Overview of SC-FDMA

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WARNING

Do not trust all the ideas I'll say!! Keep thinking!!

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- **Undergraduate Student**

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- **Interact**

Outline

- Introduction to **Principle of SC-FDMA System**

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  1. Structure of SC-FDMA

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2. Mathmatical Model

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Principle of SC-FDMA System

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- Block diagram of SC-FDMA system

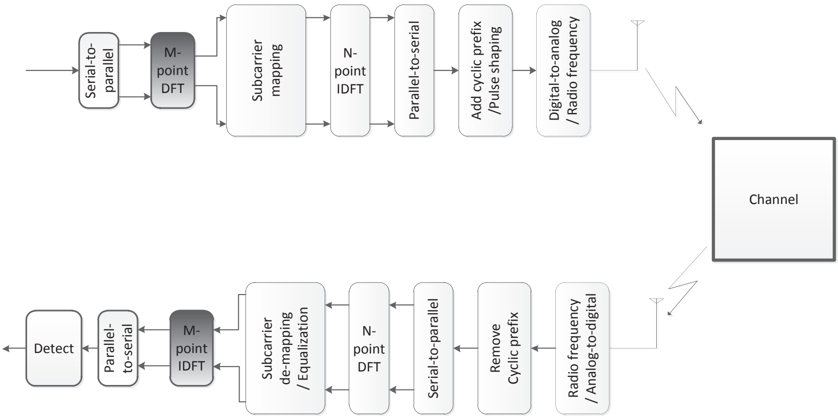

Fig: Structure of SC-FDMA system

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Mathmatical Model-Transmitter

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- DFT operation

$$X^u = F_M d^u$$

where

$$d^u = [d_1^u, d_2^u, ..., d_M^u,]^T$$

$$[F_M]_{p,q} = (1/\sqrt{M})e^{-j2\pi(pq/M)}$$

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where M_T^u is subcarrier mapping matrix

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- IDFT operation

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- add CP

$$\overline{x^u} = P_{add} F_N^{-1} M_T^u X^u$$

where

$$P_{add} = [C, I_N]^T$$

$$C = [0_{N_C \times (M - N_C)}, I_{N_C}]^T$$

Mathmatical Model-Channel and Reciever

- Propagation in the Channel

$$\overline{y} = \sum_{u=1}^{U} \overline{E^u} H^u \overline{x^u} + n$$

where

$$[\overline{E^u}]_{n,n} = e^{j2\pi\varepsilon_u n/N}, n = 0, ..., N + N_C - 1$$

and H^u is an $(N + N_C) \times (N + N_C)$ matrix

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- After Remove the CP

$$y = P_{rem}\overline{y} = \sum_{u=1}^{U} E^u H_C^u x^u + \overline{n}$$

where

$$P_{rem} = [0_{(N \times N_C)}, I_N]$$

- DFT opearation in the receiver

$$Y = F_N y = \sum_{u=1}^{U} F_N E^u H_C^u x^u + F_N \overline{n}$$

$$\Rightarrow Y = \sum_{u=1}^{U} \Omega_{cir}^u \Lambda^u \bar{X}^u + N$$

where

$$\Omega_{cir}^u = F_N E^u F_N^{-1}$$

Mathmatical Model-Recieever

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- Use a Trick

$$H_c^u = F_N^{-1} \Lambda^u F_N$$

Mathmatical Model-FDE

- FDE operation

$$\overline{Y} = W^k M_R^k Y$$

where W^k is the M by M diagonal equalisation matrix, M_R^k is de-mapping process

Mathmatical Model-IDFT

- M by M IDFT operation

$$\hat{d}^k = F_M^{-1}\bar{Y}^k = A^k d^k + \bar{A}^k d^k + \sum_{\substack{u=1 \\ u \neq k}}^{U} B^u d^u + \hat{n}$$

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The structure of all components of the equation above:
$A^k = diag(F_N^{-1} W^k \Omega_d^k \Lambda_d^k F_N)$
$\bar{A}^k = F_N^{-1} W^k \Omega_d^k \Lambda_d^k F_N - A^k$
$\bar{\bar{n}} = F_N^{-1} W^k M_R^k N$
$B_i = F_N^{-1} W^k \Omega_r^u \Lambda_d^u F_N$

