



2020浙江省通信技术前沿论坛学术报告

滤波多载波的波形调制技术

汇报人：华惊宇



浙江省新型网络标准及应用技术重点实验室
浙江工商大学信息与电子工程学院

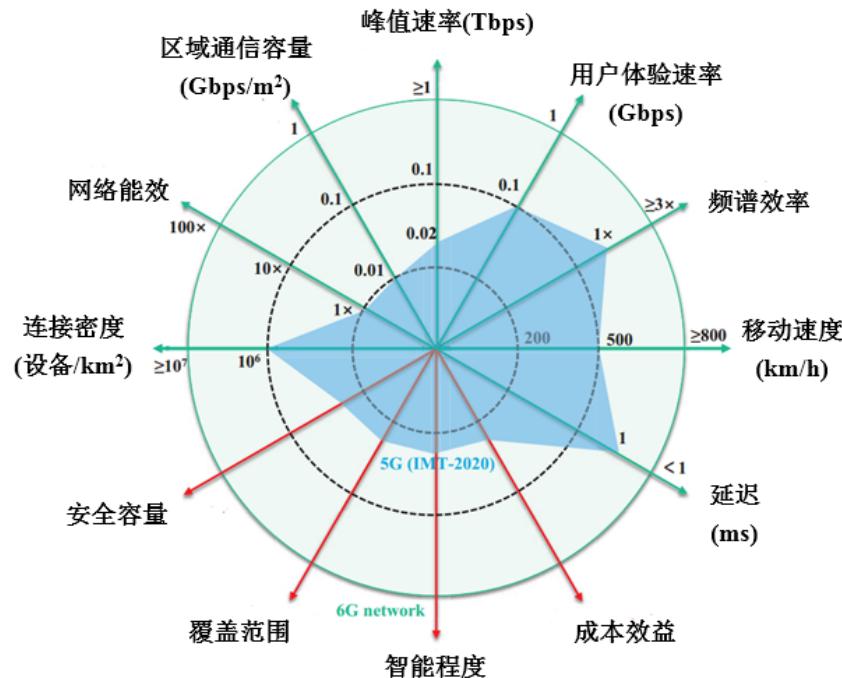


汇报提纲

- 1、背景与现状
- 2、滤波器组多载波(FBMC)
- 3、子带滤波正交频分复用(F-OFDM)

1. 背景

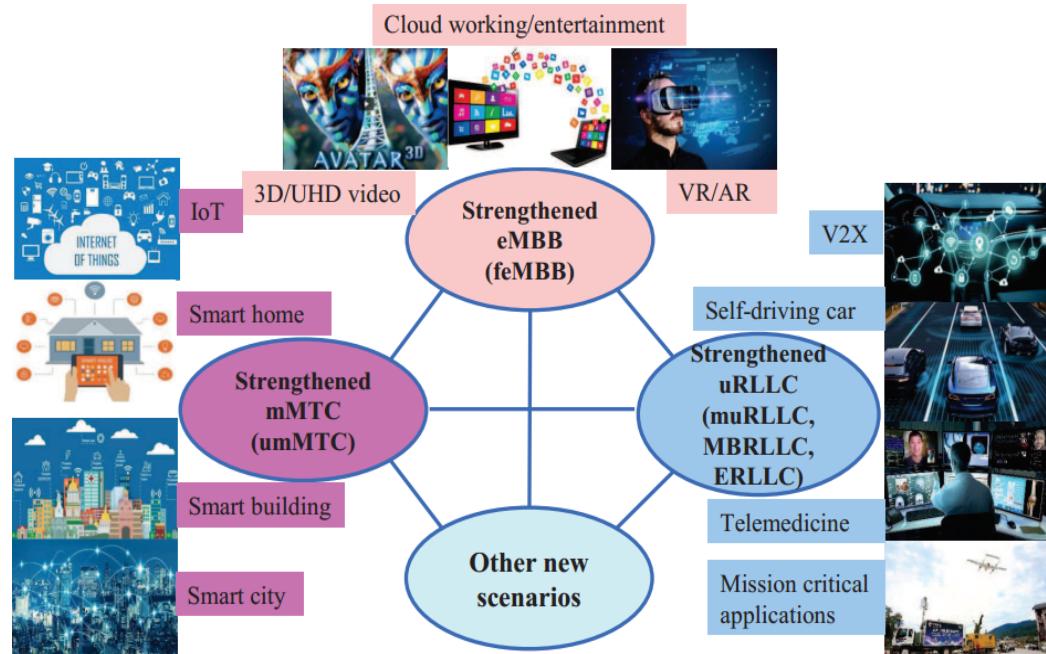
5G与6G通信网络的性能指标需求对比^[1]



新指标需求下5G物理层的不足

- A. 干扰控制
- B. 能效控制
- C. 谱效率提升

6G通信网络的应用场景^[1]



eMBB: enhanced mobile broadband
mMTC: massive machine type communications
uRLLC: ultra-reliable low latency communications

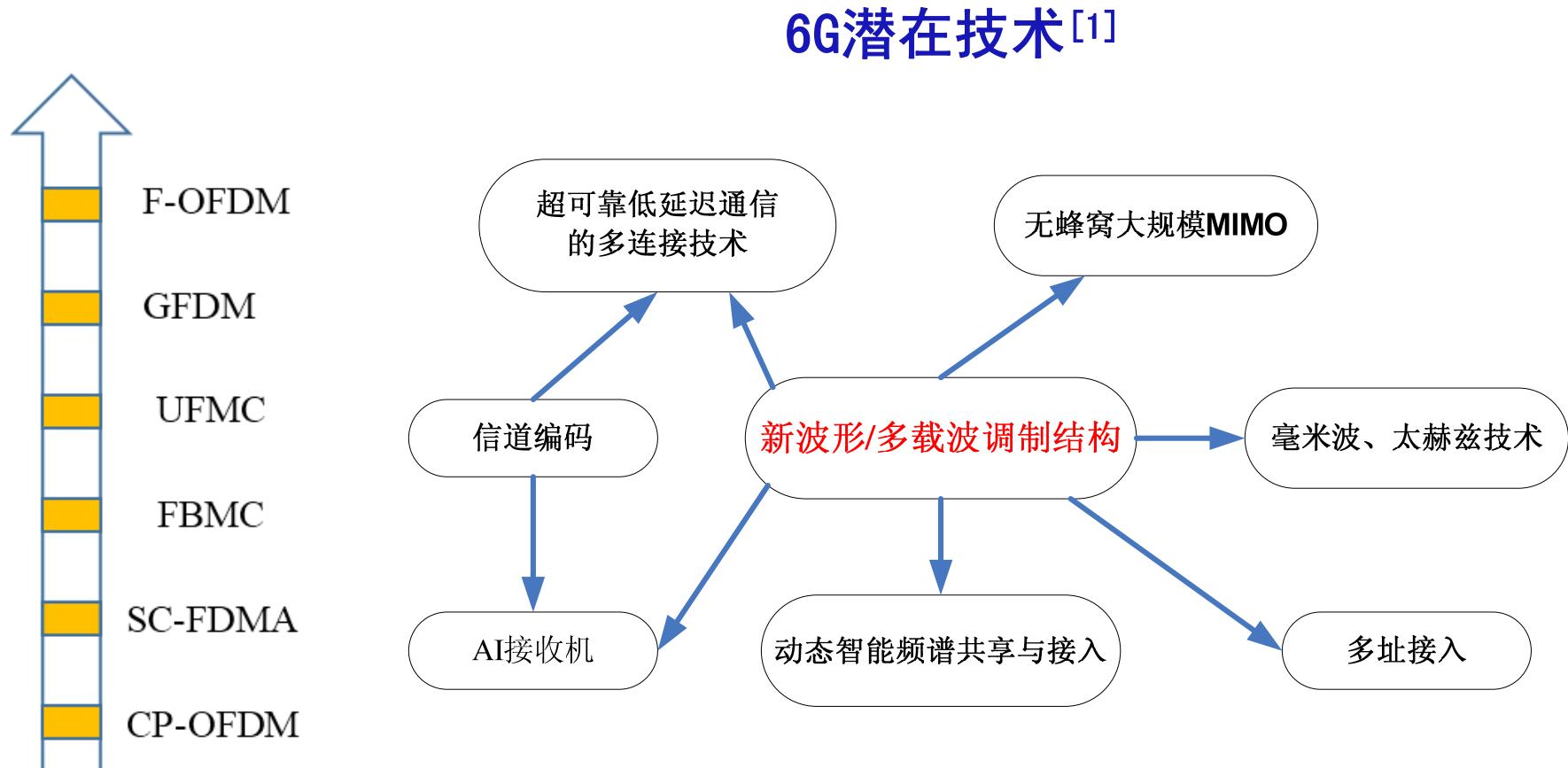
增强型移动宽带
大规模机器通信
超可靠低延迟通信

feMBB: further-eMBB
umMTC: ultra-mMTC
muRLLC: massive-uRLLC
MBRLLC: mobile broadband RLLC
ERLLC: extremely RLLC

