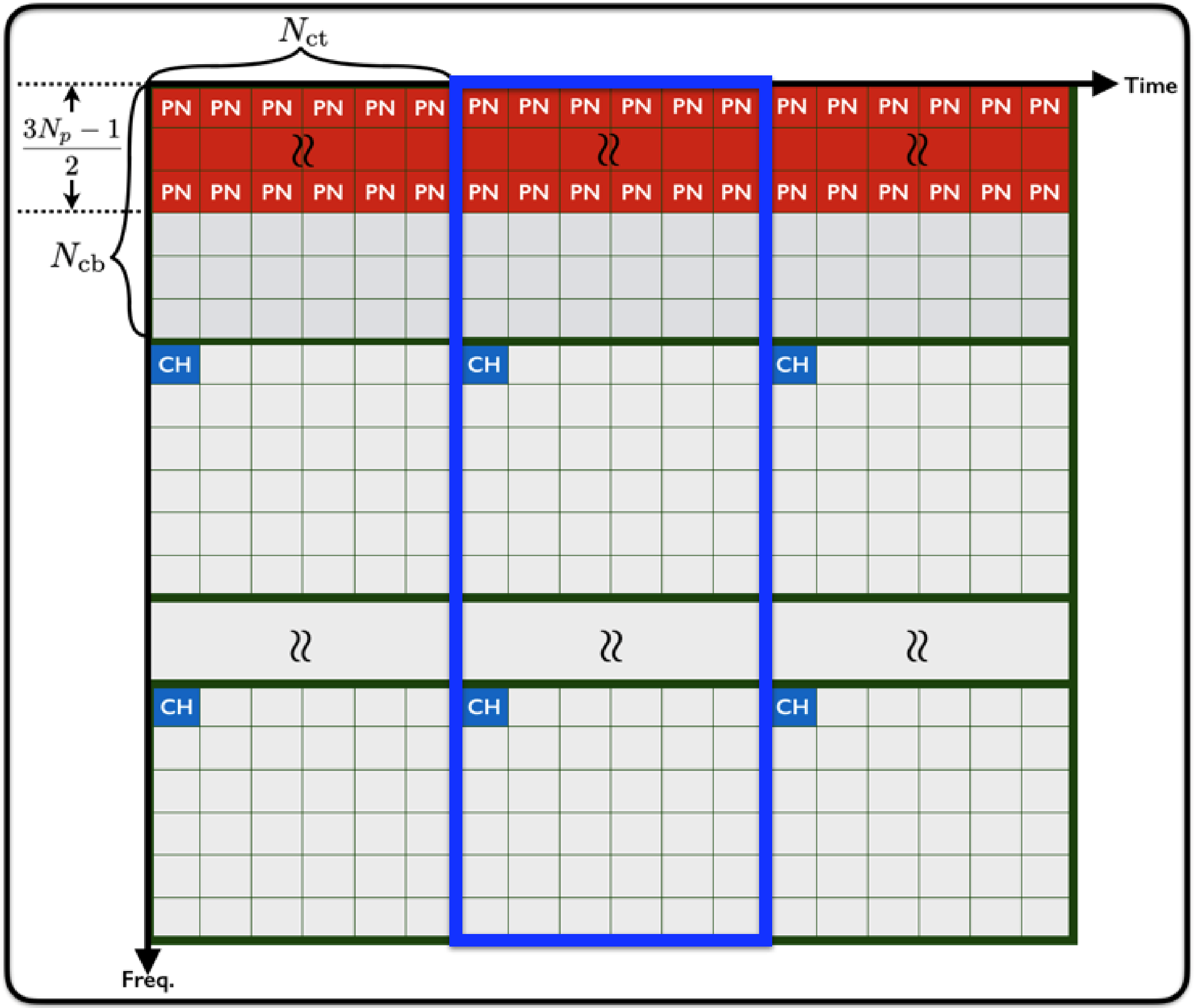
Resource Allocation



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Main steps in the algorithm

- **1st step: Estimation of Phase-Noise (PN)-Affected Channel**

  - Estimation by using PN-dedicated pilot

- **2nd step: Separation of CH and PN components**

  - Deconvolution

- **3rd step: Estimation of Intercarrier Interference(ICI)-Free Channel**

  - Estimation by using ICI-dedicated pilot

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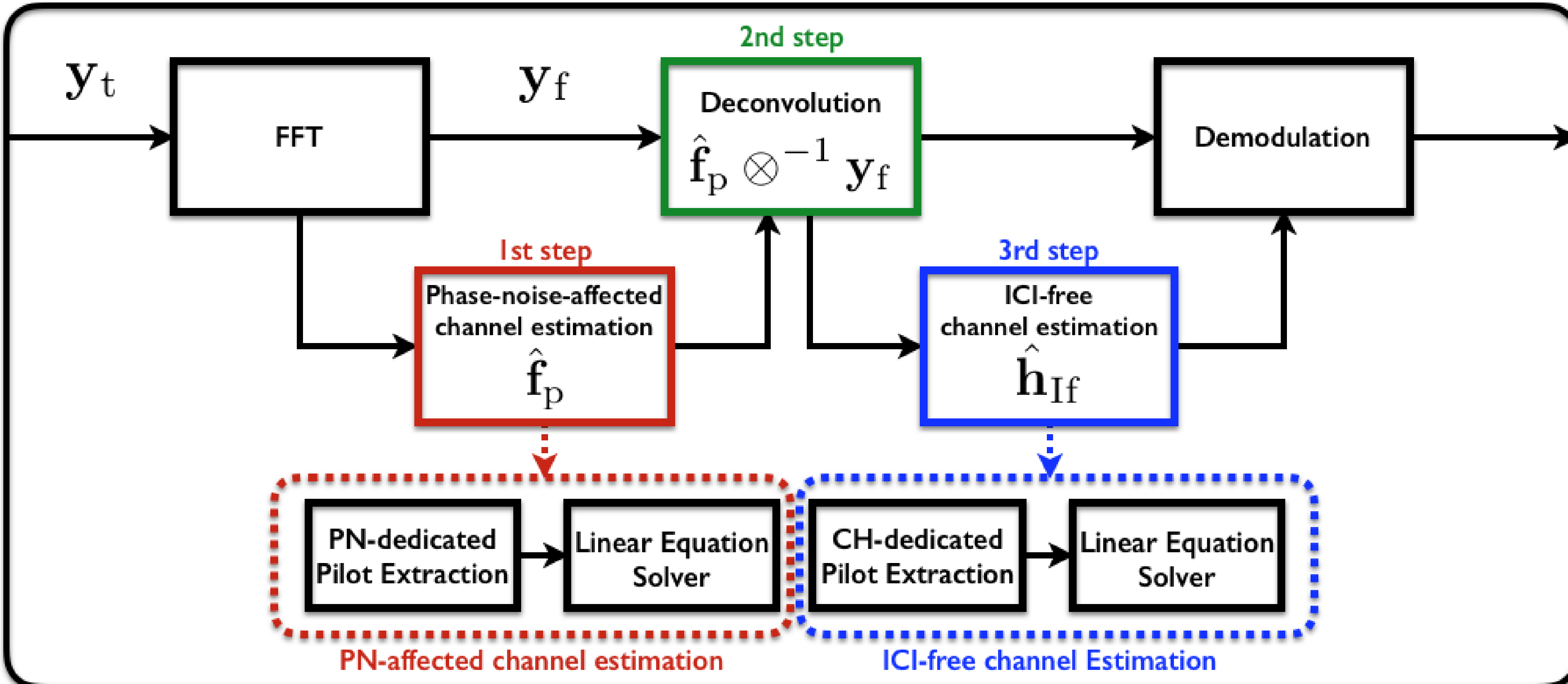
Complexity Comparison

Method	Parameter	Multiplication
