CPM-SC-IFDMA–A Power Efficient Transmission Scheme for Uplink LTE

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Introduction

Motivation

- LTE (Long Term Evolution)
  - » Represents the next major standard in mobile broadband technology
- Currently specified transmission scheme for uplink LTE
  - » QPSK modulated Single Carrier FDMA with localized subcarrier mapping (QPSK-LFDMA)
  - » Transmitted signal has a high PAPR (Peak-to-Average-Power-Ratio)
- High PAPR reduces the efficiency of the transmitter power amplifier
  - » Increases the cost of the mobile devices

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Proposed Scheme

- Proposed transmission scheme:
  - **CPM-SC-IFDMA**
  - Combines the key advantages of **CPM** (Continuous Phase Modulation) and **SC-IFDMA** (Single Carrier Frequency Division Multiple Access with Interleaved Subcarrier Mapping)
  - Input symbols are CPM modulated
  - Samples from the CPM waveform are input to the SC-IFDMA system for multiple access
- CPM-SC-IFDMA is a highly power efficient transmission scheme
  - Transmitted signal has constant amplitude
  - Very Low PAPR
  - **Makes an excellent choice for uplink LTE**

Contributions of this Work

- In this work:
  - Comparison between CPM-SC-IFDMA and CC-QPSK-LFDMA (QPSK-LFDMA scheme combined with convolutional coding)
- Performance regarding power efficiency
  - PAPR plots are compared
- Error performance
  - BER analyzed in **LTE specified channels**
  - Raw BER and net BER (BER with compensating for the power efficiency loss) are plotted

- **CPM-SC-IFDMA has superior performance relative to CC-QPSK-LFDMA by upto 3.8 dB**

Outline

- Introduction
- Background
- Power Efficiency in Mobile Communication
- Drawbacks of LTE Specified Scheme
- Advantages of CPM-SC-IFDMA
- Properties of the Selected SC-FDMA Schemes and Methodology for Selection
- CPM-SC-IFDMA Signal Model
- Simulation
- Conclusion and Future Work

Background

- Overview of LTE
- SC-FDMA System
- CPM Basics

Overview of LTE

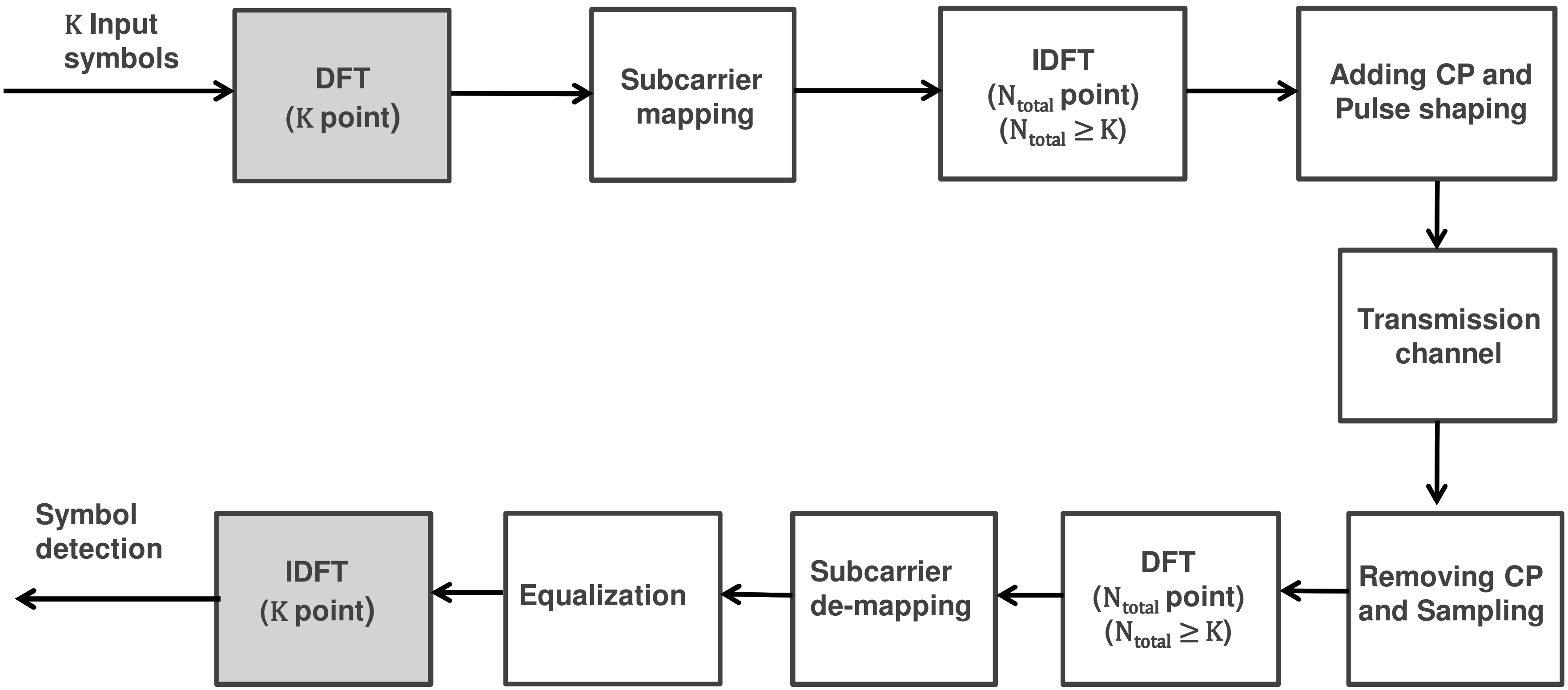
- LTE (Long Term Evolution)
  - A new, high performance air interface for mobile broadband communication
  - Developed by 3GPP and first specified in Release 8
- LTE is expected to become the dominant technology for the next generation of mobile broadband
- Several of the world's largest mobile operators have already started initial deployments of LTE