进一步增强的移动宽带
超大规模机器通信
大规模超可靠低延迟通信
移动宽带可靠低延迟通信
极其可靠且低延迟的通信

[1] Yu X H(尤肖虎), Wang C X, Huang J, et al. Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts [J]. SCIENCE CHINA Information Sciences, 2020. <https://doi.org/10.1007/s11432-020-2955-6>

1. 背景



1. 现状 调制波形发展现状^[2]

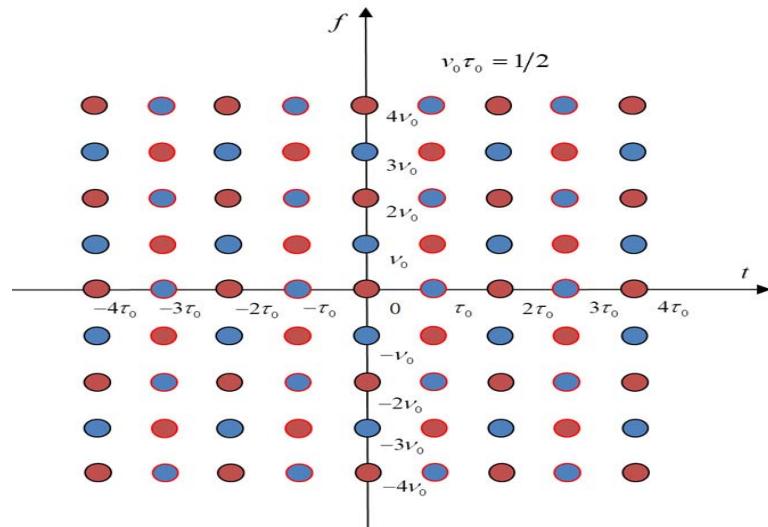
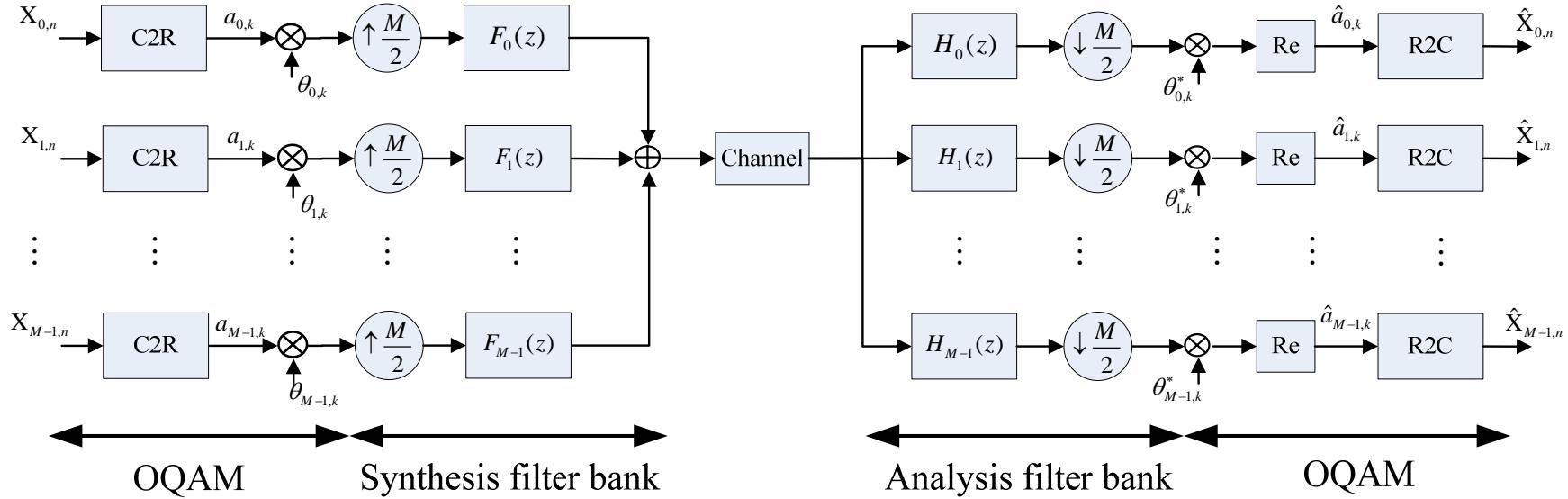
滤波多载波调制波形要求：

- 兼容OFDM调制波形；
- 可完美结合现有OFDM高级技术，比如AI接收机；
- 适应干扰控制、能效控制、谱效率提升三大重要需求。



[2] Gerzaguet R, Bartzoudis N, Baltar L G, et al. The 5G candidate waveform race: a comparison of complexity and performance [J]. EURASIP Journal on Wireless Communications and Networking, 2017, 1: 13-27..

2. FBMC 系统结构框图



Signal
Staggering

$$a_{m,k} = \begin{cases} a_{m,2n} = \begin{cases} \text{Re}\{X_{m,n}\}, m \text{ even} \\ \text{Im}\{X_{m,n}\}, m \text{ odd} \end{cases} \\ a_{m,2n+1} = \begin{cases} \text{Im}\{X_{m,n}\}, m \text{ even} \\ \text{Re}\{X_{m,n}\}, m \text{ odd} \end{cases} \end{cases}$$

2. FBMC 信号模型

发射信号:

$$s[l] = \sum_{m=0}^{M-1} \sum_{k=0}^{2K-1} a_{m,k} \underbrace{g[l - k \frac{M}{2}] e^{j2\pi k \frac{m}{M}} e^{j\theta_{m,k}}}_{\mathbf{g}_{m,k}}$$

其中:

$$\theta_{m,k} = (\pi/2)(m+k)$$

$g[n]$ 为原型滤波器系数

重建信号:

$$\hat{a}_{m_0, k_0} = \sum_{m=0}^{M-1} \sum_{k=0}^{2K-1} a_{m,k} \operatorname{Re} \left\{ \langle \mathbf{g}_{m,k}, \mathbf{g}_{m_0, k_0} \rangle \right\}$$

其中:

$$\phi_1 = \theta_{m,k} - \theta_{m_0, k_0}$$

$$\phi_2 = \frac{\pi}{2}(m - m_0)(k + k_0)$$

$$\langle \mathbf{g}_{m,k}, \mathbf{g}_{m_0, k_0} \rangle = e^{j\phi_1} e^{j\phi_2} \sum_l g[l + \frac{k_0 - k}{2} \frac{M}{2}] g[l - \frac{k_0 - k}{2} \frac{M}{2}] e^{-j2\pi(m_0 - m) \frac{l}{M}}$$

内积

2. FBMC 模糊函数

$$\langle \mathbf{g}_{m,k}, \mathbf{g}_{m_0,k_0} \rangle = e^{j\phi_1} e^{j\phi_2} \sum_l g[l + \frac{k_0 - k}{2}] g[l - \frac{k_0 - k}{2}] e^{-j2\pi(m_0 - m) \frac{l}{M}}$$

Ideal

PR

实数域
正交性

Real

NPR

$$\begin{cases} \operatorname{Re}\{\langle \mathbf{g}_{m_0,k_0}, \mathbf{g}_{m_0,k_0} \rangle\} = 1 \\ \operatorname{Re}\{\langle \mathbf{g}_{m,k}, \mathbf{g}_{m_0,k_0} \rangle\} = 0 \end{cases}$$

$$\begin{cases} \operatorname{Re}\{\langle \mathbf{g}_{m_0,k_0}, \mathbf{g}_{m_0,k_0} \rangle\} = 1 & \text{归一化} \\ \operatorname{Re}\{\langle \mathbf{g}_{m,k}, \mathbf{g}_{m_0,k_0} \rangle\} = \beta \end{cases}$$

$$\operatorname{Re}\{\mathbf{Q}_{m_0} \Psi\}$$

$$= \left[\mathbf{0}_{2K \times (2m_0 K)}, \mathbf{I}_{2K \times 2K}, \mathbf{0}_{2K \times (2(M-m_0-1)K)} \right]$$