Lease Squares (LS) / No constraint on PN [1]	PN+CH	$\text{iter} \times (64N^3 + 32N^2 + 4LN)$
LS / Non-iteration method/ Relaxed constraint on PN (Taylor Approx.) [2]	PN	$((N_p - 1)/2 + 2)^3$
	CH	$2N(N_p - 1) + 8(2N + NL + L)$
LS / State-of-the-art method / MM technique / No relaxed constraint [3]	PN+CH	$\text{iter} \times N^2$
Proposed	PN-Affected	NN_p
	ICI-Free	M

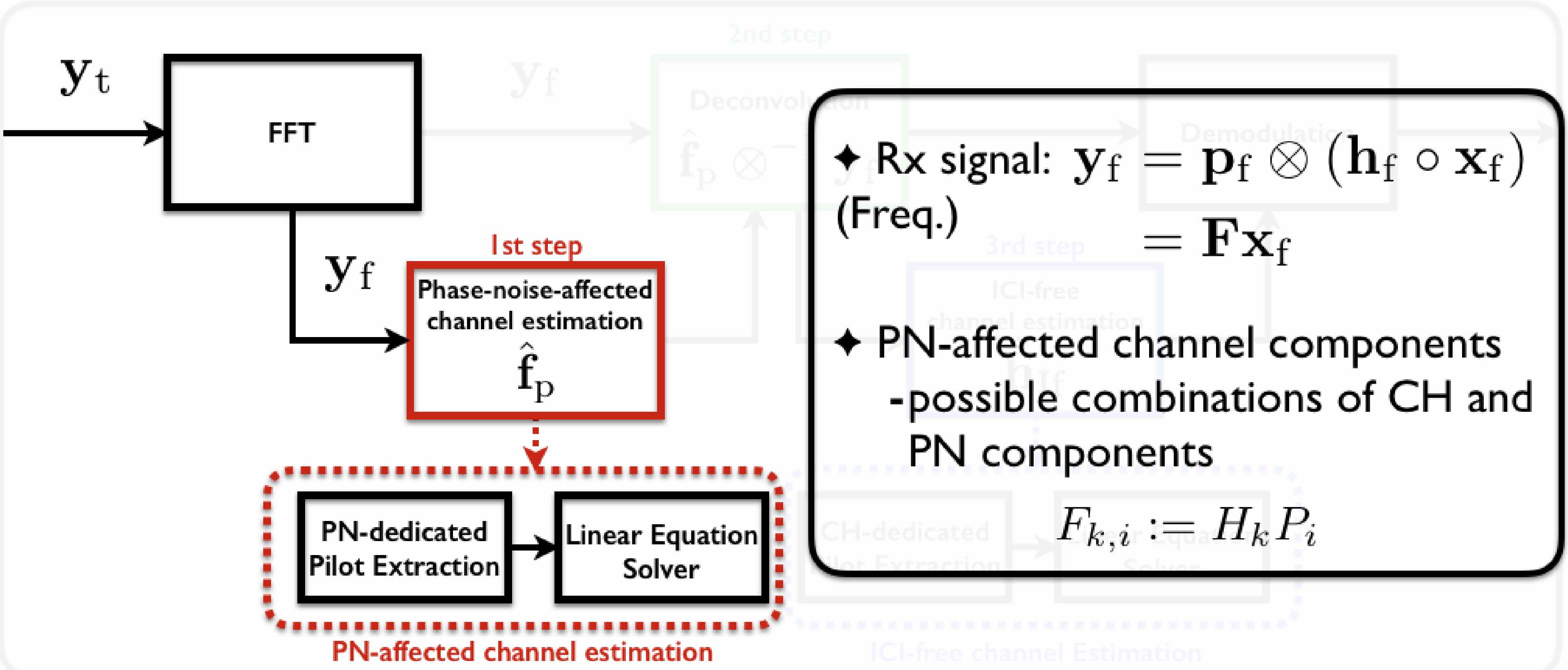
- iter: # of iteration
- N: FFT size
- L: # of channel taps for time-domain CH est.
- N_p: # of dominant PN component in frequency domain
- M: # of coherence block in the frequency domain within N