- M by M IDFT operation

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$B_i = F_N^{-1}\,W^k \Omega_r^u \Lambda_d^u F_N$

where $\Omega_d^k = M_R^k \Omega_{cir}^k M_T^k$ is interference with the kth user's data, $\Omega_r^u = M_R^k \Omega_{cir}^u M_T^u$ is the interference from the uth user, $\Lambda_d^u = M_R^u \Lambda^u M_T^u$ is the channel of uth user

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Key Technique-Cyclic Prefix

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- Cyclic prefix prevents inter-block interference

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- Channel Matrix

$$H_C^u = \begin{bmatrix} h^u[0] & 0 & . & 0 & h^u[L-1] & . & h^u[1] \\ . & h^u[0] & . & & . & . & . \\ . & & . & . & & . & h^u[L-1] \\ h^u[L-1] & . & & . & . & & 0 \\ 0 & h^u[L-1] & . & & . & . & . \\ . & . & . & . & & . & 0 \\ 0 & . & 0 & h^u[L-1] & . & . & h^u[0] \end{bmatrix}$$

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- Make linear convolution of the channel impulse response look like a circular convolution

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- Localized Subcarrier Mapping
  Symbols are assigned to N **adjacent** subcarriers
  a. Occupy consecutive subcarriers
  b. Channel-dependent scheduling provides multi-user diversity

Key Technique-Subcarrier Mapping

- Different subcarrier mapping schemes

$\{x_n\}$:

x_0	x_1	x_2	x_3

DFT $(X_k = \sum_{n=0}^{N-1} x_n e^{-j\frac{2\pi}{N}nk}, N = 4)$

$\{X_k\}$:

X_0	X_1	X_2	X_3

$\{X_{1,IFDMA}\}$	X_0	0	0	X_1	0	0	X_2	0	0	X_3	0	0
$\{X_{1,DFDMA}\}$	X_0	0	X_1	0	X_2	0	X_3	0	0	0	0	0
$\{X_{1,LFDMA}\}$	X_0	X_1	X_2	X_3	0	0	0	0	0	0	0	0

$\longrightarrow$ **frequency**

Fig: An example of different subcarrier mapping schemes for N=4, Q=3 and M=12

Key Technique-Time domain Symbol of IFDMA

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- Interleaved FDMA

$$\widetilde{x}_m(=\widetilde{x}_{Nq+n})=\frac{1}{Q}e^{j2\pi\frac{mr}{M}}\cdot x_{(m)\bmod N}$$

where $M=Q\cdot N$, $m=N\cdot q+n(0\leq q\leq Q-1,0\leq n\leq N-1)$, r is the amount of the frequency shift

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- A magic thing about IFDMA: DFT-IDFT reduces to multiply each input symbol by a complex number with unit magnitude and repeating the input sequence with proper phase rotation Q times

Key Technique-Time domain Symbol of IFDMA

- Time domain and frequency domain of **Interleaved FDMA**

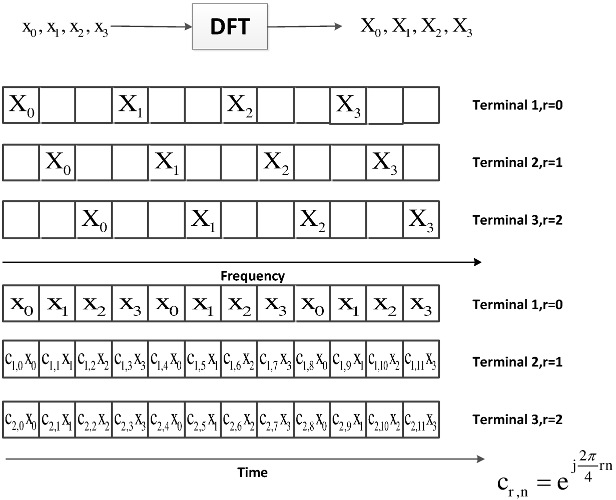

Fig: Time domain and frequency domain of Interleaved FDMA

Key Technique-Time domain Symbol of LFDMA and conventional DFDMA

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- LFDMA

$$y_n = y_{Q\cdot m+q} = \begin{cases} \frac{1}{Q} x(n)_{\mod M}, q = 0 \\ \frac{1}{Q} \cdot (1 - e^{j2\pi \frac{q}{Q}}) \cdot \frac{1}{M} \sum_{p=0}^{M-1} \frac{x_p}{1 - e^{j2\pi \{ \frac{(m-p)}{M} + \frac{q}{QM} \}}}, q \neq 0 \end{cases}$$