Background

- Overview of LTE
- SC-FDMA System
- CPM Basics

SC-FDMA System Configuration

- **SC-FDMA : A variant of OFDMA**

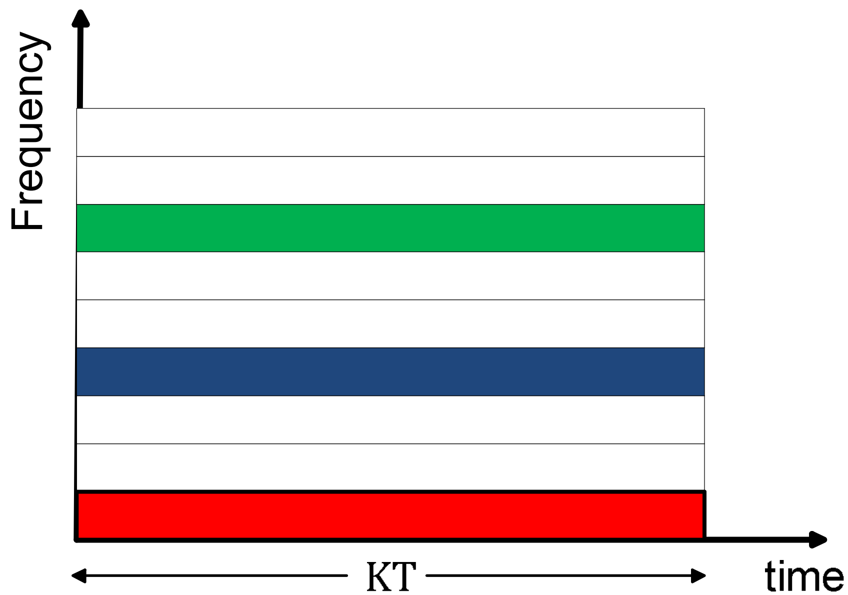


Comparison with OFDMA

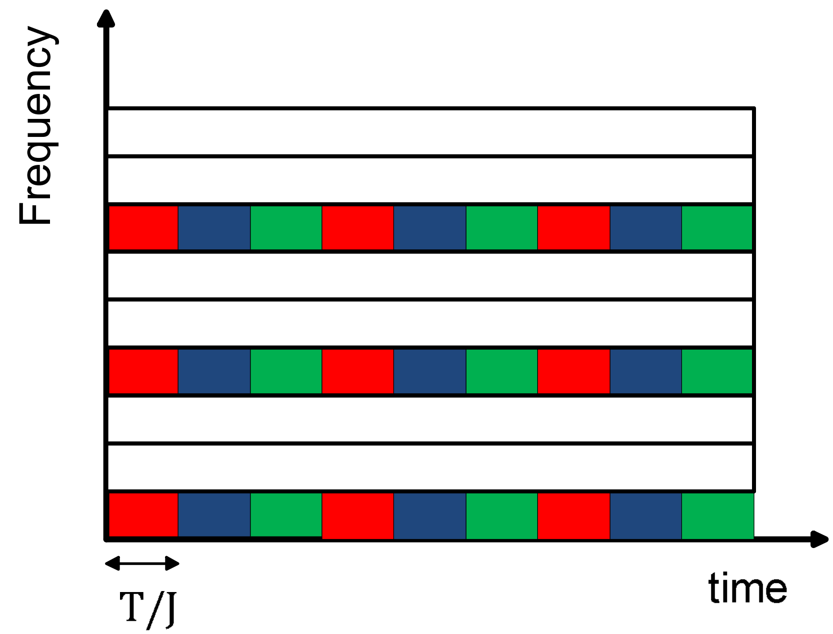
Data symbols

J users
K data symbols

OFDMA

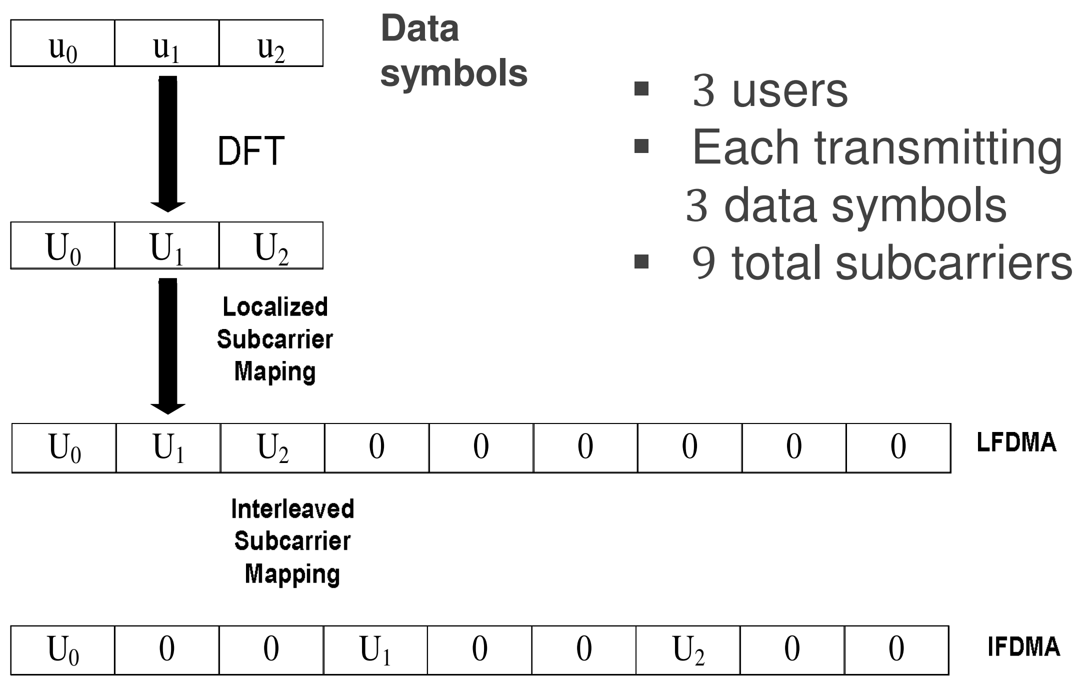


SC-FDMA



Subcarrier Mapping

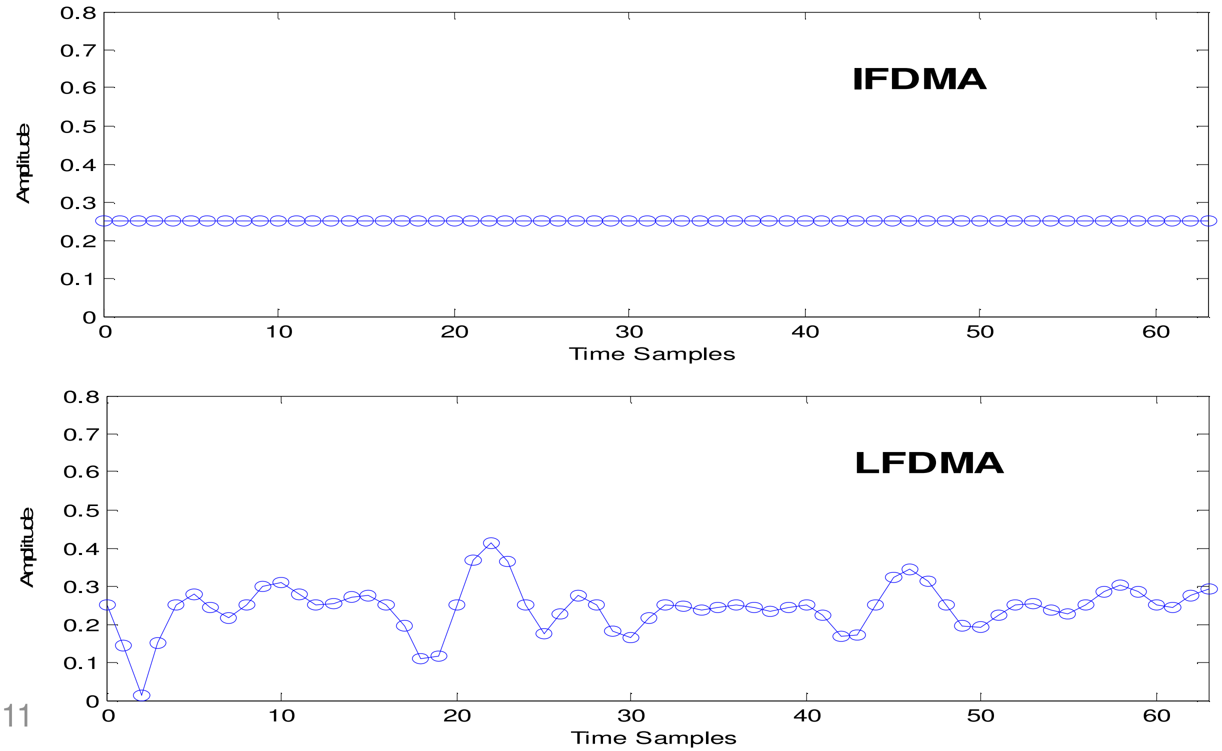
- **Localized SC-FDMA (LFDMA)**
  - DFT outputs are mapped to a set of **adjacent** subcarriers
- **Interleaved SC-FDMA (IFDMA)**
  - Subcarriers are equally spaced across the entire bandwidth



- 3 users
- Each transmitting 3 data symbols
- 9 total subcarriers

Transmitted Signal

- Transmitted time domain signal
  - IFDMA: contains only the actual input symbols, with a phase rotation and scaling factor
  - LFDMA: contains both the complex weighted sums and the actual input symbols



QPSK modulated input symbols

Background

- Overview of LTE
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- CPM Basics

CPM Basics

- Continuous Phase Modulation (CPM) :
  - A phase modulation scheme
  - Phase is varied in a continuous manner
  - No variation in signal amplitude
  - Higher bandwidth efficiency than other phase modulation schemes such as QPSK
  - Power efficiency because of constant envelope

CPM Basics

- CPM signals are defined by :

$$s(t;\boldsymbol{\beta}) \triangleq e^{j\varphi(t;\boldsymbol{\beta})} \dots\dots\dots (1)$$

  - discrete−time symbol sequence :

$$\boldsymbol{\beta} \triangleq \{\beta_i\}$$

  - M-ary symbols
  - Modulation index : h

- Phase :

$$\varphi(t;\beta) \triangleq 2\pi h \sum_i \beta_i q(t - iT) \cdots\cdots (2)$$

  - Phase response,

$$q(t) \triangleq \begin{cases} 0, & t < 0 \\ \int_0^t g(\tau)d\tau, & 0 \le t \le LT \\ \frac{1}{2}, & t \ge LT \end{cases}$$

  - Frequency pulse : $g(\tau)$
  - Length of $g(\tau)$: L

Power Efficiency in Mobile Communication

Power Efficiency in Mobile Communication

- Power efficiency
  - **A key concern in mobile communication field**
- Poor power efficiency
  - Shorter battery life
  - Increased cost of the mobile device
  - Reduced coverage
- Improving power efficiency is more important for uplink
- Uplink transmission:
  - Signal transmitted from mobile to base station
  - Transmitter is placed in the handheld mobile device which has limited power resources

