Optimal Numerology for 5G Heterogeneous Services

CD-Lab Open day (Module 1 - Nokia)

Ljiljana Marijanović
November 15, 2018
Content

Mixed numerology for 5G

Optimal numerology in single-user case

Optimal numerology in multi-user case

Summary and Future work
Content

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Summary and Future work
Introduction

- *Mixed numerology* specified by 3GPP
- *Numerology* assumes the parametrization of the multicarrier modulation

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Introduction\textsuperscript{1}

- *Mixed numerology* specified by 3GPP
- *Numerology* assumes the parametrization of the multicarrier modulation

\textsuperscript{1} 3rd Generation Partnership Project (3GPP), “Technical Specification Group Radio Access Network; NR; Physical channels and modulation”, December, 2017
Introduction

- Mixed numerology specified by 3GPP
- Numerology assumes the parametrization of the multicarrier modulation

---

Introduction

- Mixed numerology specified by 3GPP
- Numerology assumes the parametrization of the multicarrier modulation

**Numerology in 3GPP**

<table>
<thead>
<tr>
<th>Subcarrier spacing</th>
<th>Symbol duration</th>
<th>Cyclic prefix duration</th>
<th>Slot duration/size</th>
<th>Subrame duration/size</th>
<th>Frame duration/size</th>
</tr>
</thead>
</table>

**Supported transmission numerology**

<table>
<thead>
<tr>
<th>(n)</th>
<th>(\Delta f)</th>
<th>Symbol and CP duration</th>
<th>Symbols per subframe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15 kHz</td>
<td>66.67 µs / 4.69 µs</td>
<td>14</td>
</tr>
<tr>
<td>1</td>
<td>30 kHz</td>
<td>33.33 µs / 2.38 µs</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>60 kHz</td>
<td>16.67 µs / 1.19 µs</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>120 kHz</td>
<td>8.33 µs / 0.60 µs</td>
<td>112</td>
</tr>
</tbody>
</table>

---

Why mixed numerology?

- Flexible way to support diverse user requirements

  - Service requirements
    - URLLC
    - eMBB
    - mMTC

  - Channel conditions
    - Large subcarrier spacings at high velocity
    - Small subcarrier spacing with large channel delay spread

- Currently we are focused on the *Channel conditions*. 
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Setup
Setup

- Dependable Wireless Connectivity for the Society in Motion

Diagram showing a network setup with nodes labeled UE1, UE2, UE3, UE4, UE5, UE6, UE7, and UE8 connected through a network infrastructure.

- Diagram includes a tower with a signal direction arrow labeled \( \Delta f \) pointing towards a UE1 node.

- The diagram also includes a graphical representation of the network's frequency and time dimensions.
Setup
Setup
Setup

Dependable Wireless Connectivity for the Society in Motion
System model

- OFDM transmission of a single user

\[ y_{k,n} = h_{k,n} x_{k,n} + \omega_{k,n} \]

- We perform Least Square (LS) estimation for the transmitted data symbol

\[ \hat{h}_{kp, np} = \frac{y_{kp, np}}{x_{kp, np}} \]

\[ \hat{h}_{k,n} = \sum_{kp, np \in \mathcal{P}} w_{kp, np}^{\{kp, np\}} \hat{h}_{kp, np}, \]

- \( y_{k,n} \) - received OFDM symbol at freq-time data position
- \( x_{k,n} \) - transmitted OFDM symbol at freq-time data position
- \( h_{k,n} \) - frequency response at freq-time data position
- \( \omega_{k,n} \) - AWGN, ICI, ISI, IBI, channel estimation error
- \( \hat{h}_{kp, np} \) - estimated channel at pilot position
- \( w_{kp, np}^{\{kp, np\}} \) - inter/extrapolation weights
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Summary and Future work
Optimization formulation\(^2\)

\[
\begin{align*}
\text{maximize} & \quad B(D_f, D_t) \log_2(1 + \bar{\gamma}(\Delta f)) \\
\text{subject to} & \quad \Delta f \in 2^n 15\text{kHz} \\
\end{align*}
\]