-4.9413e-17	8.9518e-11	-7.9144e-18	1.0350e-10	-1.0541e-17	8.9518e-11	-4.9413e-17
4.3402e-17	-1.6153e-17	2.1465e-17	1.2262e-17	-5.7094e-18	1.6370e-17	-4.3385e-17
-9.3568e-17	-1.3020e-04	-9.8277e-18	-2.0362e-04	-4.0437e-17	-1.3020e-04	-9.3569e-17
1.0345e-16	-2.6397e-17	5.6829e-17	3.4562e-17	-3.1626e-17	2.6396e-17	-1.0345e-16
-1.3661e-17	9.4698e-16	1.7168e-16	1.0000	1.7168e-16	9.4698e-16	-1.3661e-17
1.0344e-16	2.6397e-17	5.6829e-17	3.4562e-17	-8.2032e-17	-2.6398e-17	-1.0344e-16
-9.3564e-17	-1.3020e-04	-9.8277e-18	-2.0362e-04	2.0782e-17	-1.3020e-04	-9.3563e-17
4.3271e-17	1.3830e-17	9.7643e-17	1.2262e-17	-1.1340e-16	-1.3612e-17	-4.3288e-17

PR: Perfect Reconstruction

NPR: Nearly Perfect Reconstruction

2. FBMC 干扰分析

将发射信号拆分：

$$a_{m_0, k_0} = \operatorname{Re} \left\{ \left\langle \mathbf{g}_{m_0, k_0}, \mathbf{g}_{m_0, k_0} \right\rangle \right\} a_{m_0, k_0}$$

信号部分

$$+ \sum_{m=0, m \neq m_0}^{M-1} \sum_{k=0, k \neq k_0}^{2K-1} \operatorname{Re} \left\{ \left\langle \mathbf{g}_{m, k}, \mathbf{g}_{m_0, k_0} \right\rangle \right\} a_{m, k}$$

干扰部分

$$SIR_{(m_0, k_0)} = \frac{(\operatorname{Re} \left\{ \left\langle \mathbf{g}_{m_0, k_0}, \mathbf{g}_{m_0, k_0} \right\rangle \right\})^2}{\sum_{m=0, m \neq m_0}^{M-1} \sum_{k=0, k \neq k_0}^{2K-1} (\operatorname{Re} \left\{ \left\langle \mathbf{g}_{m, k}, \mathbf{g}_{m_0, k_0} \right\rangle \right\})^2} = \frac{\mathbf{g}^T \mathbf{Q}_{(0,0)} \mathbf{g}}{\sum_{m=0, m \neq m_0}^{M-1} \sum_{k=0, k \neq k_0}^{2K-1} (\mathbf{g}^T \mathbf{Q}_{(m-m_0, k-k_0)} \mathbf{g})^2}$$

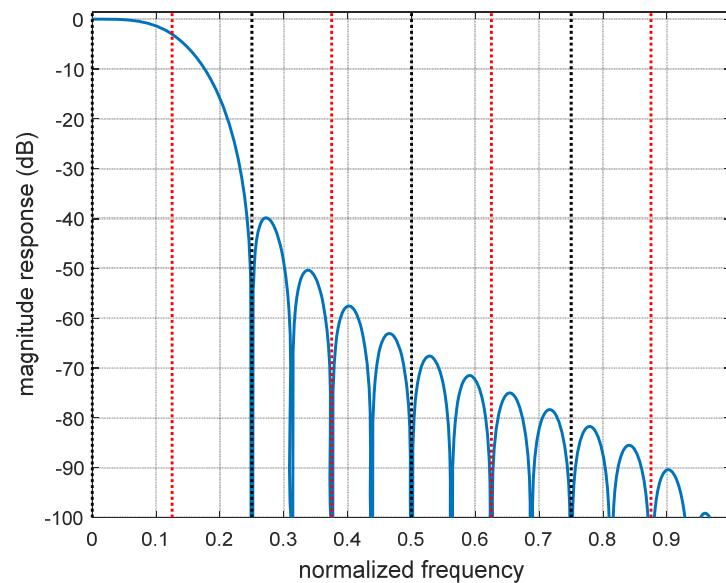
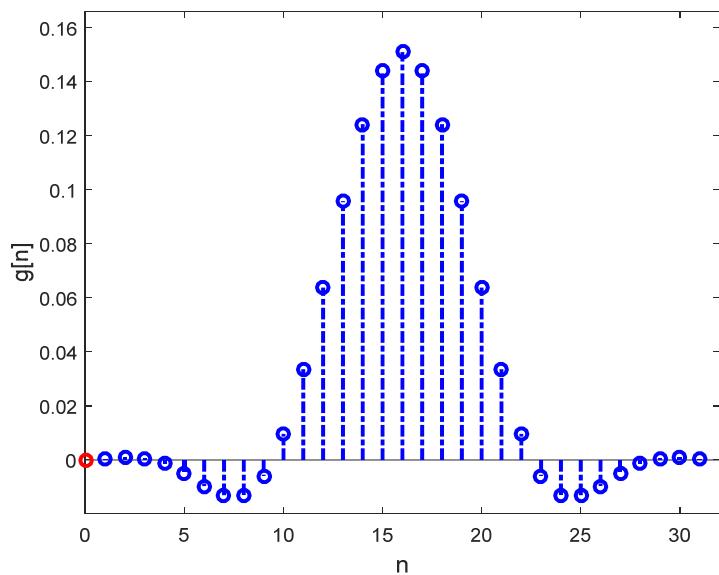
$$SINR_{(m_0, k_0)} = \frac{(\operatorname{Re} \left\{ \left\langle \mathbf{g}_{m_0, k_0}, \mathbf{g}_{m_0, k_0} \right\rangle \right\})^2}{\frac{10^{\frac{(-SNR)}{10}}}{2} (\mathbf{g}^T \mathbf{g})^2 + \sum_{m=0, m \neq m_0}^{M-1} \sum_{k=0, k \neq k_0}^{2K-1} (\operatorname{Re} \left\{ \left\langle \mathbf{g}_{m, k}, \mathbf{g}_{m_0, k_0} \right\rangle \right\})^2}$$

2. FBMC PHY原型滤波器

PHY原型滤波器系数值：

$$\begin{cases} g[0] = 0 \\ g[m+1] = p[m] \end{cases} \quad p[m] = A[0] + 2 \sum_{k=1}^{K-1} (-1)^k A[k] \cos\left(\frac{2\pi k}{KM}(m+1)\right), \quad m = 0, 1, \dots, KM - 2$$
$$A[0] = 1, A[1] = 0.97195983, A[2] = 1/\sqrt{2}, A[3] = 0.23514695$$

$M = 8, K = 4$ 下的时频域波形视图

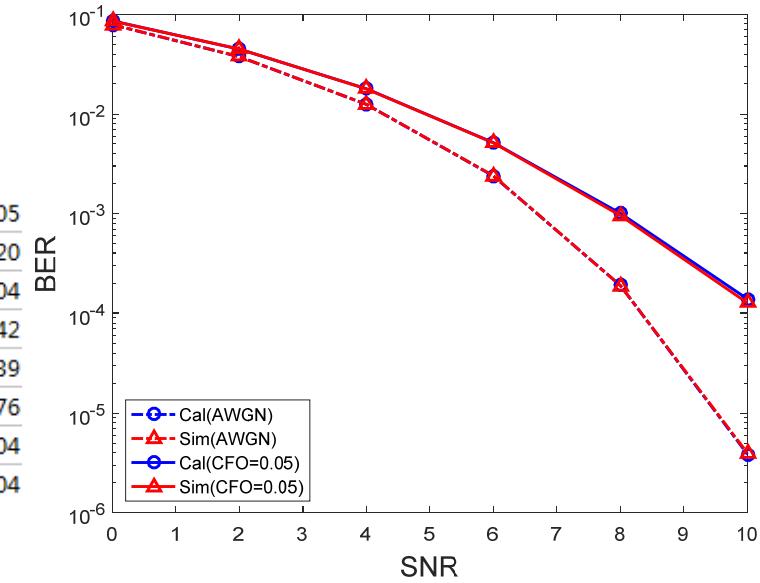
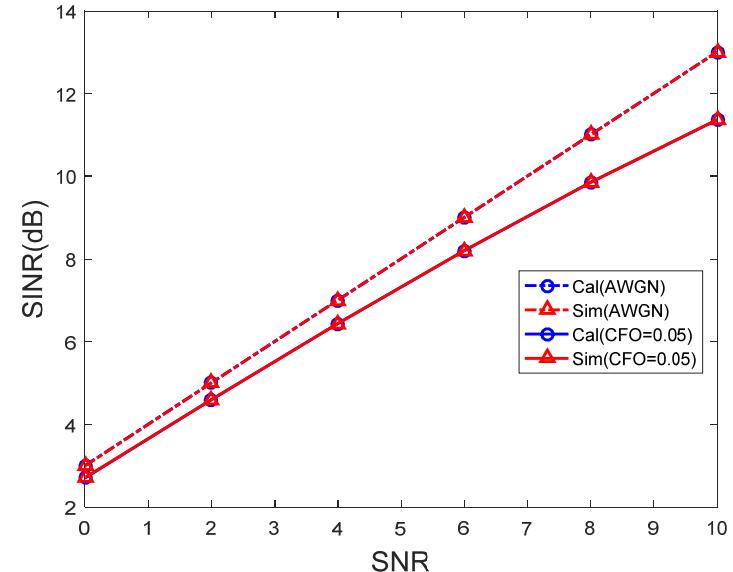