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Power Efficiency in Mobile Communication

- PAPR (Peak-to-Average-Power-Ratio)
  - » An important metric for measuring the power efficiency
- If the transmitted signal has a high PAPR
  - » Average input power in the transmitter power amplifier must be reduced to operate in the linear region
  - » Termed as: Input back-off (IB)
  - » Without input back-off
    - Non-linear distortion occurs
- Amount of Input back-off depends on the PAPR
- High PAPR reduces the efficiency of the power amplifier

Reducing the PAPR is an important design goal

Drawbacks of LTE Specified Schemes

- Currently specified in uplink LTE:
  - Modulation method: QPSK, 16-QAM and 64-QAM
  - Multiple access scheme: SC-FDMA with localized subcarrier mapping (LFDMA)
- QAM:
  - Amplitude variations leads to high PAPR
- QPSK:
  - Phase variation can be as large as $\pm\pi$
  - Envelope may go to zero momentarily
  - Large envelope fluctuations cause high PAPR
- LFDMA: High envelope fluctuations cause a large PAPR

Advantages of CPM-SC-IFDMA

- CPM Schemes
  - Continuous Phase and constant amplitude
  - Well known for power and bandwidth efficiency
- SC-IFDMA
  - Transmitted signal consists of scaled and rotated version of original input symbols
  - Amplitude of the transmitted signal determined by amplitude of the original input symbols
- Combining CPM with SC-IFDMA
  - Constant amplitude CPM samples are the input to the SC-IFDMA system
  - Transmitted signal has constant amplitude and very low PAPR

Properties of the Selected SC-FDMA Schemes and Methodology for Selection

Properties of the SC-FDMA schemes

- CPM-SC-IFDMA
  - **Scheme 1**
    - Alphabet size, $M = 4$, Raised Cosine frequency pulse with length, $L = 3$, modulation index, $h = 5/16$, and minimum squared Euclidean distance, $d^2_{min} = 1.480$;
  - **Scheme 2**
    - Alphabet size, $M = 4$, Gaussian frequency pulse with $BT = 0.25$, pulse length, $L = 3$, modulation index, $h = 5/8$, and minimum squared Euclidean distance, $d^2_{min} = 4.693$;
  - **Sampling rate:** $N=2$ **samples per symbol**
- CC-QPSK-LFDMA
  - QPSK-LFDMA combined with Convolutional coding
  - Convolutional code: rate ½, constraint length 5, octal generator polynomial $[23\ 35]$