Initial Implementation

Overall Architecture



1st Step: Estimation of PN-Affected Channel



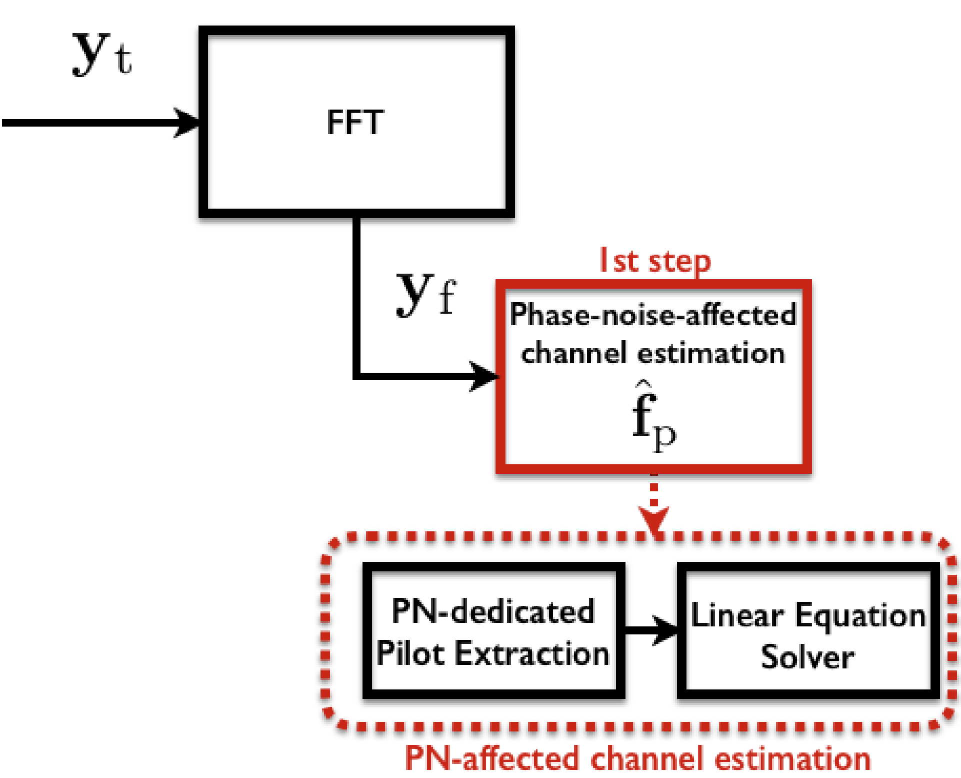
- Rx signal: (Freq.) $\mathbf{y}_\mathrm{f} = \mathbf{p}_\mathrm{f} \otimes (\mathbf{h}_\mathrm{f} \circ \mathbf{x}_\mathrm{f}) = \mathbf{F}\mathbf{x}_\mathrm{f}$
- PN-affected channel components
  - possible combinations of CH and PN components

$$F_{k,i} := H_k P_i$$

1st Step: Estimation of PN-Affected Channel

Example

- N_p (# of dominant PN) = 3, N_{cb} (# of successive subcarriers within coherence BW) = 4



$$\begin{bmatrix} Y_0 \\ Y_1 \\ Y_2 \end{bmatrix} = \underbrace{\begin{bmatrix} X_{r_{1,0}} & X_{r_{0,0}} & 0 \\ X_{r_{2,0}} & X_{r_{1,0}} & X_{r_{0,0}} \\ X_{r_{3,0}} & X_{r_{2,0}} & X_{r_{1,0}} \end{bmatrix}}_{\mathbf{X}_{\mathrm{f,p}}} \underbrace{\begin{bmatrix} F_{0,-1} \\ F_{0,0} \\ F_{0,1} \end{bmatrix}}_{\mathbf{f}_{\mathrm{p}}}$$

PN-dedicated pilot matrix (including 4-pilot)

PN-affected channel vector

- Pilot design: $\mathrm{rank}(\mathbf{X}_{\mathrm{f,p}}) = 3$

$$\hat{\mathbf{f}}_{\mathrm{p}} = \mathbf{X}_{\mathrm{f,p}}^{-1} \mathbf{y}_{\mathrm{f}}^{\mathrm{p}}$$

- Estimation complexity:

If $\mathbf{X}_{\mathrm{f,p}} = \mathbf{I}_{N_{\mathrm{p}}}$

→ **don't need any computation**

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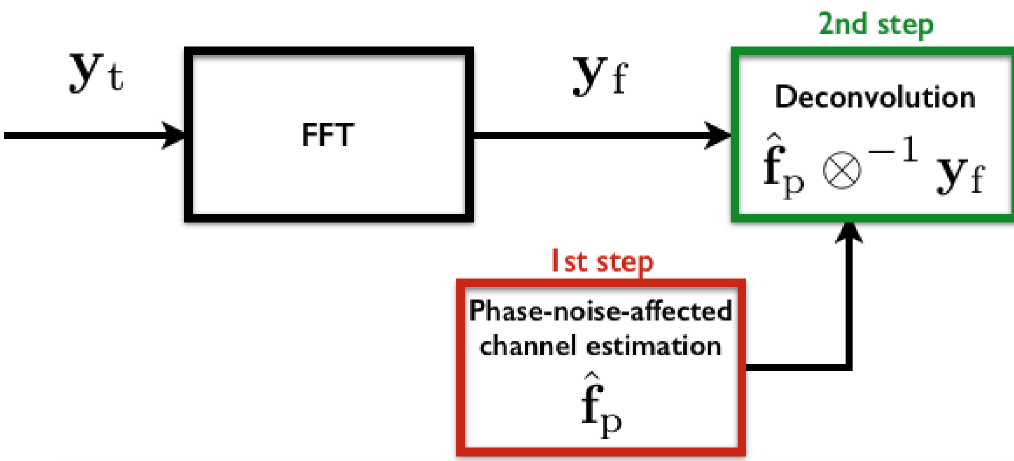
2nd Step: Separation of CH and PN components



$$\mathbf{y}_\mathrm{If} = \hat{\mathbf{f}}_\mathrm{p} \otimes^{-1} \mathbf{y}_\mathrm{f} = \mathbf{H}_\mathrm{If}\mathbf{x}_\mathrm{f}$$

Input sequences (2nd Step)

$\mathbf{y}_\mathrm{f}$: Rx signal in the frequency domain

$$\mathbf{y}_\mathrm{f} = [Y_0, Y_1, \cdots, Y_{N-1}]^\mathrm{T} \in \mathbb{C}^{N\times 1}$$

$\hat{\mathbf{f}}_\mathrm{p}$: PN-affected channel estimates

$$\hat{\mathbf{f}}_\mathrm{p} = [F_0, F_1, F_2]^\mathrm{T} \in \mathbb{C}^{N_\mathrm{p}\times 1}$$ (Np = 3)

$$\mathbf{H}_\mathrm{If} = \begin{bmatrix} \mathbf{I}_{N_\mathrm{cb}} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{H}^1_\mathrm{If} & \ddots & \vdots \\ \vdots & \ddots & \ddots & \mathbf{0} \\ \mathbf{0} & \cdots & \mathbf{0} & \mathbf{H}^{M-1}_\mathrm{If} \end{bmatrix}$$

$$\mathbf{H}^m_\mathrm{If} = H^m_\mathrm{If}\mathbf{I}_{N_\mathrm{cb}}$$

Diagonal matrix
(ICI-free channel matrix)

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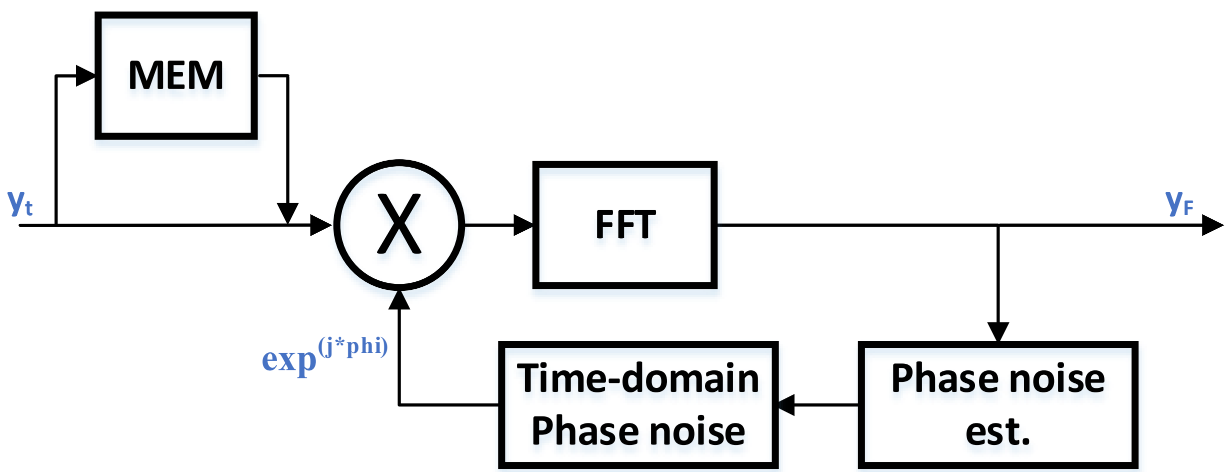
Time-domain compensation

- **Very long feedback path**
  - *Long processing latency*

+ phase noise estimation per OFDM symbol

- *Large memory consumption*
- *Low throughput*



Polynomial division/deconvolution

Deconvolution

- If *u* and *v* are vectors of polynomial coefficients, deconvolution of *u* and *v* is equivalent to the division of two polynomials (vectors)

Original long division method:

Data dependency

Output @ 2nd step: $Y_{\mathrm{If},0} \quad Y_{\mathrm{If},1} \quad Y_{\mathrm{If},2} \quad Y_{\mathrm{If},3} \cdots\cdots Y_{\mathrm{If},\mathrm{N}-1}$

$$\underbrace{\hat{F}_0 \quad \hat{F}_1 \quad \hat{F}_2}_{\text{PN-affected channel estimates}} \;\Big|\; \underbrace{Y_0 \quad Y_1 \quad Y_2 \quad Y_3 \cdots\cdots Y_{N-1}}_{\text{Rx signal in the frequency domain}}$$