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- DFDMA

$$y_n = y_{Q\cdot m+q} = \begin{cases} \frac{1}{Q} \cdot x_{(\widetilde{Q}(n)_{\mod M})_{\mod M}}, q = 0 \\ \frac{1}{Q} \cdot (1 - e^{j2\pi\frac{\widetilde{Q}}{Q}q}) \cdot \frac{1}{M} \sum_{p=0}^{M-1} \frac{x_p}{1 - e^{j2\pi\{\frac{(\widetilde{Q}m-p)}{M} + \frac{\widetilde{Q}q}{QM}\}}}, q \neq 0 \end{cases}$$

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- **BER** performence between **SC-FDMA** and **OFDMA**
- **CFO** and **TO** Comparison between **SC-FDMA** and **OFDMA**

SC-FDMA and DS-CDMA/FDE

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- Both spread narrow-band data into broader band
- They achieve processing gain or spreading gain from spreading
- They both maintain low PAPR because of the single carrier transmission

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- They achieve processing gain or spreading gain from spreading
- They both maintain low PAPR because of the single carrier transmission
- Exchanging the roles of spreading sequence and data sequence, DS-CDMA = IFDMA

SC-FDMA and DS-CDMA/FDE

SC-FDMA and DS-CDMA/FDE

- Conventional Spreading VS Exchanged Spreading

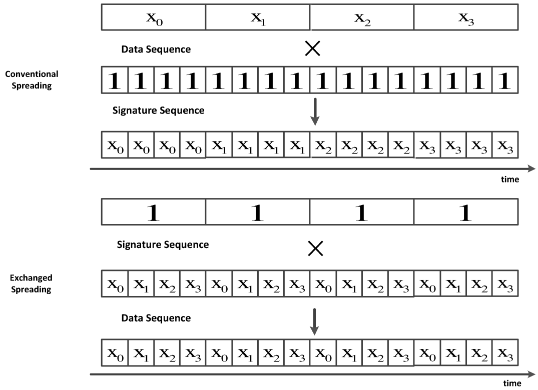

Fig: Comparison between DS-CDMA and IFDMA

PAPR comparison

PAPR comparison

- PAPR Comparison in different subcarrier mapping schemes and distinct modulation techniques

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- PAPR Comparison in different roll-off factors

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Channel Bandwidth	5MHz
Sampling Rate	5 mega-samples per second
Data Modulation format	QPSK&16QAM
Pulse shaping	Yes
Roll-off factor	1
Transmitter IFFT Size	512
Subcarrier Spacing	9.765625 kHz(=5 MHz/512)
SC-FDMA Input Block Size	16 symbols
SC-FDMA Input FFT Size	16
Bandwidth Spreading Factor	32 (=512/16)
Filter Type	Raised-cosine Filter

Different Subcarrier Mapping and Distinct Modulation Techniques

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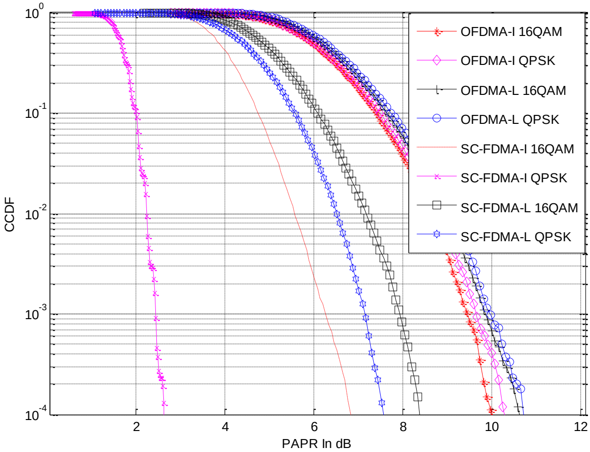
- **SC-FDMA** VS **OFDMA**, **Localized** VS **Interleaved**, **16QAM** VS **OFDMA**