Methodology for Selection

- QPSK-LFDMA: LTE specified transmission scheme
- Combined with convolutional encoding to introduces memory so that CC-QPSK-LFDMA is comparable to CPM-SC-IFDMA
- All three SC-FDMA schemes have comparable BW and similar complexities
- CC-QPSK-LFDMA scheme:
  - Rate ½ convolutional coding and QPSK modulation makes information rate 1 bit/symbol
  - Constraint length of 5 makes memory length 4 bits
- CPM-SC-IFDMA Scheme 1 and Scheme 2:
  - Alphabet size, $M=4$ and sampling rate, $N=2$ samples/symbol makes Information rate 1 bit/sample
  - $L=3$ makes memory length 4 bits

CPM-SC-IFDMA Signal Model

CPM-SC-IFDMA Transmitter

- A system with J users
  - Number of symbols transmitted by a single user : P
  - CPM waveform is sampled at : N samples/symbol
  - Samples transmitted by a single user (FFT size), $\mathrm{K} = \mathrm{PN}$
  - IFFT size (total no of subcarriers), $\mathrm{N_{total}} = \mathrm{J} \times \mathrm{K} = \mathrm{JPN}$
- PN CPM samples from the i_{th} user is denoted by
  - $\mathbf{s}_\mathrm{i} = [\, \mathrm{s_{i,0}},\, \mathrm{s_{i,1}} \cdots \cdots \mathrm{s_{i,PN-1}}]$
- Each element of $\mathbf{s}_\mathrm{i}$ is given by,
  - $\mathrm{s_{i,l}} \equiv \mathrm{s}[\mathrm{l}; \boldsymbol{\beta}] \triangleq \mathrm{e}^{\mathrm{j}\varphi(\mathrm{l};\boldsymbol{\beta})} \cdots \cdots \cdots (3)$ [the discrete-time equivalent of (1)]
- $\mathrm{K}(=\mathrm{PN})$ point DFT operation:
  - $\mathrm{S_{i,k}} = \sum_{\mathrm{l}=0}^{\mathrm{PN}-1} \mathrm{s_{i,l}} \mathrm{e}^{-\mathrm{j}2\pi \mathrm{kl}/\mathrm{PN}} \cdots \cdots \cdots (4)$ $[\mathrm{k} = 0 \cdots \cdots \mathrm{PN} - 1]$

CPM-SC-IFDMA Transmitter

- Subcarrier Mapping
  - Mapped symbols, $Y_{i,q} = \begin{cases} S_{i,k} & q = kJ + i \\ 0, & \text{otherwise} \end{cases} \dots\dots\dots\dots (5)$
- JPN point IFFT operation:
  - Output samples, $y_{i,l} = \frac{1}{JPN} \sum_{q=0}^{JPN-1} Y_{i,q} e^{j2\pi ql/JPN} \dots\dots\dots (6)$
- Output time samples can be expressed as:
  - $y_{i,l} = \frac{1}{J} s_{(i,l) \bmod K} \cdot e^{j2\pi \frac{il}{N_{total}}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (7)$
  - Scaling factor $1/J$
  - Original input symbols $s_{(i,l)}$
  - Multiplication by $e^{j2\pi \frac{il}{N_{total}}}$ represents phase rotation

CPM-SC-IFDMA Transmitter

- Cyclic Prefix (CP) is added
- Converting to continuous-time waveform by pulse shaping

$$x(t) = \sum_{n=-C_p N}^{JPN-1} y_{i,l} G(t - \tilde{T}) \cdots\cdots\cdots\cdots\cdots\cdots (8)$$

  - Spectral Raised Cosine (SRC) pulse

$$G(t) = \frac{\sin(\pi t/\tilde{T})}{\pi t/\tilde{T}} \frac{\cos(\pi \alpha t/\tilde{T})}{1 - 4\alpha^2 t^2/\tilde{T}^2} \cdots\cdots\cdots\cdots (9)$$

CPM-SC-IFDMA Receiver

- Received signal, $\mathrm{r(t)}$ $\xrightarrow{\text{Sampling}}$ discrete-time sequence $\mathbf{r}$
- CP is discarded
- In frequency selective channels, $\mathbf{r}$ can be expressed as :

$$\mathbf{r} = \sum_{i=0}^{J-1} \mathbf{h} \otimes \mathbf{y}_i + \mathbf{n} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (10)$$

  - $\mathbf{h}$: discrete-time channel impulse response
  - $\mathbf{n}$: AWGN noise
  - $\mathbf{y}_i$: sequence transmitted by the i_{th} user terminal
- JPN point DFT operation

$$\mathbf{r} \xrightarrow{\text{DFT}} \widetilde{\mathbf{R}} \cdots\cdots\cdots\cdots\cdots (11)$$

CPM-SC-IFDMA Receiver

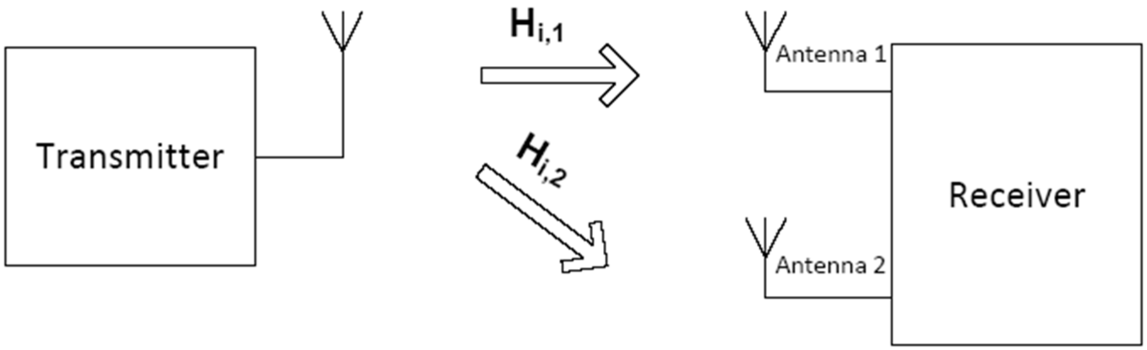
- The i_{th} user's data is extracted
  - » $R_{i,q} = \widetilde{R}_k$ for $k = qJ + i \cdots\cdots\cdots\cdots\cdots\cdots (12)$ $[q = 0 \cdots\cdots PN - 1]$
- Received signal in the frequency domain
  - » $\mathbf{R_i} = \mathbf{H_i S_i} + \mathbf{W} \quad \cdots\cdots\cdots\cdots\cdots\cdots (13)$
    - $\mathbf{H_i}$: vector containing the channel coefficients corresponding to the i_{th} user
    - $H_{i,q} = \widetilde{H}_k$ for $k = qJ + i$ [channel coefficient extraction]
    - $\widetilde{\mathbf{H}}$: channel response in the frequency domain

$$\mathbf{h} \xrightarrow{\mathrm{DFT}} \widetilde{\mathbf{H}}$$

- Removing the channel effect
  - » Maximal ratio combining followed by amplitude scaling