2. FBMC PHY原型滤波器

性能指标	测量值
通带波形(R_p)	3.0dB
阻带衰减(A_s)	40dB
通带误差能量(E_p)	5e-3
阻带误差能量(E_s)	1e-5
Nyquist引起的ISI	8e-4

CFO=0.05时，实数域正交性：

2.2449e-04	2.7707e-04	6.1103e-04	4.9684e-06	-6.4386e-04	-3.1007e-04	-1.9166e-04	2.8037e-05
-1.9887e-04	0.0033	0.0099	0.0131	0.0097	0.0027	-8.0654e-04	-0.0020
0.0052	0.0063	0.0142	-8.4495e-05	-0.0150	-0.0074	-0.0045	6.5197e-04
-0.0024	0.0211	0.0588	0.0963	0.0581	0.0168	-0.0066	-0.0142
0.0307	0.0294	1.3959e-04	0.9868	-0.0164	-0.0355	-0.0267	0.0039
0.0037	-0.0043	0.0066	-0.0578	0.0048	-0.0017	0.0054	0.0076
0.0052	0.0063	0.0142	-8.4495e-05	-0.0150	-0.0074	-0.0045	6.5197e-04
4.8082e-04	1.8503e-04	0.0037	-0.0051	0.0034	4.0959e-04	5.6394e-04	5.9173e-04



2. FBMC 原型滤波器设计

□ 纯滤波器设计方法

以阻带衰减(As)或者阻带误差能量(Es)为优化目标；以通带波动(Rp)、Nyquist引起的ISI(ISI_t)、时域拖尾(Et)等性能为约束对象的约束优化问题。

$$\begin{aligned} & \min_{\mathbf{g}} \max_{\omega \in [\omega_s, \pi]} |\mathbf{c}^T(\omega)\mathbf{g}| \\ s.t. & \left\{ \begin{array}{l} |1 - \mathbf{c}^T(\omega)\mathbf{g}| \leq \delta_p^m, \omega \in [0, \omega_p] \\ \sum_k |\mathbf{g}^T \mathbf{Q}_k \mathbf{g}| / \mathbf{g}^T \mathbf{g} \leq \delta_{ISI}^m \\ \mathbf{g}^T \mathbf{Q}_t \mathbf{g} \leq \delta_t^m \end{array} \right. \end{aligned}$$

$$\begin{aligned} & \min_{\mathbf{g}} \mathbf{g}^T \mathbf{Q}_s \mathbf{g} \\ s.t. & \left\{ \begin{array}{l} |1 - \mathbf{c}^T(\omega)\mathbf{g}| \leq \delta_p^m, \omega \in [0, \omega_p] \\ \sum_k |\mathbf{g}^T \mathbf{Q}_k \mathbf{g}| / \mathbf{g}^T \mathbf{g} \leq \delta_{ISI}^m \\ \mathbf{g}^T \mathbf{Q}_t \mathbf{g} \leq \delta_t^m \end{array} \right. \end{aligned}$$

$$\sum_k |\mathbf{g}^T \mathbf{Q}_k \mathbf{g}| / \mathbf{g}^T \mathbf{g} \leq \delta_{ISI}^m \quad \begin{matrix} \text{时域约束} \\ \text{近似为} \\ \text{频域约束} \end{matrix} \rightarrow \left\{ \begin{array}{l} \mathbf{g}^T \mathbf{Q}(\omega) \mathbf{g} \leq 1 + \delta_{ISI}^m, \omega \in [0, \frac{\pi}{M}] \\ \sqrt{2} \cdot \mathbf{R}(\frac{\pi}{M}) \mathbf{g} \geq \sqrt{1 - \delta_{ISI}^m} \end{array} \right.$$

求解算法：半定规划(SDP)，二阶锥规划(SOCP)

2. FBMC 原型滤波器设计

□ 从系统性能考虑的滤波器设计方法

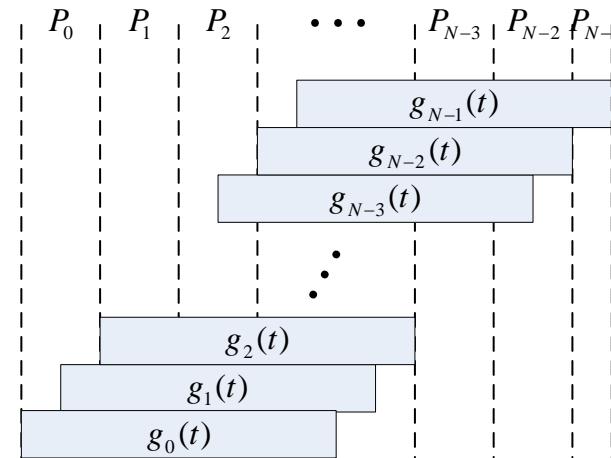
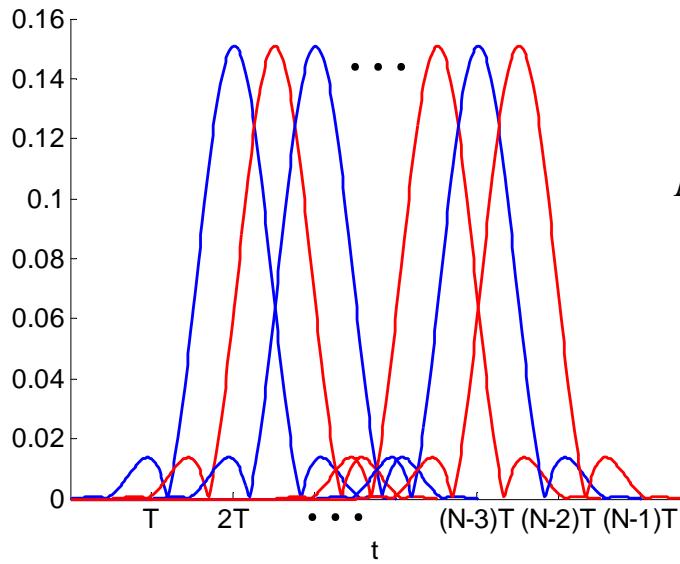
在纯滤波器设计方法的基础上，联合考虑实数域正交误差(基于模糊函数的计算，与SINR直接相关)进行(约束)优化设计。

$$\begin{aligned} & \min_{\mathbf{g}} \max_{(m_0, k_0)} (\mathbf{g}^T \mathbf{Q}_{(0,0)} \mathbf{g} - 1)^2 + \sum_{m=0, m \neq m_0}^{M-1} \sum_{k=0, k \neq k_0}^{2K-1} (\mathbf{g}^T \mathbf{Q}_{(m-m_0, k-k_0)} \mathbf{g})^2 \\ & s.t. \begin{cases} |\mathbf{c}^T(\omega) \mathbf{g}| \leq \delta_s^m, \omega \in [\omega_s, \pi] \\ |1 - \mathbf{c}^T(\omega) \mathbf{g}| \leq \delta_p^m, \omega \in [0, \omega_p] \\ \mathbf{g}^T \mathbf{Q}_s \mathbf{g} \leq E_s^m \end{cases} \end{aligned}$$

$$\min_{\mathbf{g}} \max_{(m_0, k_0)} (\mathbf{g}^T \mathbf{Q}_{(0,0)} \mathbf{g} - 1)^2 + \sum_{m=0, m \neq m_0}^{M-1} \sum_{k=0, k \neq k_0}^{2K-1} (\mathbf{g}^T \mathbf{Q}_{(m-m_0, k-k_0)} \mathbf{g})^2 + \alpha \cdot \mathbf{g}^T \mathbf{Q}_s \mathbf{g} + \beta \cdot (\mathbf{g}^T \mathbf{Q}_p \mathbf{g} + 2\mathbf{g}^T \mathbf{b} + \mathbf{c})$$