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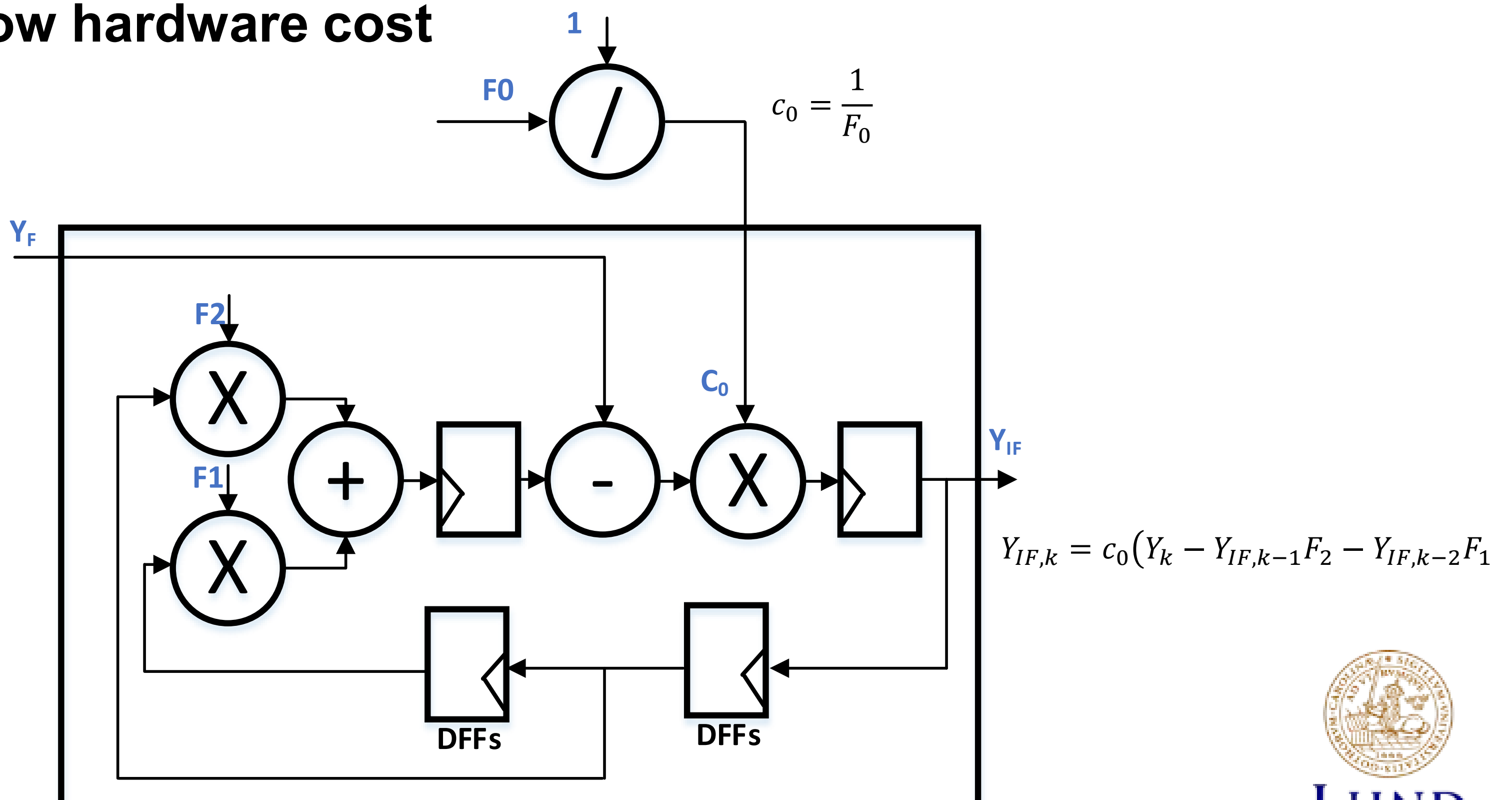
Block diagram (3-tap ICI)

- Limited throughput due to the data dependency (better than feeding back to time domain)
- Very low hardware cost



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Equivalent model of deconvolution

Linear combination of c_k and Y_k

$$Y_{\mathrm{If},k} = \sum_{\ell=0}^{k} c_{k-\ell} Y_\ell$$

$Y_{\mathrm{If},k}$: Output of deconvolution

: Quotient of polynomial division of $\mathbf{y}_{\mathrm{f}}$ and $\hat{\mathbf{f}}_{\mathrm{p}}$

Y_k : Rx signal in the frequency domain

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Parallel polynomial division

✱ **Generation of coefficient vector $\mathbf{c}$**

: (Input) PN-affected channel estimates $\hat{\mathbf{f}}_{\mathrm{p}} = [F_0, F_1, F_2]^{\mathrm{T}} \in \mathbb{C}^{N_{\mathrm{p}} \times 1}$

: (Output) Coefficient vector $\mathbf{c} = [c_0, c_1, \ldots, c_{N-1}]^{\mathrm{T}} \in \mathbb{C}^{N \times 1}$

✱ **Multiplication of Rx signal (Freq.) Y_k and coefficient c_k**

: (Input 1) Rx signal vector $\mathbf{y}_{\mathrm{f}} = [Y_0, Y_1, \cdots, Y_{N-1}]^{\mathrm{T}} \in \mathbb{C}^{N \times 1}$

: (Input 2) Coefficient vector $\mathbf{c}$

: (Output) $\mathbf{y}_{\mathrm{If}} = [Y_{\mathrm{If},0}, Y_{\mathrm{If},1}, \ldots, Y_{\mathrm{If},N-1}]^{\mathrm{T}} \in \mathbb{C}^{N \times 1}$