Different Subcarrier Mapping and Distinct Modulation Techniques

- **SC-FDMA** VS **OFDMA**, **Localized** VS **Interleaved**, **16QAM** VS **OFDMA** CCDF is **complemantary** cumulative distribution function



Different Roll-off Factor

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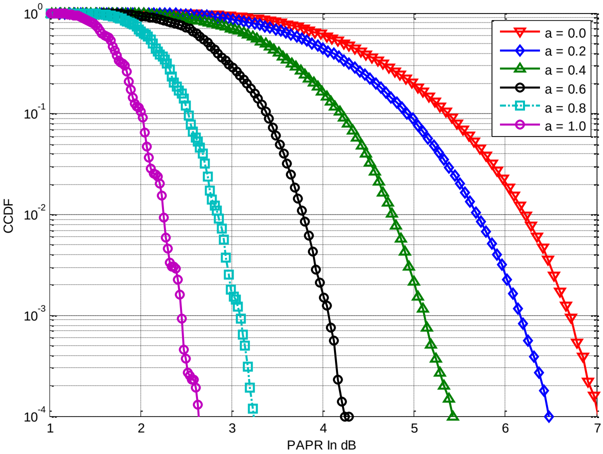
- Different roll-off factor in **interleaved** subcarrer mapping



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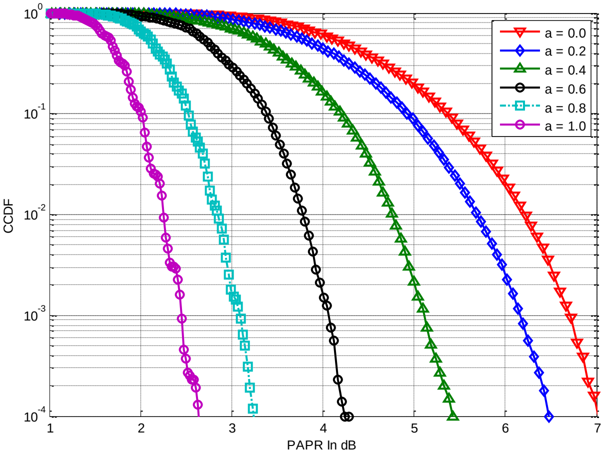

- Pulse shaping significantly influences PAPR **only in IFDMA**

Uncoded BER Performance Comparison

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- BER simulation parameters

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- BER simulation parameters

Channel Bandwidth	5 MHz
Sampling rate	5 mega-samples per second
Data modulation format	QPSK
Pulse shaping	None
Cyclic prefix	20 samples(4 μs)
Transmitter IFFT size	512
Subcarrier spacing	9.765625 kHz(=5 MHz/512)
SC-FDMA input block size	16 symbols
Subcarrier mapping	Interleaved
Channel estimation	Perfect
Equalization	Zero forcing or minimum mean square error(MMSE)
Channel coding	None
Detection	Hard decision
Number of iteration	10^6

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- BER simulation performance (**SC-FDMA** VS **OFDMA**)

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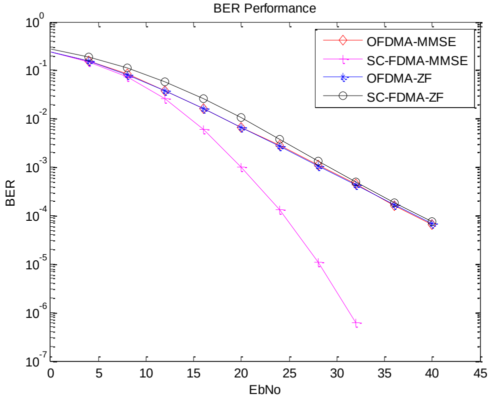