求解算法：序列二次规划(SQP)，梯度类算法，智能算法

2. FBMC PAPR问题



$$\left\{ \begin{array}{l} PAPR_i = 10 \log_{10} \frac{\max_{iM \leq l \leq (i+1)M} |s(l)|^2}{P_{ave}}, i = 0, 1, 2K-2 \\ PAPR_i = 10 \log_{10} \frac{\max_{iM \leq l \leq (i+0.5)M} |s(l)|^2}{P_{ave}}, i = 2K-1 \end{array} \right.$$

其中：

P_{ave} 是发射信号 $s(l)$ 的平均功率。

2. FBMC PAPR问题

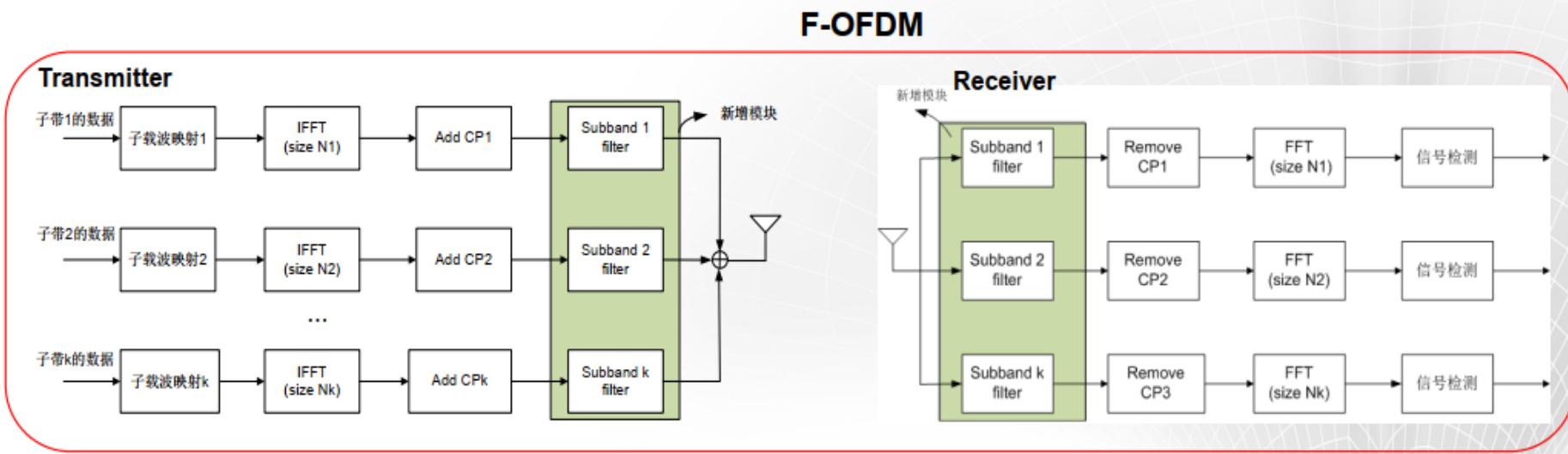
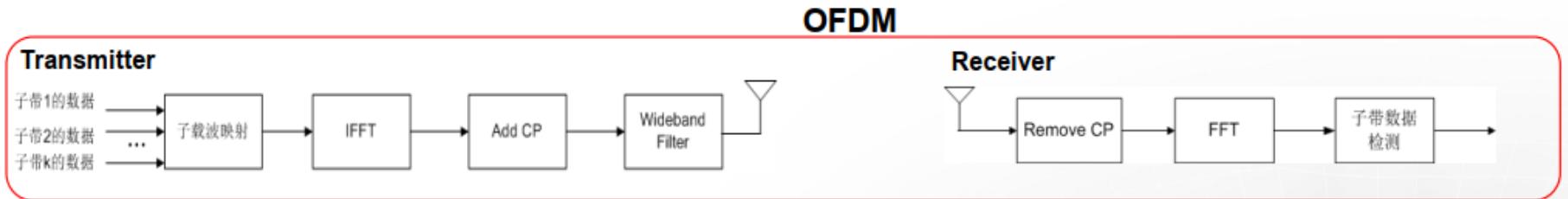
□ 传统PAPR方法+滤波器优化

针对现有FBMC降PAPR方法，如选择性映射(selective mapping, SLM)、部分发射序列(partial transmit sequence, PTS)、音调保留(tone reservation, TR)和有源星座扩展(active constellation extension, ACE)以及DFT-spread方法，结合FBMC原型滤波器优化设计，改善PAPR的同时，保证或者改善带外辐射性能、实数域正交性能(也就是SIR结果)。

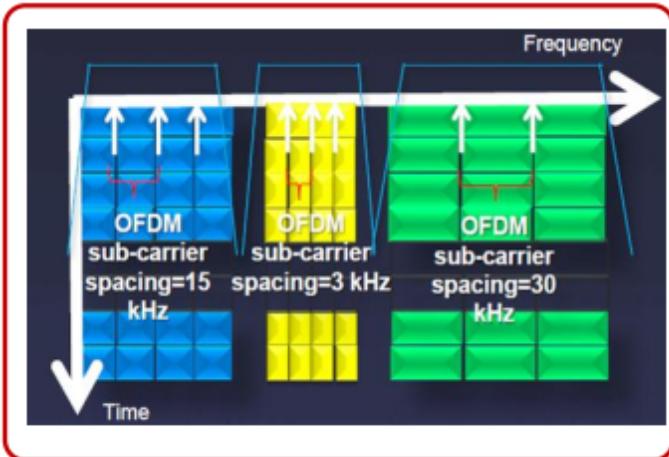
□ 纯滤波器优化设计方法

针对FBMC_PAPR定义，在滤波器层级构建与其直接相关的数学模型，作为PAPR性能指标，将其融入到FBMC原型滤波器设计方法中，实现FBMC原型滤波器性能与PAPR性能的折衷优化。

3. f-OFDM标准结构



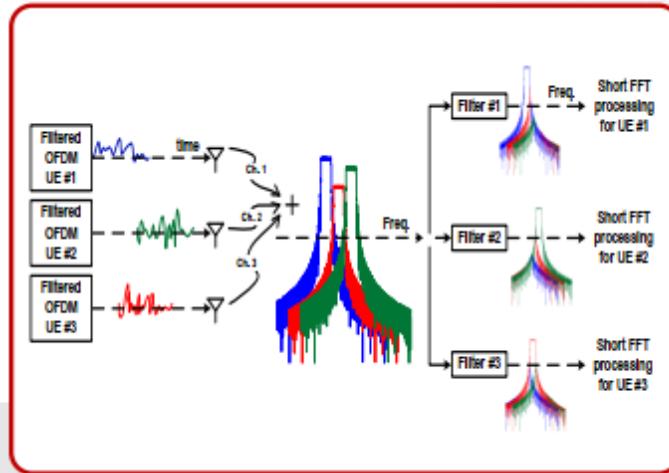
3. f-OFDM的优势



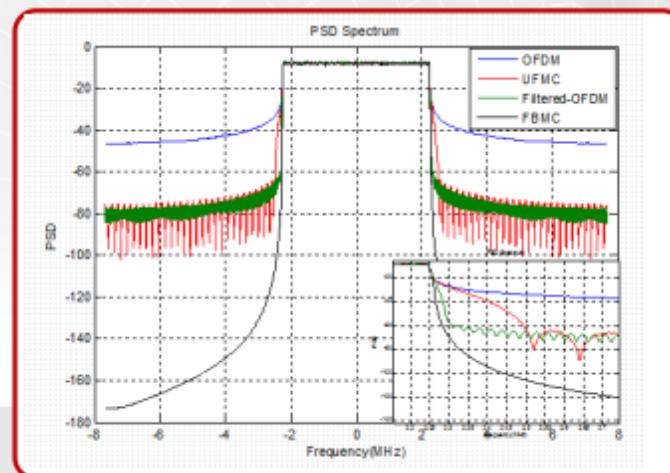
Co-existence of waveform with different OFDM primitive