CPM-SC-IFDMA Receiver

- **Maximal Ratio Combining (MRC)**
  - Two-antenna based receiver structure is specified in LTE
  - MRC is applied to combine the two received signals



  - $H_{i,1}$ and $H_{i,2}$: frequency domain coefficient vector corresponding to the two antennas
  - $R_{i,1}$ and $R_{i,2}$: frequency domain representations of the received signal via the two antennas

CPM-SC-IFDMA Receiver

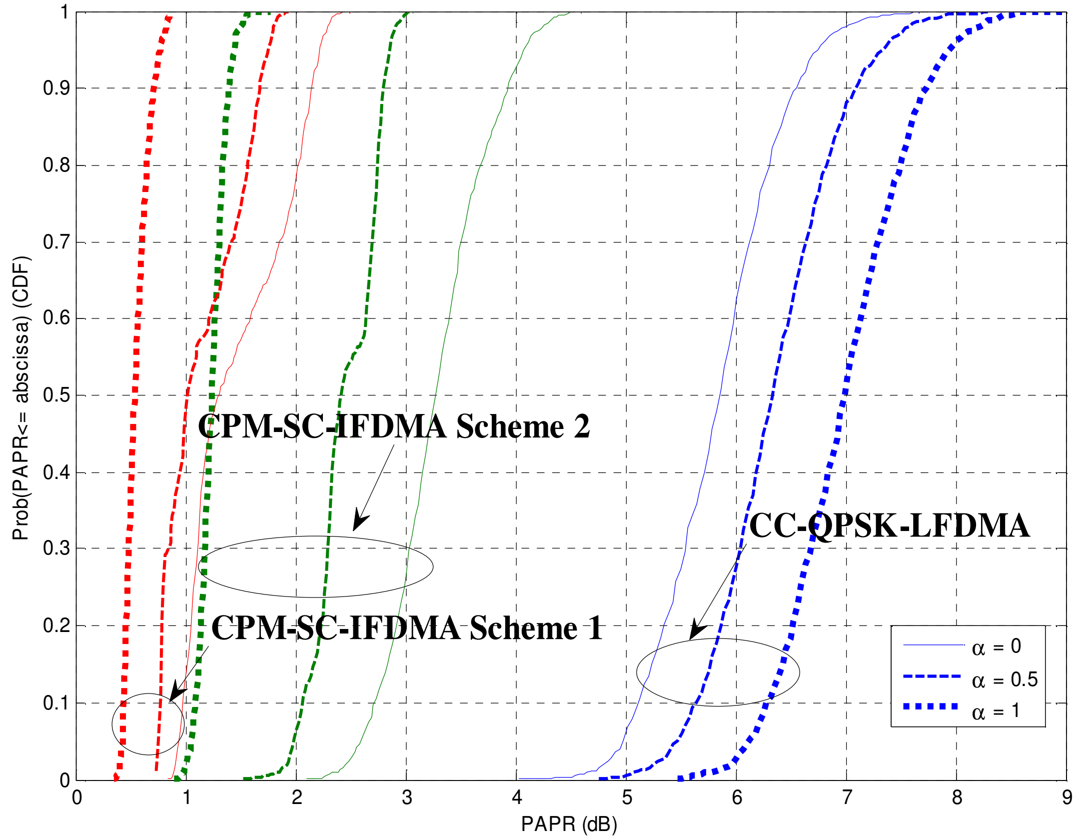
- Combined signal, $\hat{\mathrm{R}}_i = \dfrac{(\mathrm{R}_{i,1}\mathrm{H}^*_{i,1} + \mathrm{R}_{i,2}\mathrm{H}^*_{i,2})}{(|\mathrm{H}_{i,1}|^2 + |\mathrm{H}_{i,2}|^2)}$ ……………… (15)
- Multiplication by $\mathrm{H}^*_{i,1}$ and $\mathrm{H}^*_{i,2}$:
  - Corrects the channel phase
  - Blends the two signals in the correct ratio
- Division by ($|\mathrm{H}_{i,1}|^2 + |\mathrm{H}_{i,2}|^2$) : Scales the amplitude
- These two steps together removes the channel effect
- Equalization is not required
- PN point IDFT operation : $\widehat{\mathbf{R}}_{\mathbf{i}} \xrightarrow{\mathrm{IDFT}} \hat{\mathbf{r}}_{\mathbf{i}}$ ……………… (16)
- Symbol detection
  - **Viterbi Algorithm (VA)**

Simulation

- PAPR Analysis
- BER Simulation

PAPR Analysis

- At 90% CDF, for $\alpha = 0$,
  - Scheme 1 < CC-QPSK-LFDMA by 4.42 dB
  - Scheme 2 < CC-QPSK-LFDMA by 2.64 dB
  - PAPR difference increases with the increase of α
- Maximum PAPR advantage
  - 7 dB for Scheme 1
  - 6.34 dB for Scheme 2