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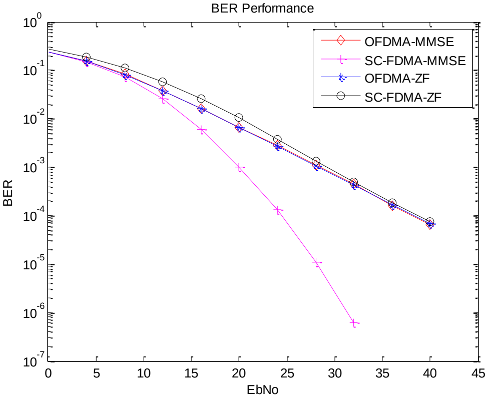
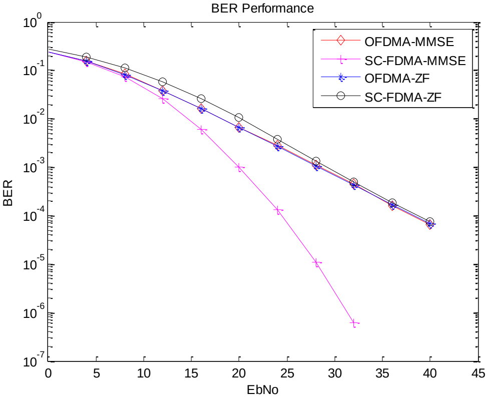


- OFDMA -two curves coincide strictly

$$R = Fhx + Fn \Rightarrow R = (FhF^{-1})Fx + N \Rightarrow R = HX + N$$

- BER simulation performance (**SC-FDMA** VS **OFDMA**)



- OFDMA -two curves coincide strictly
  ZF-$D = H^{-1}(HX + N) <====> $ **MMSE** $D = \Lambda^{-1} H^{*}(HX + N)$
  where $\Lambda = diag(|H_1|^2 + \sigma^2, ..., |H_L|^2 + \sigma^2)$

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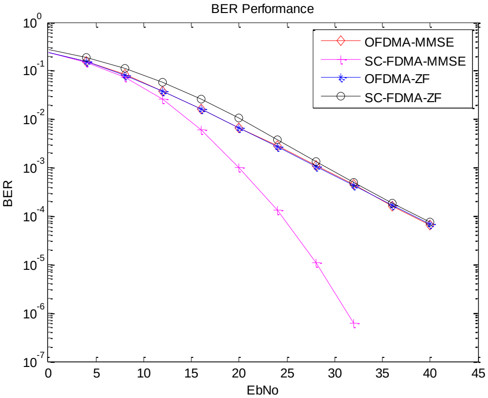

- SC-FDMA with **ZF equalization** ====>Low SNR: noise dominates

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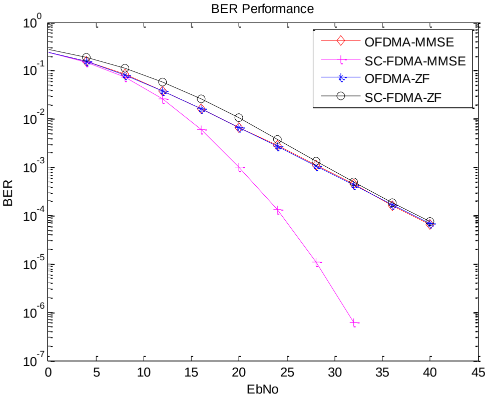

- SC-FDMA with **ZF equalization** ====>Low SNR: noise dominates ===> Deep fading enlarge the noise ===> May cause error burst
  The noise part after IDFT: $\sum_n e^{i\theta_n} \frac{N_n}{H_n}$

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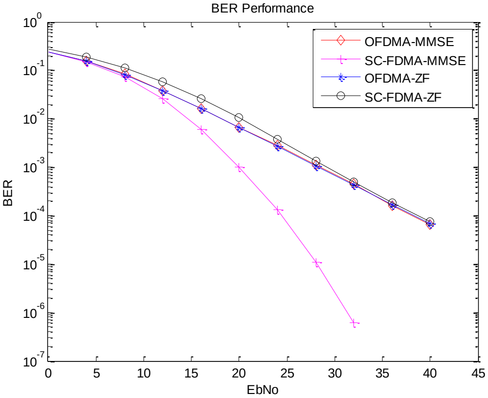

