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
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

Frequency

Frequency

time

KT

T/J

T

4/15/2011
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

- **Data symbols**
  - 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
Background

- Overview of LTE
- SC-FDMA System
- 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:

\[ s(t; \beta) \triangleq e^{j\varphi(t;\beta)} \ldots \ldots (1) \]

  - discrete-time symbol sequence:
    \[ \beta \triangleq \{ \beta_i \} \]
  - M-ary symbols
  - Modulation index: \( h \)

- Phase:

\[ \varphi(t; \beta) \triangleq 2\pi h \sum_i \beta_i q(t - iT) \ldots \ldots (2) \]

  - Phase response,

\[ q(t) \triangleq \begin{cases} 0, & t < 0 \\ \int_0^t g(\tau)d\tau, & 0 \leq t \leq LT \\ \frac{1}{2}, & t \geq LT \end{cases} \]

  - 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
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, $d_{\text{min}}^2 = 1.480$;
  - **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, $d_{\text{min}}^2 = 4.693$;
  - **Sampling rate**: $N=2$ samples per symbol

• **CC-QPSK-LFDMA**
  - QPSK-LFDMA combined with Convolutional coding
  - Convolutional code: rate $\frac{1}{2}$, 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 $\frac{1}{2}$ 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), \( K = PN \)
  - IFFT size (total no of subcarriers), \( N_{\text{total}} = J \times K = JPN \)

- **PN CPM samples from the \( i_{th} \) user is denoted by**
  - \( s_i = [s_{i,0}, s_{i,1}, \cdots, s_{i,PN-1}] \)

- **Each element of \( s_i \) is given by,**
  - \( s_{i,l} \equiv s[l; \beta] = e^{j\varphi(l; \beta)} \cdots (3) \)  \[\text{the discrete-time equivalent of (1)}\]

- **\( K(=PN) \) point DFT operation:**
  - \( S_{i,k} = \sum_{l=0}^{PN-1} s_{i,l} e^{-j2\pi kl/PN} \cdots (4) \) \[k = 0 \cdots PN - 1\]
CPM-SC-IFDMA Transmitter

- Subcarrier Mapping
  - Mapped symbols, \( Y_{i,q} = \begin{cases} S_{i,k} & q = kJ + i \\ 0, & \text{otherwise} \end{cases} \) \( \ldots \ldots \ldots \ldots \ldots (5) \)

- JPN point IFFT operation:
  - Output samples, \( y_{i,l} = \frac{1}{JPN} \sum_{q=0}^{JPN-1} Y_{i,q} e^{j2\pi ql/JPN} \ldots \ldots \ldots \ldots \ldots (6) \)

- Output time samples can be expressed as:
  - \( y_{i,l} = \frac{1}{J} S_{(i,l) \mod K} \cdot e^{j2\pi \frac{il}{N_{total}}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (7) \)
  - 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

\[ x(t) = \sum_{n=-C_pN}^{JPN-1} y_{i,1}G(t - \tilde{T}) \ldots \ldots \ldots (8) \]

» Spectral Raised Cosine (SRC) pulse

\[ G(t) = \frac{\sin(\pi t / \tilde{T})}{\pi t / \tilde{T}} \frac{\cos(\pi \alpha t / \tilde{T})}{1 - 4\alpha^2 t^2 / \tilde{T}^2} \ldots \ldots \ldots (9) \]
CPM-SC-IFDMA Receiver

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

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

  » $h$: discrete-time channel impulse response
  » $n$: AWGN noise
  » $y_i$: sequence transmitted by the $i_{th}$ user terminal

- JPN point DFT operation

$$r \xrightarrow{\text{DFT}} \tilde{R} \cdots \cdots \cdots \cdots \cdots (11)$$
CPM-SC-IFDMA Receiver

• The $i_{th}$ user’s data is extracted
  \[ R_{i,q} = \tilde{R}_k \text{ for } k = qJ + i \text{ } \cdots \cdots \cdots \cdots (12) \quad [q = 0 \ldots PN - 1] \]

• Received signal in the frequency domain
  \[ R_i = H_i S_i + W \text{ } \cdots \cdots \cdots \cdots (13) \]
  \begin{itemize}
  \item $H_i$: vector containing the channel coefficients corresponding to the $i_{th}$ user
  \item $H_{i,q} = \tilde{H}_k$ for $k = qJ + i$ [channel coefficient extraction]
  \item $\tilde{H}$: channel response in the frequency domain
  \[ h \xrightarrow{\text{DFT}} \tilde{H} \]
  \end{itemize}

• Removing the channel effect
  \[ \text{Maximal ratio combining followed by amplitude scaling} \]
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

\[
\mathbf{H}_{i,1} \quad \text{and} \quad \mathbf{H}_{i,2} : \text{frequency domain coefficient vector corresponding to the two antennas}
\]

\[
\mathbf{R}_{i,1} \quad \text{and} \quad \mathbf{R}_{i,2} : \text{frequency domain representations of the received signal via the two antennas}
\]
CPM-SC-IFDMA Receiver

- Combined signal, $\hat{R}_i = \frac{(R_{i,1}H_{i,1}^* + R_{i,2}H_{i,2}^*)}{(|H_{i,1}|^2 + |H_{i,2}|^2)}$ ............... (15)