α : roll-off factor of the SRC pulse

PAPR Analysis

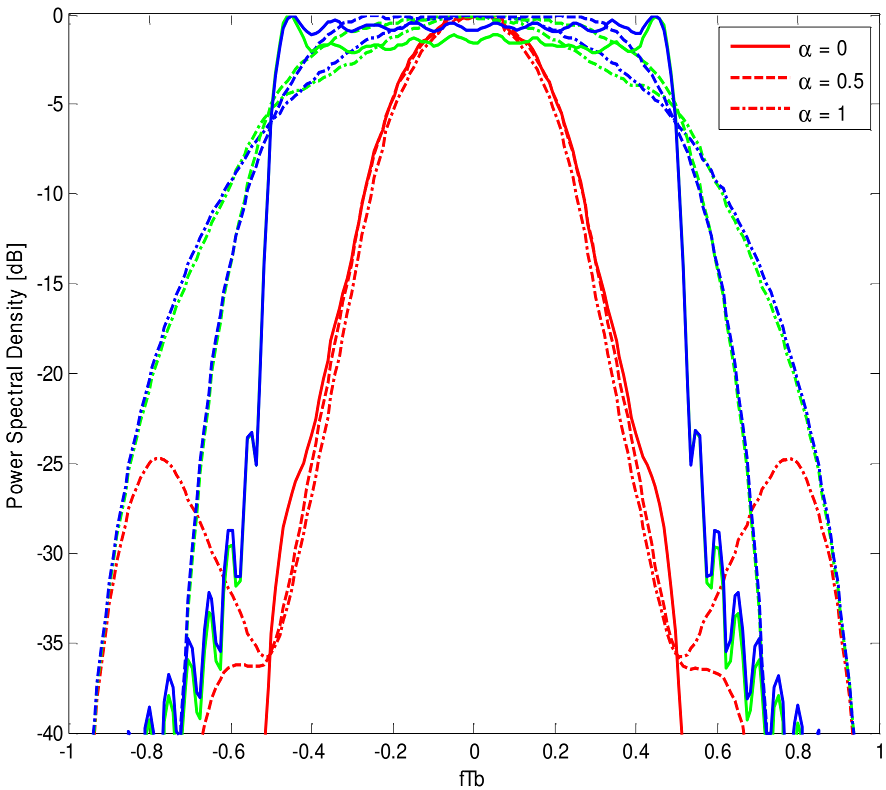
- PAPR value
  - A measure of the required input back-off (IB)
  - Indicates how much power efficiency is lost
  - **Needs to be accounted for in the BER plots to make a true comparison between the BER performance of the CPM-SC-IFDMA schemes and the CC-QPSK-LFDMA scheme**
- PAPR values are added to the SNR (E_b/N_0) values, plotted along the X-axis in the BER plots
- To select which PAPR values are to be added, the bandwidths are compared

Bandwidth Comparison

- Scheme 1 with $\alpha = 0.5$ and Scheme 2 with $\alpha = 0$ have similar bandwidth as CC-QPSK-LFDMA with $\alpha = 0$

Scheme	$IB_{90\%}$ [dB]	$IB_{99\%}$	α
CPM-SC-FDMA Scheme 1	2.14	2.34	0
	1.67	**1.84**	**0.5**
	0.72	0.85	1
CPM-SC-FDMA Scheme 2	**3.92**	**4.35**	**0**
	2.81	2.96	0.5
	1.39	1.53	1
CC-QPSK-LFDMA	**6.56**	**7.22**	**0**
	7.12	7.83	0.5
	7.73	8.36	1

- $IB_{90\%}$: PAPR value at 90% CDF
- $IB_{99\%}$: PAPR value at 99% CDF



Red: CPM-SC-IFDMA Scheme 1
Blue: CPM-SC-IFDMA Scheme 2
Green: CC-QPSK-LFDMA

Simulation

- PAPR Analysis
- BER Simulation

LTE Channels

- LTE specification for frequency selective channels
  - Channel parameters
  - Delay profiles
- For this work
  - Three frequency selective channels are selected
    - Extended Pedestrian A Channel (EPA)
    - Extended Vehicular A Channel (EVA)
    - Extended Typical Urban Channel (ETU)
- Channel Parameters of the LTE Channel Models

Model	Number of channel taps	Delay spread (r.m.s)	Maximum excess tap delay (span)
Extended Pedestrain A (EPA)	7	45 ns	410 ns
Extended Vehicular A (EVA)	9	357 ns	2510 ns
Extended Tyical Urban (ETU)	9	991 ns	5000 ns

LTE Channels

- Tapped Delay Profiles of LTE Channels

EPA Channel

Excess tap delay [ns]	Relative power [dB]
0	0.0
30	-1.0
70	-2.0
90	-3.0
110	-8.0
190	-17.2
410	-20.8

EVA Channel

Excess tap delay [ns]	Relative power [dB]
0	0.0
30	-1.5
150	-1.4
310	-3.6
370	-0.6
710	-9.1
1090	-7.0
1730	-12.0
2510	-16.9

ETU Channel

Excess tap delay [ns]	Relative power [dB]
0	-1.0
50	-1.0
120	-1.0
200	0
230	0
500	0
1600	-3.0
2300	-5.0
5000	-7.0

Simulation Parameters

- Transmission Parameters of LTE

Channel Bandwidth (MHz)	1.4	3	5	10	15	20
Number of RBs	6	15	25	50	75	100
Number of occupied subcarriers	72	180	300	600	900	1200
IDFT(Tx)/DFT(Rx) size	128	256	512	1024	1536	2048
Sample rate [MHz]	1.92	3.84	7.68	15.36	23.04	30.72
Samples per slot	960	1920	3840	7680	11520	15360

- Simulation Parameters for this work

Channel Bandwidth	5 MHz
Number of occupied subcarriers (N_{total})	300
IDFT/DFT size ($N_{\text{IDFT/DFT}}$)	300
Sampling rate (f_s)	7.68 MHz
Sample duration (T_s)	130 ns
CP duration	4.69μs (36 samples)

Insertion of Guard band

- Guard band prevents out-of-band radiation
- In LTE,
  - Guard band is implemented by assigning zeros to the unused subcarriers during the IFFT operation in the transmitter
- Transmission parameters specified in LTE

Channel Bandwidth (MHz)	1.4	3	5	10	15	20
Number of RBs	6	15	25	50	75	100
Number of occupied subcarriers	72	180	300	600	900	1200
IDFT(Tx)/DFT(Rx) size	128	256	512	1024	1536	2048
Sample rate [MHz]	1.92	3.84	7.68	15.36	23.04	30.72
Samples per slot	960	1920	3840	7680	11520	15360

  - IFFT size ($N_{IDFT/DFT}$) > Number of occupied subcarriers (N_{total})
  - Remaining subcarriers have zero magnitude