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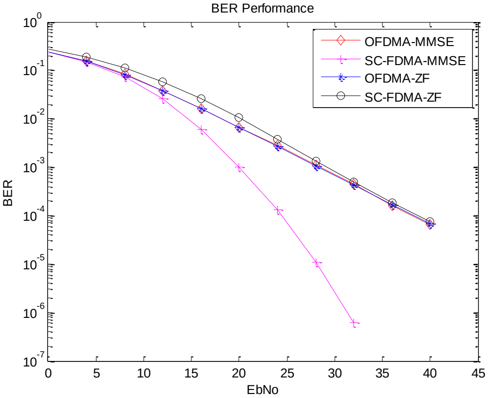

- SC-FDMA with **ZF equalization** ====>High SNR: fading dominates ===> total influences are same

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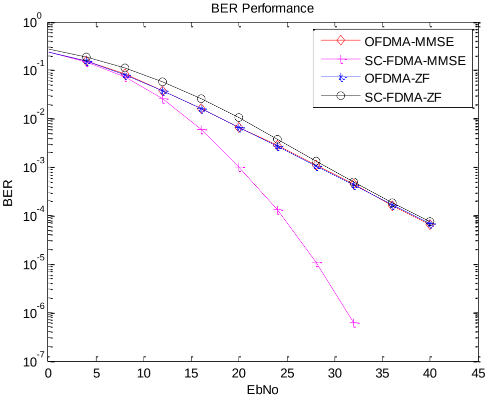

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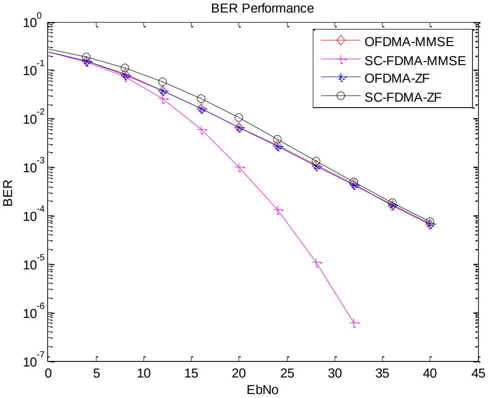

- SC-FDMA with **MMSE equalization** ====>Low SNR: noise dominates ===> Same performance between OFDMA and SC-FDMA

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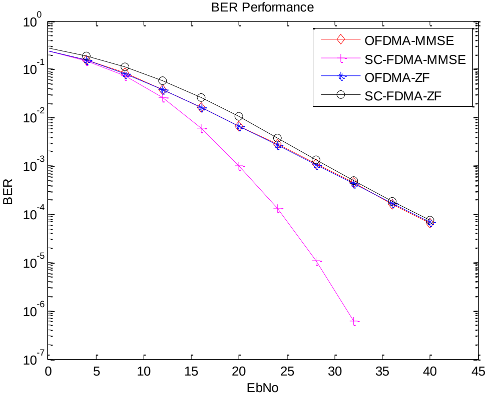

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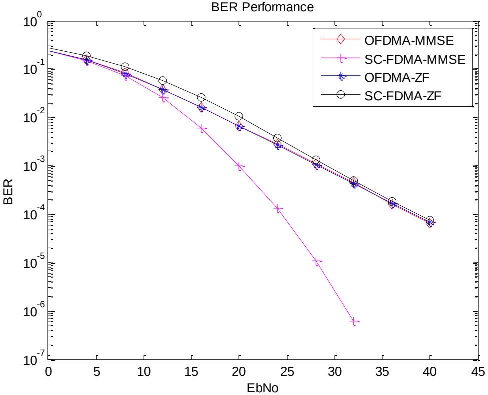
Uncoded BER Performance Comparison

- BER simulation performance (**SC-FDMA** VS **OFDMA**)



- SC-FDMA with **MMSE equalization** ====>High SNR: fading dominates ===> MMSE prevents noise enlargement ===> IDFT averages the noise
  The noise part after IDFT:$\sum_{n} e^{i\theta_n} \frac{H_n^* N_n}{|H_n|^2+\sigma^2}$