Different Cyclic prefix for each specific sub-band



Support asynchronous OFDMA transmission



Good Out-of-band leakage rejection

3. f-OFDM的收发机描述

发送端：

子带 j 中第 n 个符号的时域发送数据可以表示为：

$$a_{j,n}(k) = \frac{1}{N_j} \sum_{u=0}^{N_j-1} A_{j,n}(u) e^{j2\pi uk/N_j}, 0 \leq k \leq N_j - 1$$

 加CP

$a_j^{CP}(k')$
 发送滤波

用户 j 的发送信号： $x_j(k' - D_j) = a_j^{CP}(k' - D_j) \otimes f_{j,Tx}(k')$
其中 D_j 表示用户 j 的发送时延。

3. f-OFDM的收发机描述

接收端：

$$y(k') = \sum_{j=0}^{J-1} x_j(k' - D_j) \otimes h_j(k') \cdot c_j(k') + z(k')$$

基站接收信号：

$$= \sum_{j=0}^{J-1} a_j^{CP} (k' - D_j) \otimes f_{j,Tx}(k') \otimes h_j(k') \cdot c_j(k') + z(k')$$

匹配滤波



其中 $c_j(k')$ 表示用户 j 的 CFO。

目标用户 i 的接收信号： $r_{N_i}(k') = y(k') \otimes f_{i,Rx}(k')$

$$= a_i^{CP} (k' - D_i) \otimes f_{i,Tx}(k') \otimes h_i(k') \cdot c_i(k') \otimes f_{i,Rx}(k')$$

$$+ \sum_{\substack{j=0 \\ j \neq i}}^{J-1} a_j^{CP} (k' - D_i - \Delta_{ij}) \otimes f_{j,Tx}(k') \otimes h_j(k') \cdot c_j(k') \otimes f_{i,Rx}(k')$$

$$+ z(k') \otimes f_{i,Rx}(k')$$

其中 $\Delta_{ij} = D_j - D_i$ 表示用户 j 和 i 之间的 TO。

目标用户 i 第 n 个符号中



去除 CP 和群延时，并作 DFT

第 m 个子载波上的频域

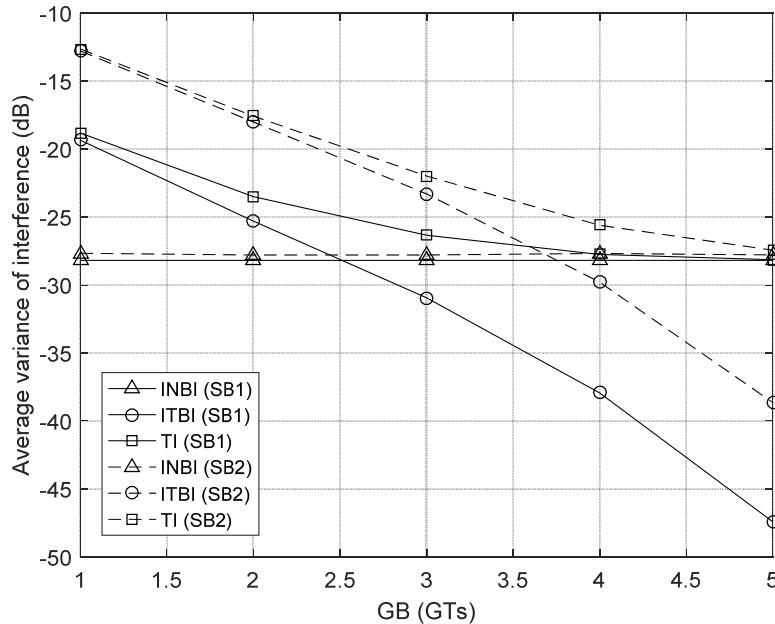
$$R_{i,n}(m) = A_{i,n}(m) H_{e_i,n}(m) + I_{i,n}(m) + Z_{i,n}(m)$$

接收信号：

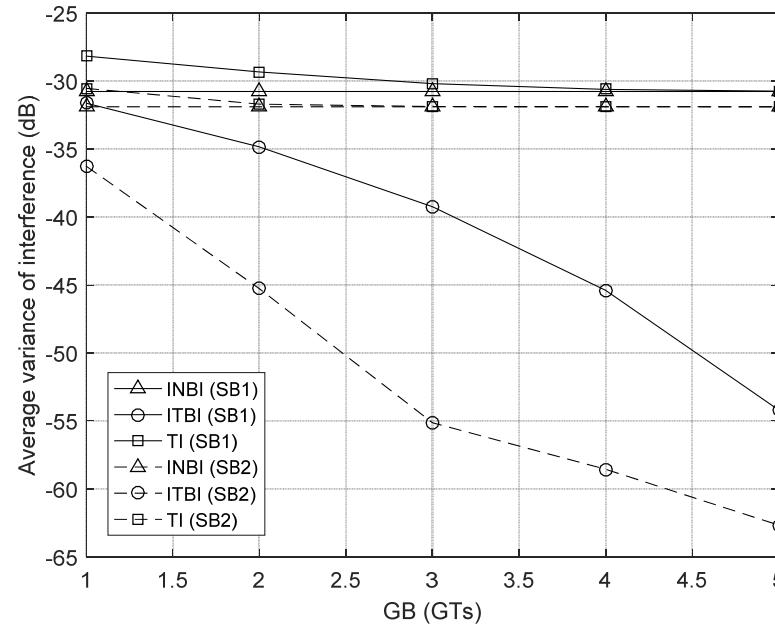
$$I_{i,n}(m) = I_{\text{INBI}_{i,n}}(m) + \sum_{\substack{j=0 \\ j \neq i}}^{J-1} I_{\text{ITBI}_{ij,n}}(m)$$

干 扰

3. f-OFDM的干扰仿真分析



ESs

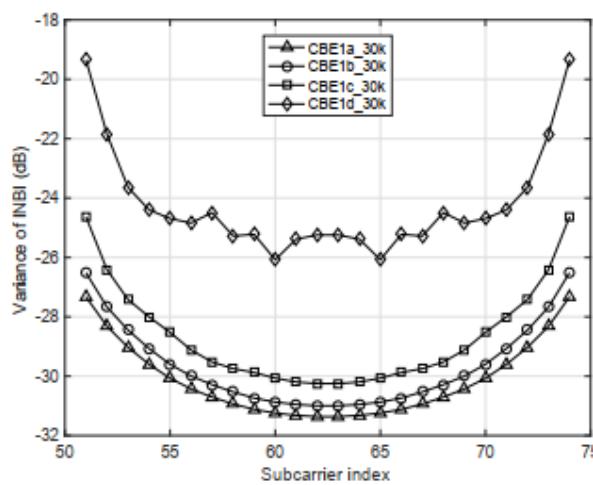


ISs

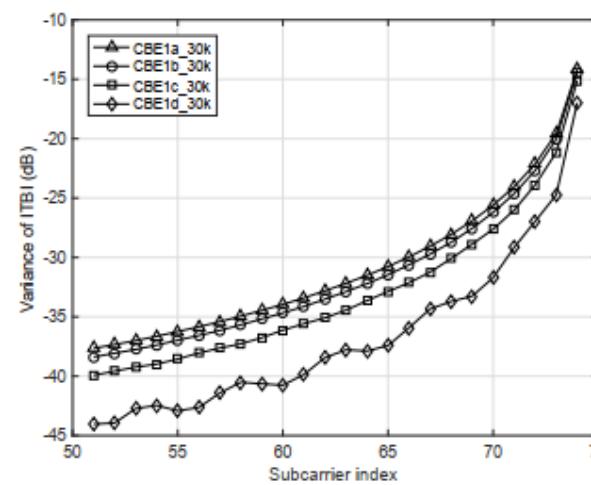
- 1) 两个子带的边沿INBI基本一致，且基本不随GB的增加而发生波动；
- 2) 从ESs上看，当GB比较小时，两个子带边沿ITBI的差距会造成边沿TI的不平衡。当GB较大时，边沿TI不平衡的现象会减轻；
- 3) 从ISs上看，虽然两个子带的内部ITBI差距仍然很大，但由于此时两个子带的ITBI都已经处于很低的水平，所以并不会造成两个子带TI的显著差距。