Insertion of Guard Band

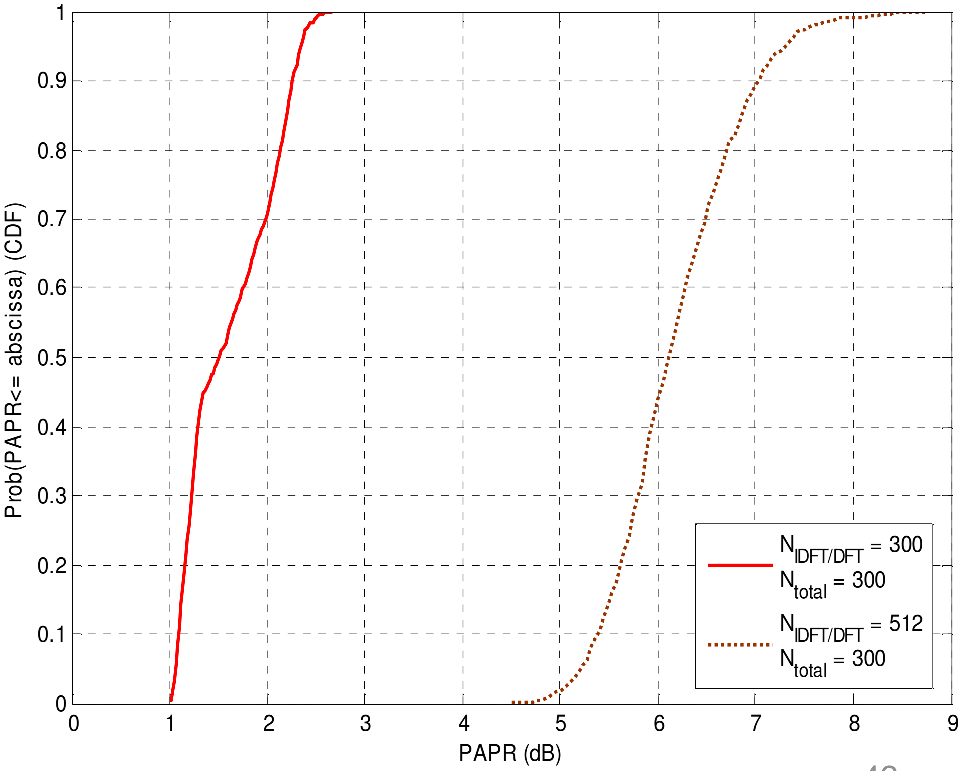
- Time domain representation of IFDMA and LFDMA are derived assuming

IFFT size ($N_{IDFT/DFT}$) = Number of occupied subcarriers (N_{total})

- Low PAPR feature of IFDMA cannot be maintained if

$$N_{IDFT/DFT} > N_{total}$$

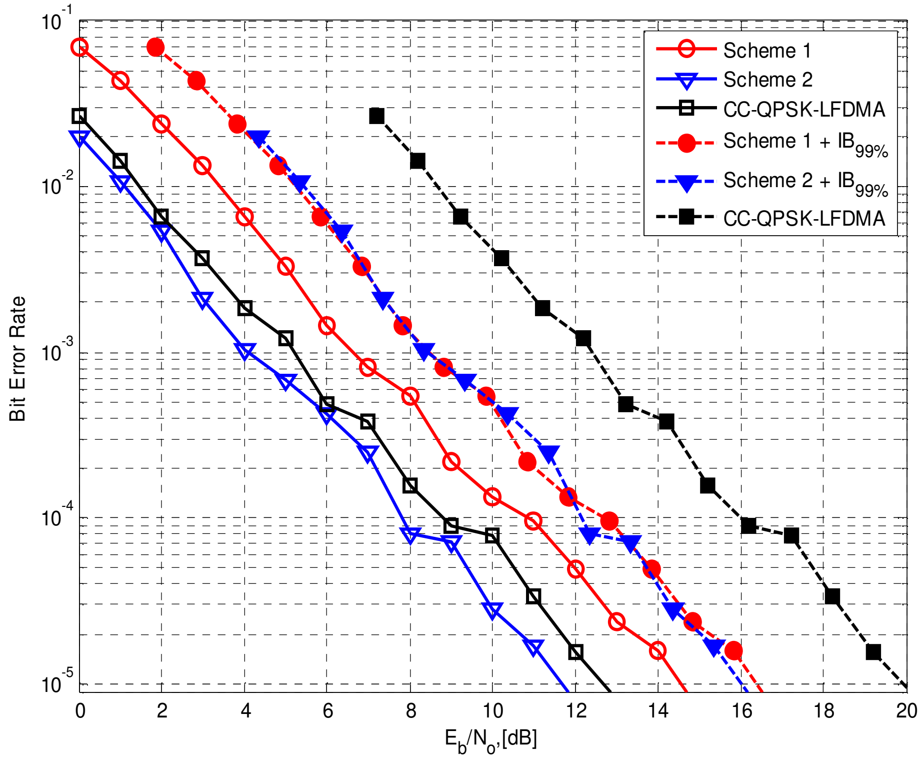
- **Guard band can be inserted by moving the center of the used band to the desired distance (in frequency) away from the next occupied channel.**



Simulation Results

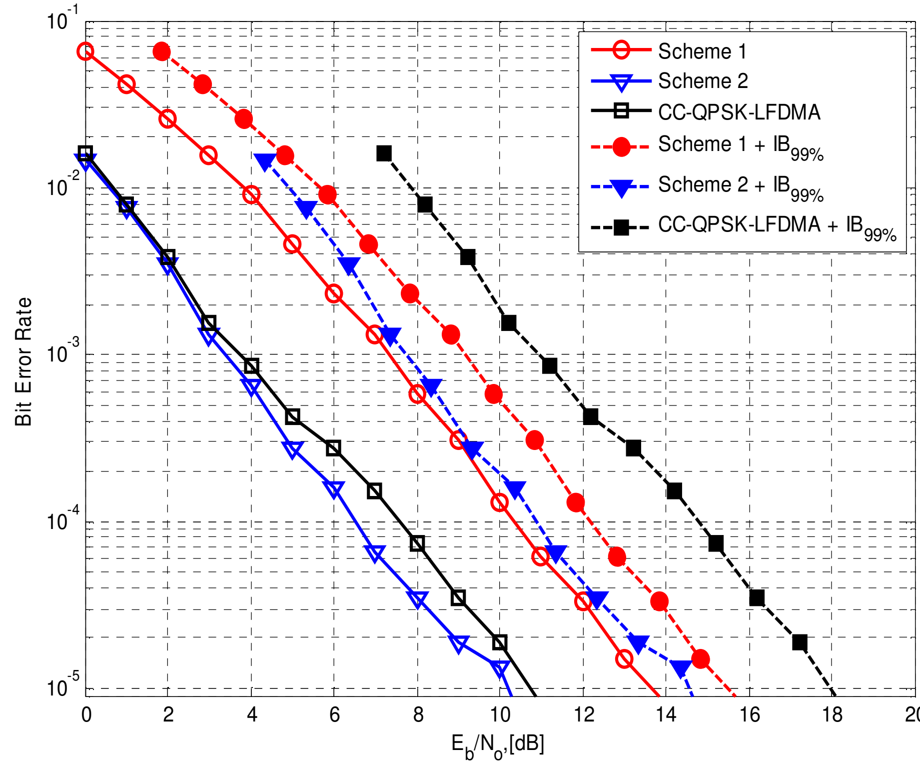
Target BER : 10^{-5}

BER in the EPA channel



Scheme 1 < CC-QPSK-LFDMA by **3.5** dB
Scheme 2 < CC-QPSK-LFDMA by **3.8** dB
(after adding the $IB_{99\%}$ values)