Compasrison in Carrier Offset and Timing Offset-**Uncoded**

Compasrison in Carrier Offset and Timing Offset-**Uncoded**

- SC-FDMA with Carrier Frequency Offset - **MMSE**

Received Signal = Desired Signal + MMSE-SI + MUI + Noise

Compasrison in Carrier Offset and Timing Offset-**Uncoded**

- SC-FDMA with Carrier Frequency Offset - **MMSE**

Received Signal = **Desired Signal** + **MMSE-SI** + **MUI** + **Noise**

- SC-FDMA with Carrier Frequency Offset and Time Offset - **MMSE**

Received Signal = **Desired Signal** + **MMSE-SI** + **CF-SI** + **PF-SI/NF-SI** + **MUI+Noise**

- SC-FDMA with Carrier Frequency Offset - **MMSE**

Received Signal = **Desired Signal** + **MMSE-SI** + **MUI** + **Noise**

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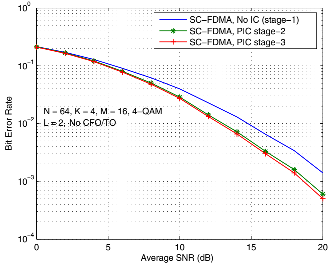

Fig. 2. BER performance of SC-FDMA without and with IC cancellation. $N = 64$, $K = 4$, $M = 16$, $L = 2$, 4-QAM, No CFO and TO. *IC removes residual interference and improves performance.*

Comparison in Carrier Offset and Timing Offset

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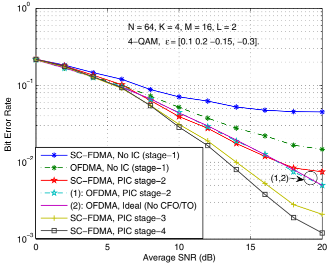
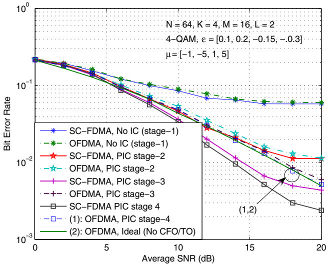


Fig. 3. Comparison of BER performance between SC-FDMA and OFDMA with CFO. $N = 64$, $K = 4$, $M = 16$, 4-QAM, $L = 2$, $\epsilon = [0.1, 0.2, -0.15, -0.3]$. No TO. User 1 is desired user. *SC-FDMA (without IC) performs worse than OFDMA in the presence of CFO. With the proposed PIC, however, SC-FDMA recovers its frequency diversity advantage and outperforms OFDMA.*



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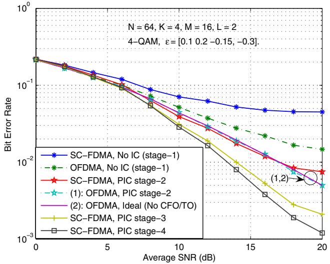

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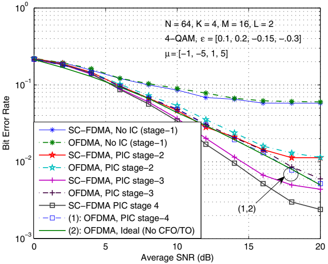

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- **Only CFO**: Without Parallel Interference Canceler
  The BER in OFDMA is better than that in SC-FDMA

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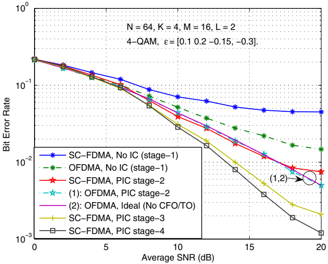

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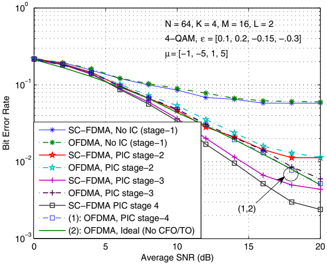

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- **Only CFO**: Without Parallel Interference Canceler
  SC-FDMA suffers **more** from CFO

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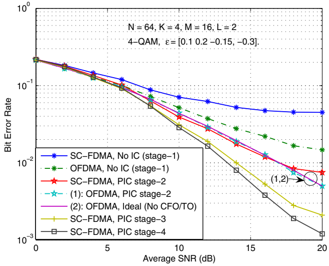

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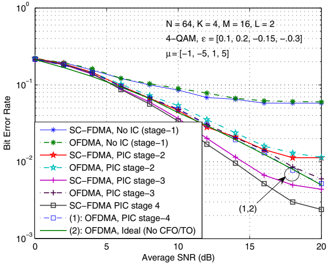

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- **Only CFO**: With Parallel Interference Canceler
  1st stage PIC makes OFDMA reach OFDMA's ideal performance.