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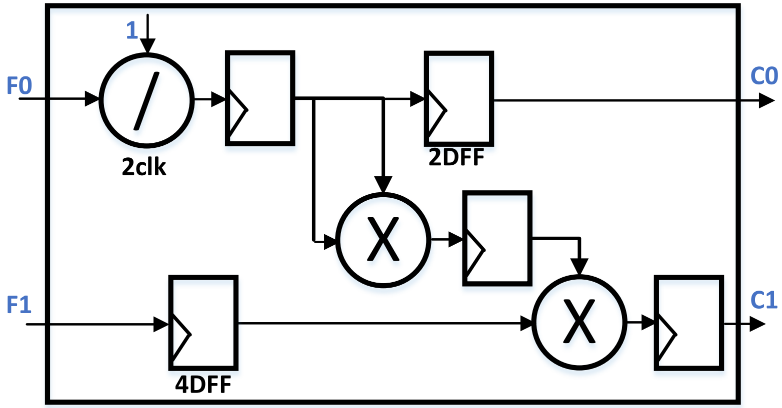
Block diagram (2-way parallell)

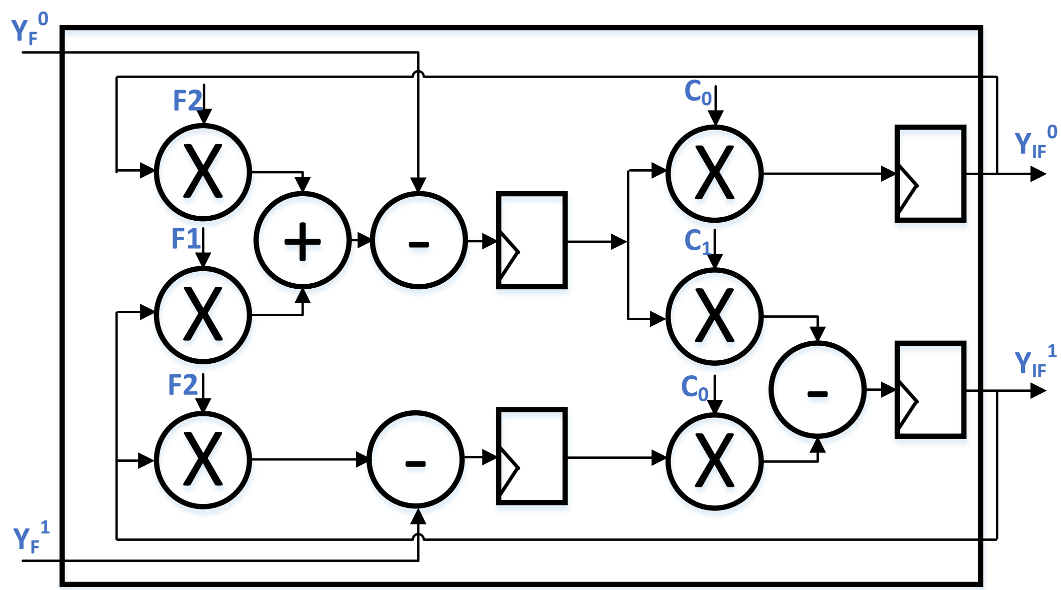


$$c_0 = \frac{1}{F_0}$$

$$c_1 = \frac{F_1}{F_0^2}$$

$$Y_{IF,i} = c_0(Y_i - Y_{IF,i-2}F_2 - Y_{IF,i-1}F_1)$$

$$Y_{IF,i+1} = \begin{matrix} c_1(Y_i - Y_{IF,i-2}F_2 - Y_{IF,i-1}F_1) \\ -c_0(Y_{i+1} - Y_{IF,i-1}F_2) \end{matrix}$$



Throughput-complexity trade-off

➢ **Synthesis results using 28nm technology**

Parallelism	Clock frequency	Throughput	Gate count	Area efficiency
1	500MHz	250MS/s	18.8k	13.3MS/s/kG
2	500MHz	500MS/s	44.7k	11.2MS/s/kG
4	500MHz	1GS/s	104.2k	9.6MS/s/kG
8	500MHz	2GS/s	211k	9.4MS/s/kG