- Multiplication by $H_{i,1}^*$ and $H_{i,2}^*$:
  - Corrects the channel phase
  - Blends the two signals in the correct ratio

- Division by $(|H_{i,1}|^2 + |H_{i,2}|^2)$: Scales the amplitude

- These two steps together removes the channel effect

- Equalization is not required

- PN point IDFT operation: $\hat{R}_i \xrightarrow{\text{IDFT}} \hat{r}_i$ ............... (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 $\alpha$
- Maximum PAPR advantage
  - 7 dB for Scheme 1
  - 6.34 dB for Scheme 2

$\alpha$ : 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 $\alpha = 0$

<table>
<thead>
<tr>
<th>Scheme</th>
<th>$\text{IB}_{90%}$ [dB]</th>
<th>$\text{IB}_{99%}$ [dB]</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPM-SC-FDMA Scheme 1</td>
<td>2.14</td>
<td>2.34</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1.67</td>
<td>1.84</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>0.72</td>
<td>0.85</td>
<td>1</td>
</tr>
<tr>
<td>CPM-SC-FDMA Scheme 2</td>
<td>3.92</td>
<td>4.35</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2.81</td>
<td>2.96</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>1.39</td>
<td>1.53</td>
<td>1</td>
</tr>
<tr>
<td>CC-QPSK-LFDMA</td>
<td>6.56</td>
<td>7.22</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>7.12</td>
<td>7.83</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>7.73</td>
<td>8.36</td>
<td>1</td>
</tr>
</tbody>
</table>

- $\text{IB}_{90\%}$: PAPR value at 90% CDF
- $\text{IB}_{99\%}$: 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

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of channel taps</th>
<th>Delay spread (r.m.s)</th>
<th>Maximum excess tap delay (span)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extended Pedestrian A (EPA)</td>
<td>7</td>
<td>45 ns</td>
<td>410 ns</td>
</tr>
<tr>
<td>Extended Vehicular A (EVA)</td>
<td>9</td>
<td>357 ns</td>
<td>2510 ns</td>
</tr>
<tr>
<td>Extended Typical Urban (ETU)</td>
<td>9</td>
<td>991 ns</td>
<td>5000 ns</td>
</tr>
</tbody>
</table>
LTE Channels

- Tapped Delay Profiles of LTE Channels

**EPA Channel**

<table>
<thead>
<tr>
<th>Excess tap delay [ns]</th>
<th>Relative power [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>30</td>
<td>-1.0</td>
</tr>
<tr>
<td>70</td>
<td>-2.0</td>
</tr>
<tr>
<td>90</td>
<td>-3.0</td>
</tr>
<tr>
<td>110</td>
<td>-8.0</td>
</tr>
<tr>
<td>190</td>
<td>-17.2</td>
</tr>
<tr>
<td>410</td>
<td>-20.8</td>
</tr>
</tbody>
</table>

**ETU Channel**

<table>
<thead>
<tr>
<th>Excess tap delay [ns]</th>
<th>Relative power [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1.0</td>
</tr>
<tr>
<td>50</td>
<td>-1.0</td>
</tr>
<tr>
<td>120</td>
<td>-1.0</td>
</tr>
<tr>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>230</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>1600</td>
<td>-3.0</td>
</tr>
<tr>
<td>2300</td>
<td>-5.0</td>
</tr>
<tr>
<td>5000</td>
<td>-7.0</td>
</tr>
</tbody>
</table>

**EVA Channel**

<table>
<thead>
<tr>
<th>Excess tap delay [ns]</th>
<th>Relative power [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>30</td>
<td>-1.5</td>
</tr>
<tr>
<td>150</td>
<td>-1.4</td>
</tr>
<tr>
<td>310</td>
<td>-3.6</td>
</tr>
<tr>
<td>370</td>
<td>-0.6</td>
</tr>
<tr>
<td>710</td>
<td>-9.1</td>
</tr>
<tr>
<td>1090</td>
<td>-7.0</td>
</tr>
<tr>
<td>1730</td>
<td>-12.0</td>
</tr>
<tr>
<td>2510</td>
<td>-16.9</td>
</tr>
</tbody>
</table>
Simulation Parameters

- Transmission Parameters of LTE

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

<table>
<thead>
<tr>
<th>Channel Bandwidth</th>
<th>5 MHz</th>
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</thead>
<tbody>
<tr>
<td>Number of occupied subcarriers ($N_{total}$)</td>
<td>300</td>
</tr>
<tr>
<td>IDFT/DFT size ($N_{IDFT/DFT}$)</td>
<td>300</td>
</tr>
<tr>
<td>Sampling rate ($f_s$)</td>
<td>7.68 MHz</td>
</tr>
<tr>
<td>Sample duration ($T_s$)</td>
<td>130 ns</td>
</tr>
<tr>
<td>CP duration</td>
<td>4.69 μs (36 samples)</td>
</tr>
</tbody>
</table>
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

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<td>11520</td>
<td>15360</td>
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- 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

\[ \text{IFFT size } (N_{\text{IDFT/DFT}}) = \text{Number of occupied subcarriers } (N_{\text{total}}) \]

• Low PAPR feature of IFDMA cannot be maintained if

\[ N_{\text{IDFT/DFT}} > N_{\text{total}} \]

• 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

BER in the EVA 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)

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

BER in the AWGN 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)

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!