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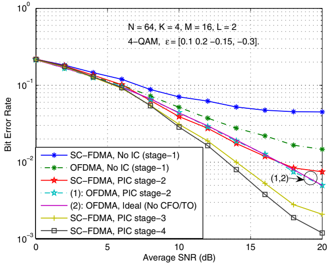

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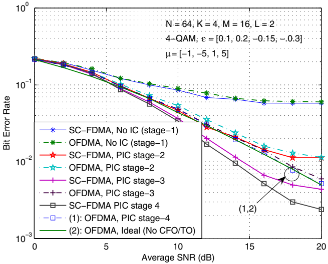

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  1st stage PIC makes OFDMA reach OFDMA's ideal performance.
  SC-FDMA is better than OFDMA in BER performance in 3rd and 4th stage.

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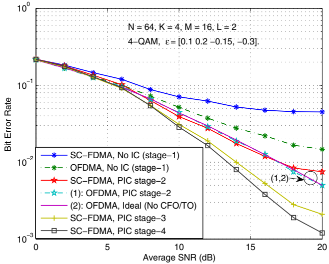

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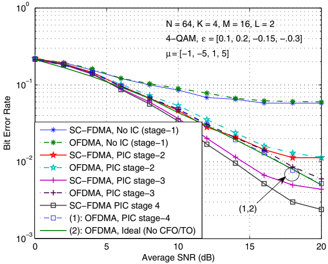

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- **Only CFO**: With Parallel Interference Canceler
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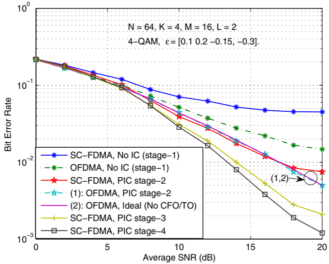

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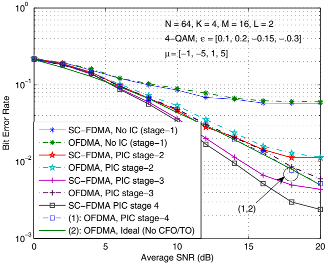

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- **Only CFO and TO**: Without Parallel Interference Canceler
  Same performance

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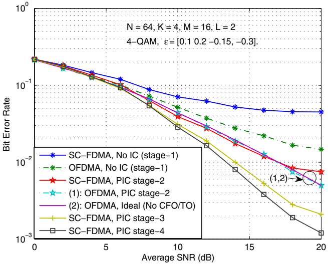

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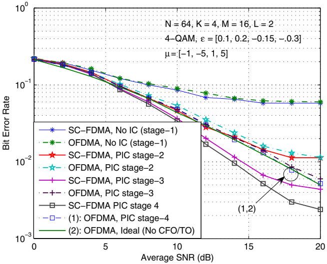

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- **Only CFO and TO**: With Parallel Interference Canceler
  SC-FDMA has superiority over OFDMA with three or four stages of PIC

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Outline

- Introduction to **Principle of SC-FDMA System**

    1. Structure of SC-FDMA
    2. Mathmatical Model
    3. Key techniques in the SC-FDMA

- Comparison **SC-FDMA System** to **OFDMA System** and **DS-CDMA System**

- Summary, Conclusions and Thoughts

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- Uncode SC-FDMA has better BER performance than OFDMA in MMSE due to **frequency diversity**
- SC-FDMA suffers **more** from CFO while PIC could restore the frequency diversity

Thoughts

- Why could SC-FDMA be treated as single carrier, which has low PAPR ?

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- From Project Officer LuoSheng's opinion

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- Is pre-DFT the most attractive and efficient pre-coding for OFDMA?

Reference

- Please feel free to e-mail **liuyunxiang1991@gmail.com** for a reference list.

Acknowledge

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- Thanks to **Dr. Nguyen**
- Thanks to **Audiences here!**

Thanks

YunXiang LIU