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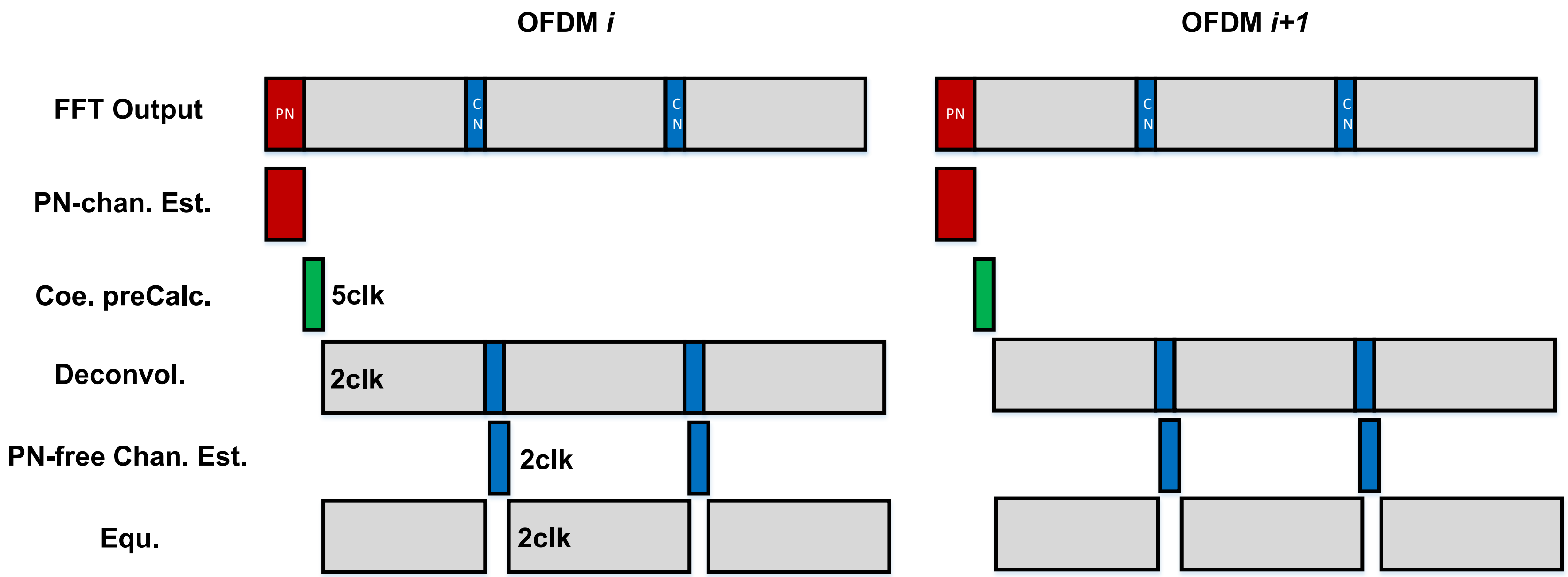
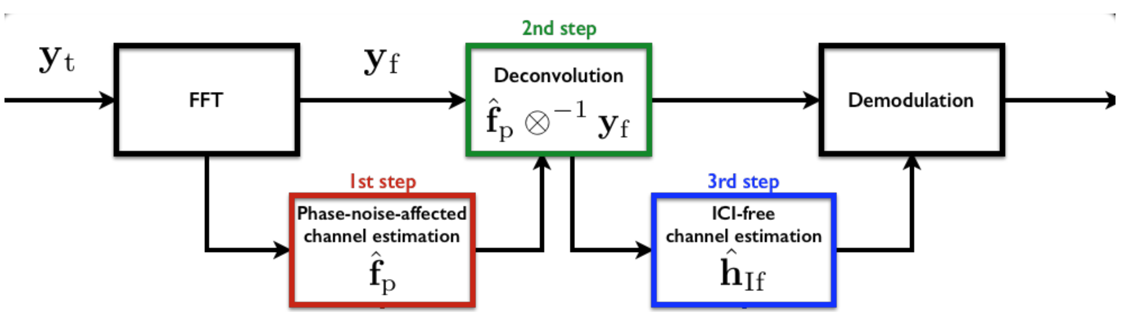
Timing diagram





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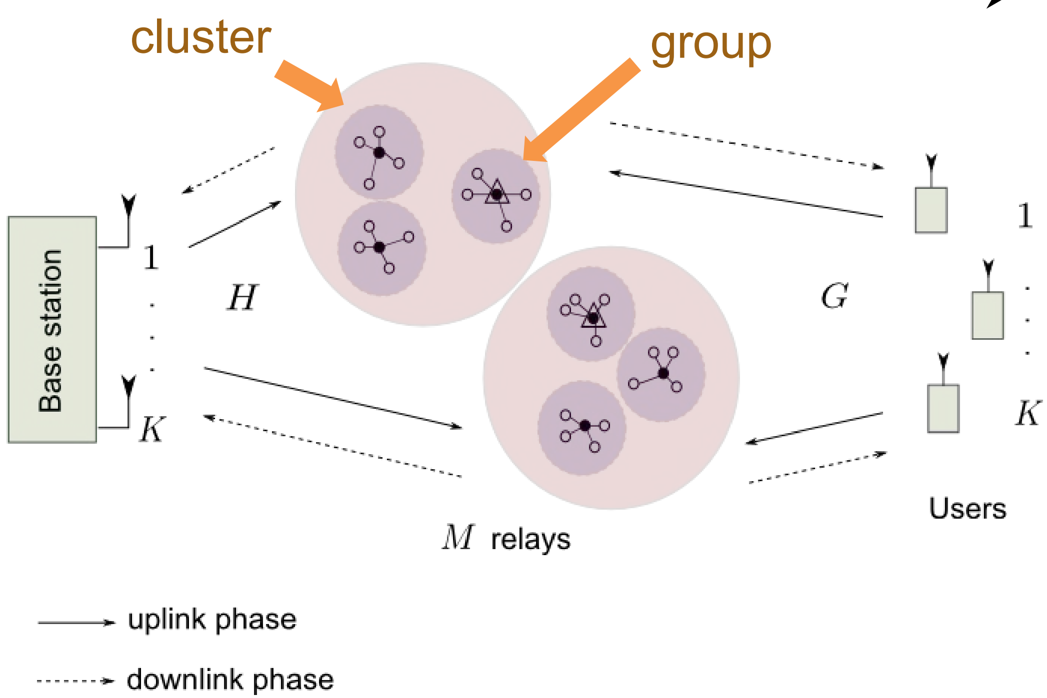
System-level consideration