f-OFDM的干扰仿真分析

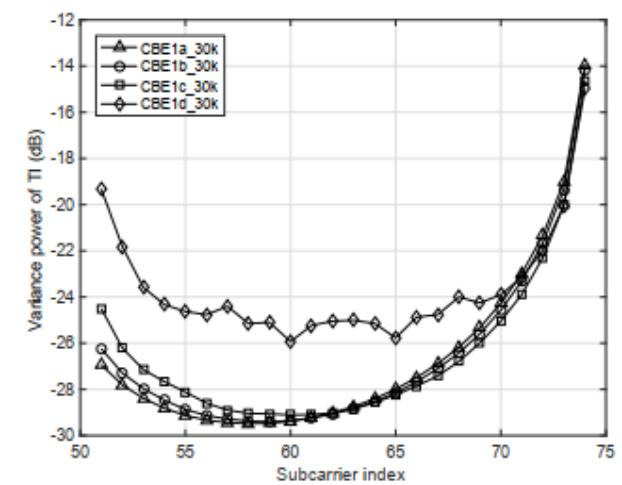
SB filters	Name	Length (samples)	Fp (MHz)	Fs (MHz)	Ft (MHz)	Rp (dB)	As (dB)
Filters of SB ₁	Hann _{30k}	512	0.36	0.5543	0.1943	0.055	-44.0
	CBE1a _{30k}	512	0.36	0.5543	0.1943	0.005	-52.8
	CBE1b _{30k}	512	0.36	0.5376	0.1776	0.010	-52.8
	CBE1c _{30k}	512	0.36	0.5167	0.1567	0.050	-52.8
	CBE1d _{30k}	512	0.36	0.4785	0.1185	0.400	-52.8
	CBE2a _{30k}	512	0.36	0.5543	0.1943	0.050	-74.6
	CBE2b _{30k}	512	0.36	0.5154	0.1554	0.050	-51.8
	CBE2c _{30k}	512	0.36	0.4766	0.1166	0.050	-34.6
	CBE2d _{30k}	512	0.36	0.4572	0.0972	0.050	-26.8
Filters of SB ₂	Hann _{15k}	1024	0.36	0.4571	0.0971	0.055	-44.0
	CBE _{15k}	1024	0.36	0.4571	0.0971	9e-3	-59.7