\(n \in \{-1, 0, 1, 2, 3\}\)

\(^2\) Lj. Marijanovic, S. Schwarz, M. Rupp “Optimal Numerology in OFDM Systems Based on Imperfect Channel Knowledge”, VTC Spring 2018
maximize \( B(D_f, D_t) \log_2(1 + \bar{\gamma}(\Delta f)) \)

subject to \( \Delta f \in 2^n \times 15 \text{kHz} \)
\( n \in \{-1, 0, 1, 2, 3\} \)

---

Optimization formulation^2

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& \quad n \in \{-1, 0, 1, 2, 3\}
\end{align*}
\]

\[
\bar{\gamma} = \frac{\sigma_d^2}{\sigma_n^2 + (\sigma_{ICl}^2(\Delta f) + \sigma_{e}^2(\Delta f))\sigma_d^2}
\]

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ICI power for different numerology

![Graph showing ICI power for different numerologies]

- 7.5kHz
- 15kHz
- 30kHz
- 60kHz
- 120kHz

User velocity [km/h] vs. $\sigma^2_{ICI}$
### Parameters used for simulations

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>1.44MHz</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2.5GHz</td>
</tr>
<tr>
<td>SNR</td>
<td>30dB</td>
</tr>
<tr>
<td>Modulation coding scheme</td>
<td>Adaptive</td>
</tr>
<tr>
<td>Channel Model</td>
<td>TDL-A</td>
</tr>
<tr>
<td>Delay spread ($T_{rms}$)</td>
<td>45ns, 370ns</td>
</tr>
</tbody>
</table>
### Throughput Performances

<table>
<thead>
<tr>
<th>User Velocity [km/h]</th>
<th>Throughput [Mbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.5kHz</td>
</tr>
<tr>
<td></td>
<td>15kHz</td>
</tr>
<tr>
<td></td>
<td>30kHz</td>
</tr>
<tr>
<td></td>
<td>60kHz</td>
</tr>
<tr>
<td></td>
<td>120kHz</td>
</tr>
</tbody>
</table>

![Graph showing throughput performances](attachment:image.png)

The graph illustrates the throughput performance of TDL-45ns under varying user velocities and channel bandwidths.
Throughput performances

Throughput [Mbit/s]

User velocity [km/h]

TDL-45ns

7.5kHz
15kHz
30kHz
60kHz
120kHz
LTE
Throughput performances

**TDL-45ns**

- Throughput [Mbit/s] vs User velocity [km/h]

**TDL-370ns**

- Throughput [Mbit/s] vs User velocity [km/h]
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Interband interference

\[ \sigma^2_{\text{IBI}}(k) = \left| \sum_{k'=0}^{N-1} \sin(c(k'+1)\pi q+k^2\Delta f) \right|^2 \]

- \( k, k' \) - subcarrier indices
- \( N \) - total number of subcarriers within certain subband
- \( q \geq 1 \) - ratio between two subcarrier spacings

---

Interband interference

\[ \sigma^2_{IIBI}(k) = \left[ \sum_{k' = 0}^{N-1} \left| \text{sinc}\left( (k' + 1) \frac{\pi}{q} + \frac{k}{2\Delta f} \right) \right|^2 \right] \]

- \( k, k' \) - subcarrier indices
- \( N \) - total number of subcarriers within certain subband
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Integer linear problem formulation - IP method

\[ \tilde{\gamma} = \frac{\sigma_d^2}{\sigma_n^2 + (\sigma_{ICl}^2 + \sigma_{ISI}^2 + \sigma_{e}^2)\sigma_d^2 + \sigma_{IBl}^{max}} \]