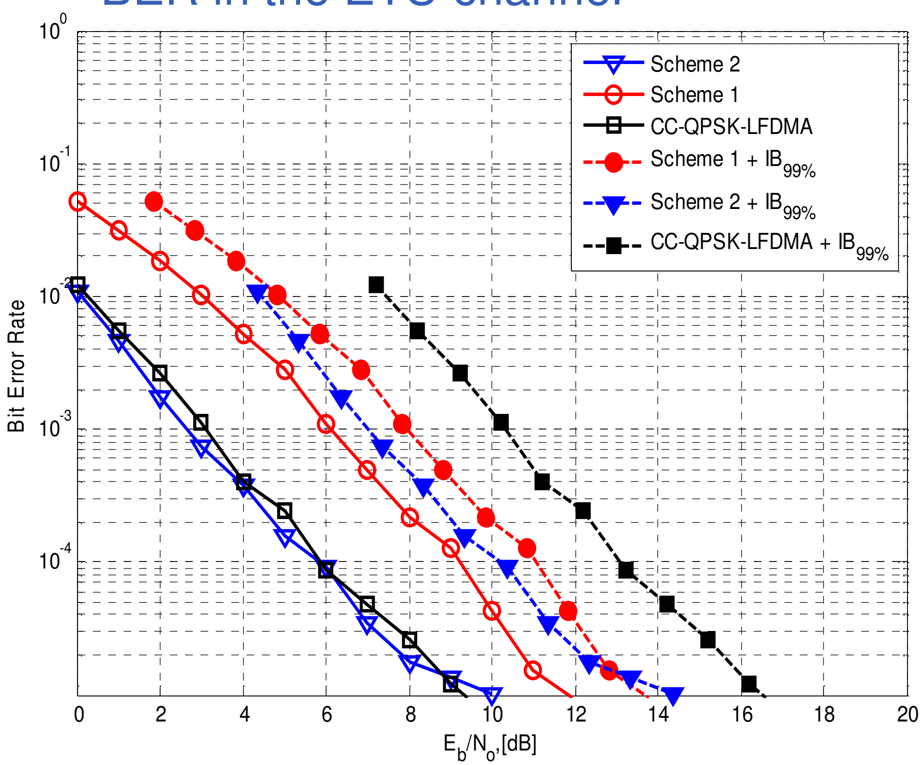
BER in the EVA channel



Scheme 1 < CC-QPSK-LFDMA by **2.4** dB
Scheme 2 < CC-QPSK-LFDMA by **3.4** dB
(after adding the $IB_{99\%}$ values)

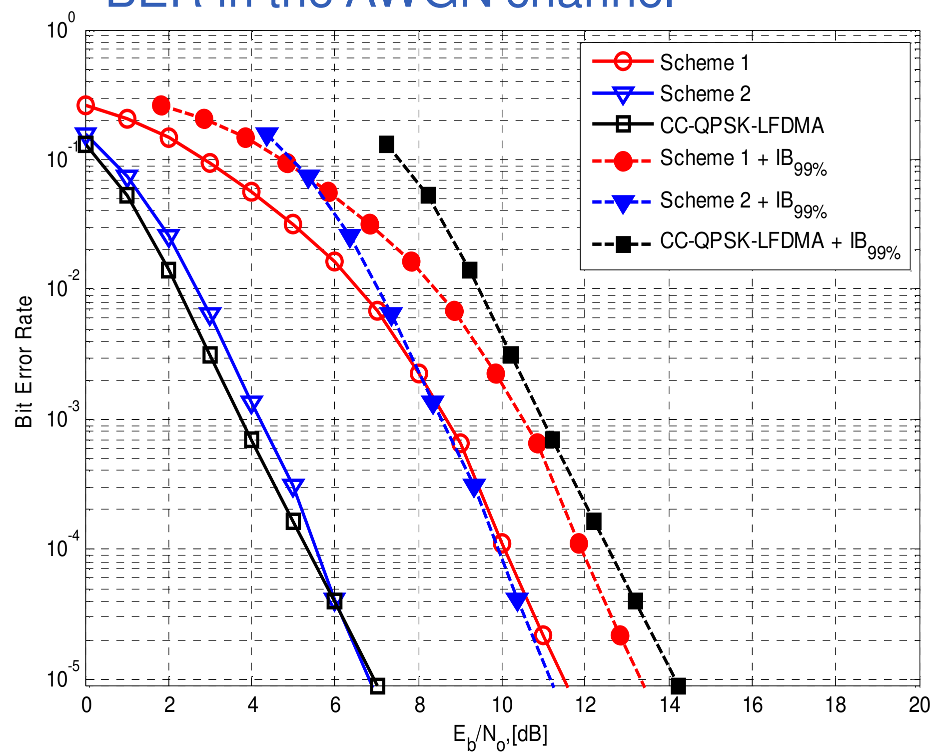
Simulation Results

BER in the ETU channel



Scheme 1 < CC-QPSK-LFDMA by **2.9** dB
Scheme 2 < CC-QPSK-LFDMA by **2.3** dB
(after adding the $IB_{99\%}$ values)

BER in the AWGN channel



Scheme 1 < CC-QPSK-LFDMA by **0.8** dB
Scheme 2 < CC-QPSK-LFDMA by **3** dB
(after adding the $IB_{99\%}$ values)

Conclusion and Future Work

- Summary of Results
  - From PAPR analysis
    - power efficiency advantage for the CPM-SC-IFDMA scheme can be as high as **7** dB (at 90% CDF)
  - From BER simulation
    - CPM-SC-IFDMA outperform the CC-QPSK-LFDMA scheme by up to **3.8** dB (at a BER of 10^{-5}) when input back-off values are taken into consideration

When power efficiency is considered, the proposed scheme is more desirable than the current modulation-multiple access scheme specified for LTE

Conclusion and Future Work

- Future Work
  - Designing an algorithm for finding the numerically optimum CPM scheme that can be combined with SC-IFDMA
  - Calculating how much increase in the cell radius can be achieved by utilizing the power efficiency of CPM-SC-IFDMA
  - Analyzing the effect of MIMO (multiple antenna in both transmitter and receiver) on the simulation results

Thank You!