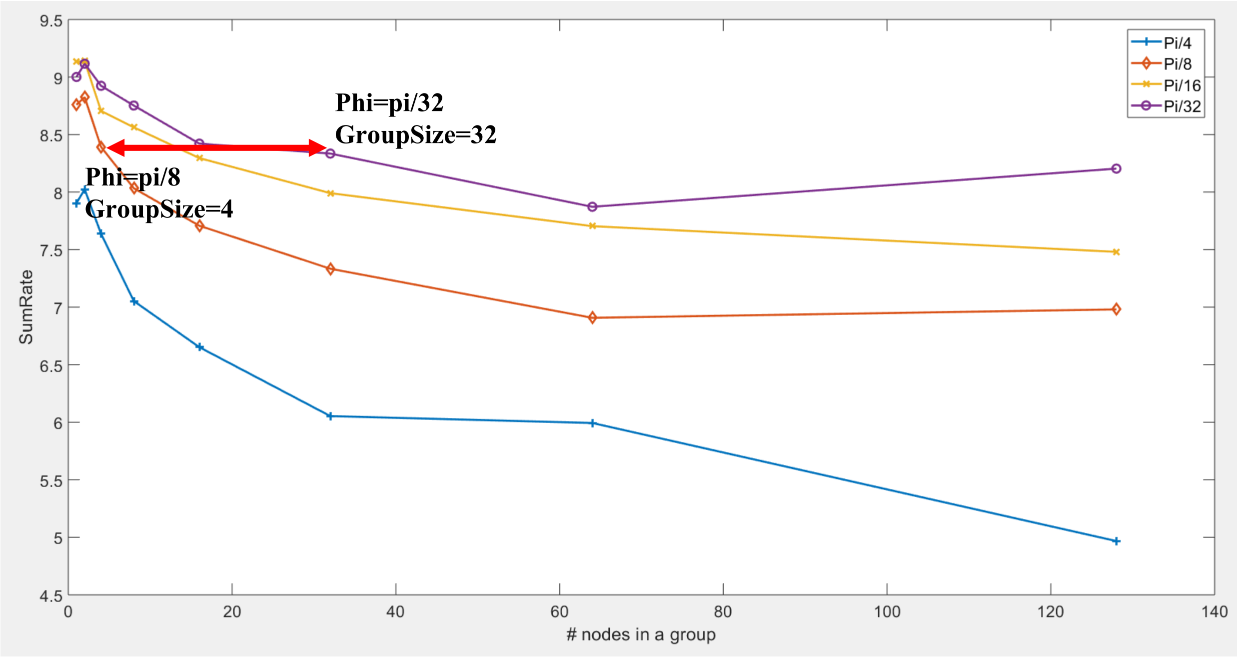
Correlated/un-correlated phase noise in distributed massive MIMO systems



- **Three levels of cooperation:**
  - Group: share both **receive symbols** and **CSI**, but phase noise can be **correlated**
  - the total # nodes is128, K=2, chang the # nodes within each group
  - Phase noise uniformly distributed between [-phi/2,phi/2]

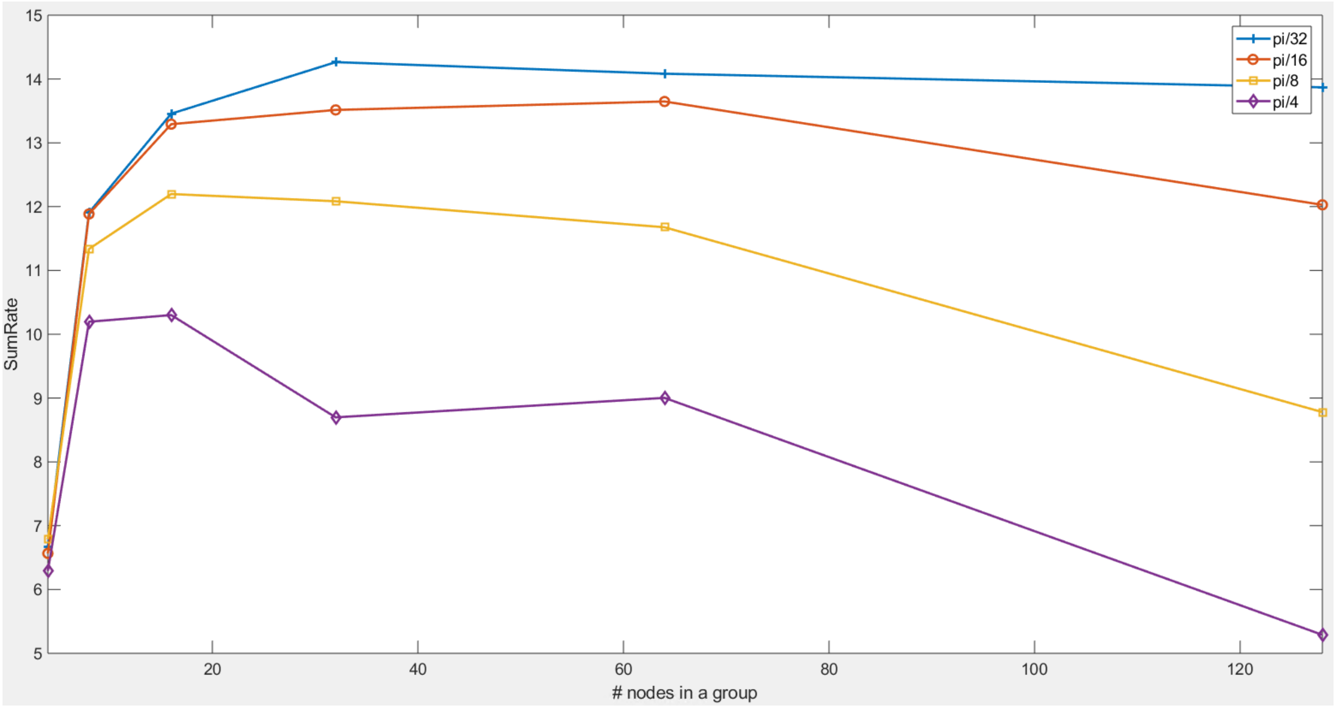
Correlated/un-correlated phase noise in distributed massive MIMO systems

- **With matched filtering processing, 12dB SNR**
  - Uncorrelated phase noise can be **averaged out** by distributed array processing



Correlated/un-correlated phase noise in distributed massive MIMO systems

- **With zero-forcing processing, 12dB SNR**
    - Trade-off between **phase noise mitigation** and **inter-UE inteference cancellation**



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Discussion on tape-out