---

Integer linear problem formulation - IP method

\[ \tilde{\gamma} = \frac{\sigma_d^2}{\sigma_n^2 + (\sigma_{ICl}^2 + \sigma_{ISI}^2 + \sigma_{IBI}^2)\sigma_d^2 + \sigma_{IBI}^{max}} \]

maximize \[ z \]
subject to
\[ \sum_{\Delta f} \log_2(1 + \tilde{\gamma}_{\Delta f,u}) \Delta N_{\Delta f,u} \geq z, \quad \Delta f \in S, u \in U, z \in \mathbb{R} \]
\[ N_{\Delta f,u}^l \leq N_{\Delta f,u}^h, \quad \forall u \in U, \quad \{N_{\Delta f,u}^l, N_{\Delta f,u}^h\} \in \mathbb{N}_0 \]
\[ \sum_{\Delta f} a_{\Delta f,u} = 1, \]
\[ a_{\Delta f,u} \leq \Delta N_{\Delta f,u} \leq N_{\text{total}} a_{\Delta f,u}, \quad a_{\Delta f,u} \in \{0, 1\} \]
\[ N_{\Delta f,u'}^l - N_{\Delta f,u}^h \geq G(\Delta f, \Delta f') a_{\Delta f,u}, \quad \Delta f' > \Delta f, u' \neq u \]
\[ N_{\Delta f,u+1}^l - N_{\Delta f,u}^h = 0, \]
\[ \Delta N_{\Delta f,u} = 2^{(s-1)c_s}, \quad s \in \{1, 2, 3, 4\}, c_s \in \mathbb{N}_0, \]

The other problem formulation approaches

- Linear programming solution - LP method
  - Low computational complexity even with large bandwidth and high number of users
  - Suboptimal solution

- Heuristic approaches

\[ \Delta f \approx \sqrt{\frac{B_D}{T_{rms}}} \]

- Optimal heuristic
  - Optimally divides the bandwidth based on LP method

- Pure heuristic
  - Divides the total bandwidth into the allocated subbands according to the number of users that are assigned to the subbands
The other problem formulation approaches

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<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>subcarrier spacing</td>
<td>15 kHz 30 kHz 60 kHz 120 kHz</td>
</tr>
<tr>
<td>number of symbols per subframe</td>
<td>14 28 56 128</td>
</tr>
<tr>
<td>CP duration</td>
<td>4.76 µs 2.38 µs 1.18 µs 0.59 µs</td>
</tr>
<tr>
<td>bandwidth</td>
<td>5 MHz</td>
</tr>
<tr>
<td>carrier frequency</td>
<td>5.9 GHz</td>
</tr>
<tr>
<td>channel model</td>
<td>TDL-A</td>
</tr>
<tr>
<td>pilot pattern</td>
<td>diamond</td>
</tr>
<tr>
<td>number of user</td>
<td>7</td>
</tr>
</tbody>
</table>
Numerical results

- Numerical results for $v = 100 \text{ km/h}$
  - $D_1 \in \{100, 200\} \text{ ns}$
  - $D_2 \in \{30, 50, 100, 200\} \text{ ns}$
  - $D_3 \in \{30, 50, 100, 200, 300, 400, 500\} \text{ ns}$

- Bands considered:
  - $V_1 \in \{100, 200\} \text{ km/h}$
  - $V_2 \in \{5, 50, 100, 200\} \text{ km/h}$
  - $V_3 \in \{5, 50, 100, 200, 300, 400\} \text{ km/h}$
Numerical results

\[ v = 100 \text{ km/h} \]

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Numerical results

\( T_{\text{rms}} = 200 \text{ ns} \)

\( v = 100 \text{ km/h} \)

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V_1 & \sim \{100, 200\} \text{ km/h} \\
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Dependable Wireless Connectivity for the Society in Motion

Numerical results

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Normalized achievable rate

IP
LP
optimal heuristic
pure heuristic
LTE
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Summary

- Large subcarrier spacings are more robust to ICI, but suffer of ISI and large interpolation error with large rms delay spread channels.
- Interband interference occurs due to the different numerology in multi-user scenario.
- The LP method provides a highly favorable tradeoff between computational complexity and performance.
- We gain with the mixed numerology compared to an LTE.
Summary

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Future work

▶ Optimal numerology based on QoS requirements - latency, reliability

▶ Employ the OFDM-based modulation schemes

▶ PhD defense - first half of 2020
Future work

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Thank you for your attention!
{ljiljana.marijanovic@nt.tuwien.ac.at}
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