(a) Variances of INBI: SB₁, CBE1_{30k}



(b) Variances of ITBI: SB₁, CBE1_{30k}



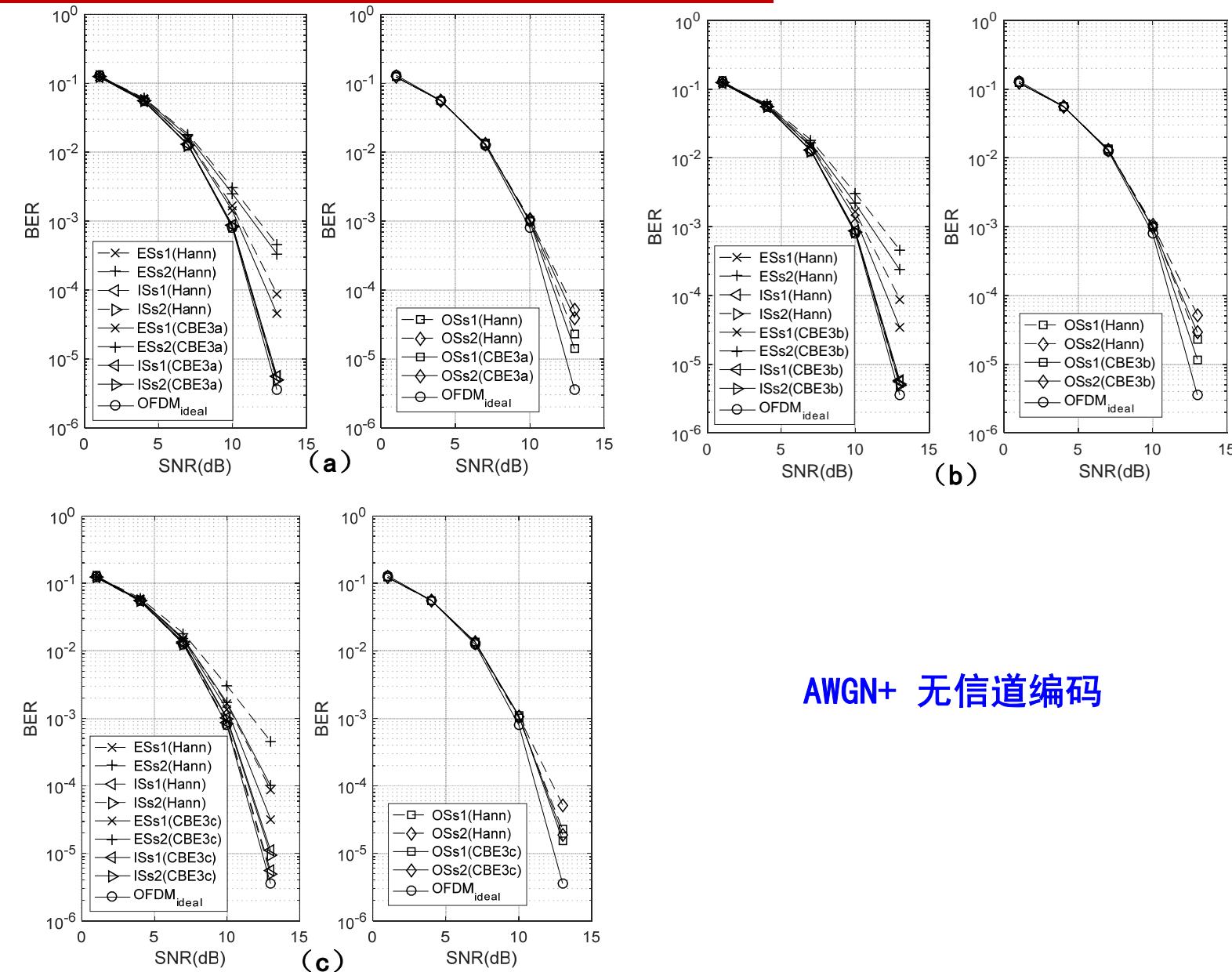
(c) Variances of TI: SB₁, CBE1_{30k}

f-OFDM的干扰仿真分析

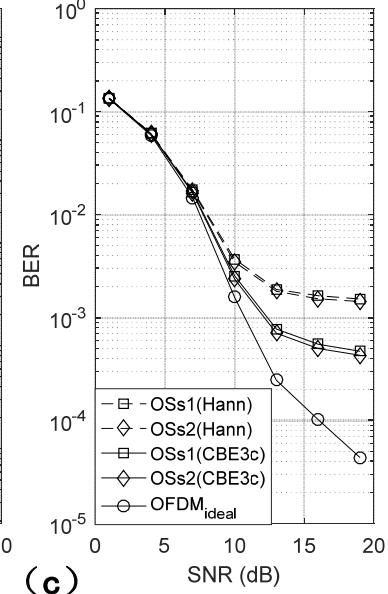
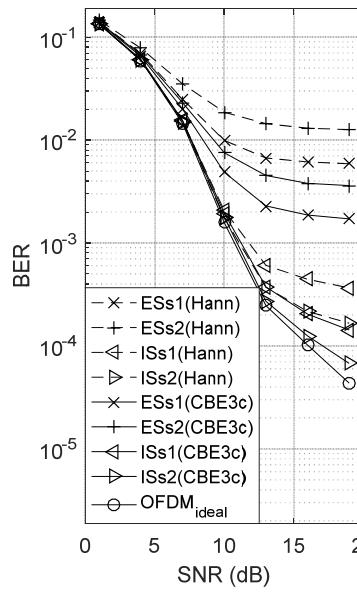
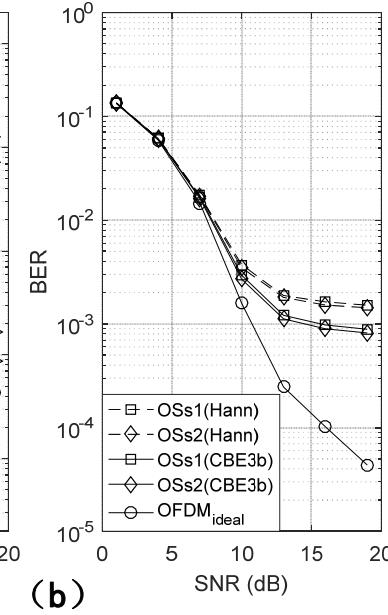
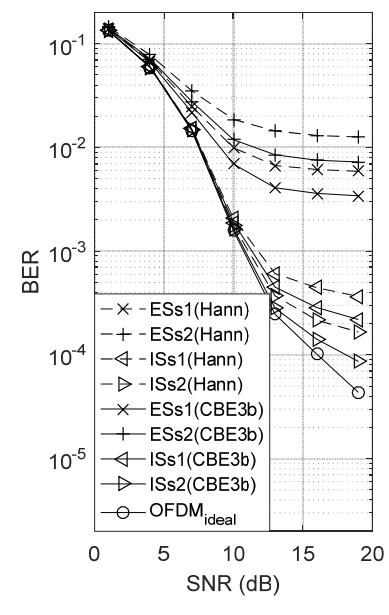
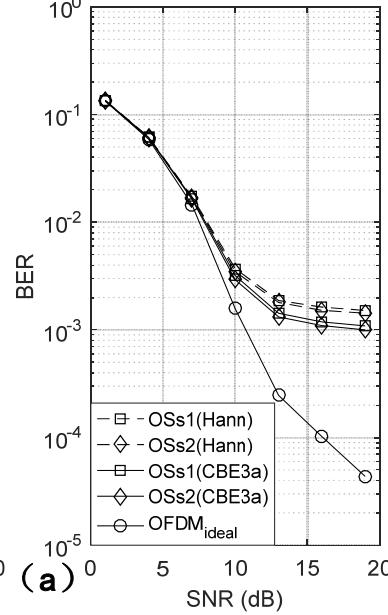
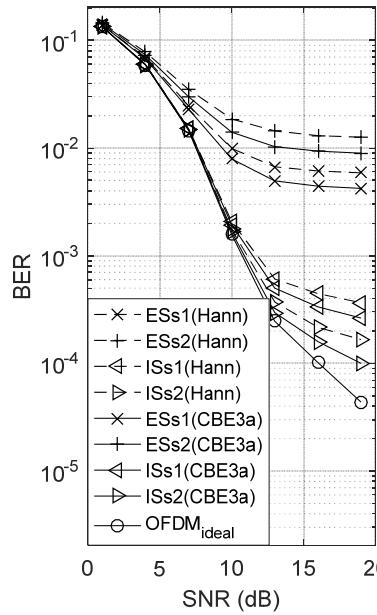
SB filters	Name	Length(samples)	Fp(MHz)	Fs(MHz)	Ft(MHz)	Rp(dB)	As(dB)
Filters of SB ₁	Hann _{30k}	512	0.36	0.5543	0.1943	0.055	-44.0
	CBE3a _{30k}	512	0.36	0.4572	0.0972	0.020	-20.4
	CBE3b _{30k}	512	0.36	0.4572	0.0972	0.055	-27.1
	CBE3c _{30k}	512	0.36	0.4572	0.0972	0.440	-42.5
Filters of SB ₂	Hann _{15k}	1024	0.36	0.4571	0.0971	0.055	-44.0
	CBE3a _{15k}	1024	0.36	0.4086	0.0486	0.020	-20.7
	CBE3b _{15k}	1024	0.36	0.4086	0.0486	0.055	-27.5
	CBE3c _{15k}	1024	0.36	0.4086	0.0486	0.440	-43.9

BER仿真中的滤波器参数

f-OFDM的干扰仿真分析

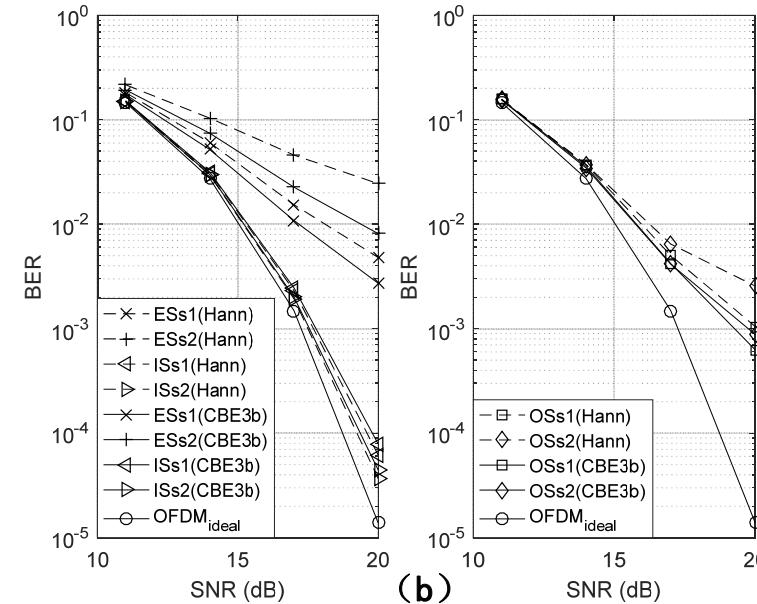
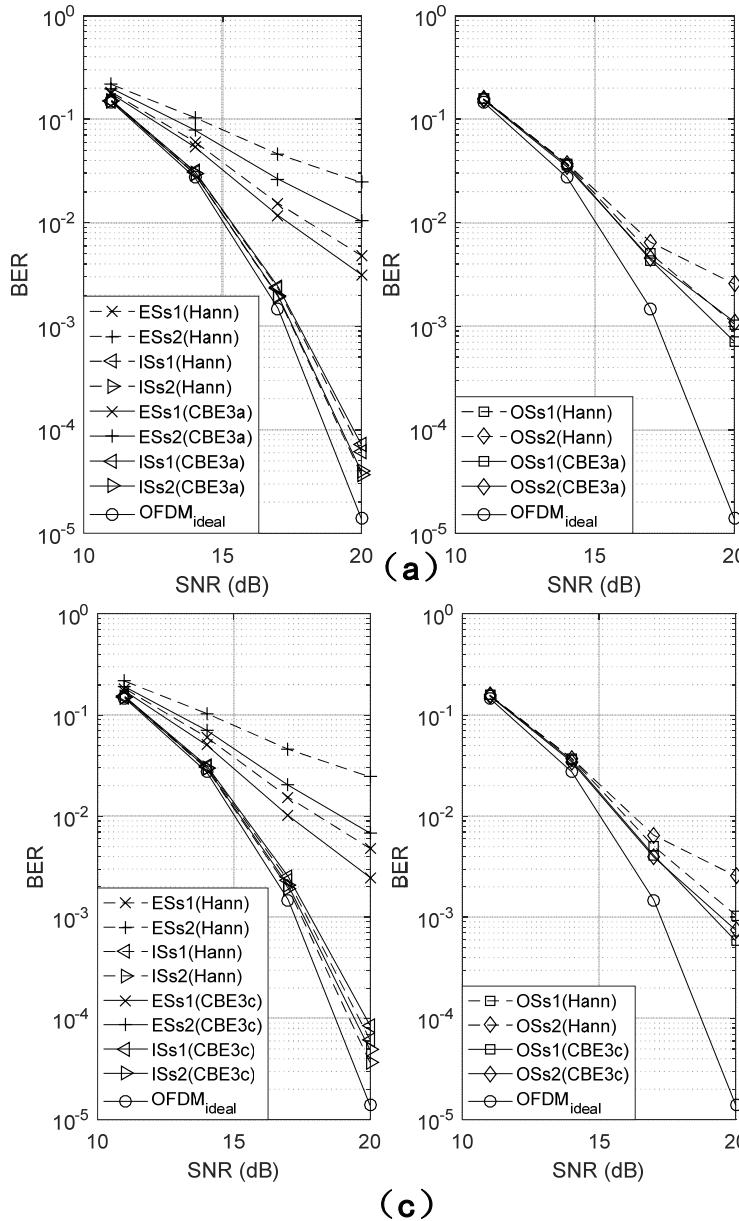


f-OFDM的干扰仿真分析



AWGN+ extended pedestrian A
(EPA) model多径信道

f-OFDM的干扰仿真分析



AWGN+ (2, 1, 3)卷积码

谢谢！