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| Project | **IEEE 802.16 Broadband Wireless Access Working Group <**<http://ieee802.org/16>**>** |
| Title | **Benefits of Specific PHY Layer Parameters to Support 1MHz Channels** |
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| Re: | IEEE 802.16s GRIDMAN Task Group Discussions and Call for Contributions |
| Abstract | Provides an evaluation of specific feature modifications for achieving channel BWs less than 1.25 MHz for Smart Grid Applications with a focus on PHY throughput.  |
| Purpose | This document is intended to facilitate the GRIDMAN Task Group discussions eventually leading to a proposed amendment to IEEE Std 802.16-2012.  |
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**Benefits of Specific PHY Layer Parameters to Support 1 MHz Channels**

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**Date: August 23, 2016**

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# Introduction

Considerable progress has been made in GRIDMAN Task Group discussions that will eventually lead to a proposed amendment to IEEE Std 802.16™-2012 [1] in support of channel BWs less than 1.25 MHz for Smart Grid applications. In our Session #104 GRIDMAN meetings it became apparent that we needed to better understand the impact of specific feature amendments or changes to the current standard and the impact these changes would have on the resulting channel performance. This contribution is intended to provide these additional insights. While there are many performance metrics of concern as called out in the System Requirements Document [2], the PHY throughput is probably the best to use as a primary comparative measure while at the same time providing a tradeoff that must also be considered.

# 1.25 MHz Channel BW Implementation per IEEE Std 802.16-2012

The current IEEE standard, IEEE Std 802-16-2012, with mandatory and optional features supports channel bandwidths from 1.25 MHz to 20 MHz. The implementation for a 1.25 MHz can serve as a starting point as we move forward considering an amendment to support channel BWs less than 1.25 MHz.

The following table shows the specified subcarrier alignment for PUSC permutation called out in the standard. The table also shows the ***optional UL PUSC*** implementation ([1] 8.4.6.2.5, Table 8-275). With optional UL PUSC, the number of data subcarriers are the same for the UL and DL, an implementation option more suited to Smart Grid applications with its UL traffic bias.

**Table 1:** **1.25 Channel BW implementation with current standard, IEEE Std 802.16-2012**

|  |  |  |
| --- | --- | --- |
|  |  | **Baseline Per IEEE Std 802.16-2012** |
|  | **Permutation** | 1. **PUSC**
 | 1. **PUSC (Optional UL)**
 |
|  | **Channel BW** | **1.25 MHz** | **1.25 MHz** |
| 1 | FFT (Total Subcarriers) | 128 | 128 |
| 2 |   | DL | UL | DL | UL (opt) |
| 3 | DC Subcarriers | 1 | 1 | 1 | 1 |
| 4 | Guard Subcarriers - Left | 22 | 16 | 22 | 10 |
| 5 | Guard Subcarriers - Right | 21 | 15 | 21 | 9 |
| 6 | Used Subcarriers (DC + Pilots + Data) | 85 | 97 | 85 | 109 |
| 7 | Pilot Subcarriers | 12 | 32 | 12 | 36 |
| 8 | Data Subcarriers | 72 | 64 | 72 | 72 |
| 9 | Subchannels | 3 | 4 | 3 | 6 |
| 10 | Data Subcarriers per Subchannel | 24 | 16 | 24 | 12 |
| 11 | Pilot Subcarriers per Subchannel | 4 | 8 | 4 | 6 |
| 12 | Sampling Factor | 28/25  | 28/25  |
| 13 | Sampling Frequency | 1.40 MHz | 1.40 MHz |
| 14 | Subcarrier Spacing | 10.94 kHz | 10.94 kHz |
| 15 | Occupied BW (including DC subcarrier) | 929.69 kHz | 1060.9 kHz | 929.69 kHz | 1192.2 kHz |

Further assumptions to assess the throughput for a 1.25 MHz channel BW at the PHY Layer are:

* 64-QAM with 5/6 coding in both the DL and the UL ([1] 8.4.6.1.2.1, 64-QAM 8.1.1)
* 5 ms Frame size and 1/8 Cyclic prefix
* 7 DL Overhead (OH) symbols and 4 UL OH symbols
* 1 Symbol for TR-Gap
* 1x1 MIMO for BS and SS
* 2 bps per Hz average spectral efficiency over the coverage area as shown in Fig. 1.

**Figure 1:** *This approach for estimating ‘average spectral efficiency’ simply assumes endpoints are uniformly distributed over the coverage area and all endpoints are subject to the same excess path loss denoted by n>2. See ref [3]*

**Table 2: PHY Layer throughput analysis for 1.25 MHz channel with current IEEE 802.16 standard**

|  |  | **Baseline Per IEEE Std 802.16-2012** |
| --- | --- | --- |
|  | **Permutation** | 1. **PUSC**
 | 1. **PUSC (Optional UL)**
 |
|  | **Channel BW** | **1.25 MHz** | **1.25 MHz** |
| 16 | Symbol Time - microsec | 91.43 us | 91.43 us |
| 17 | Guard Time (Cyclic Prefix) - microsec | 11.43 us | 11.43 us |
| 18 | Symbol Duration - microsec | 102.86 us | 102.86 us |
| 19 | Frame size - ms | 5 ms | 5 ms |
| 20 | Samples per Frame  | 7000.0 | 7000.0 |
| 21 | Frames per sec | 200.0 | 200.0 |
| 22 | # OFDMA Symbols per Frame | 48 | 48 |
| 23 | Symbols for TR-Gap | 1 | 1 |
| 24 | Net OFDMA Symbols per frame  | 47 | 47 |
| 25 | TTG+RTG Gap in microsec | 165.71 us | 165.71 us |
| 26 | Range Limit with 1 Symbol TR-Gap | 15.44 mi | 15.44 mi |
| 27 | TR-Gap Symbols for 40 mi range | 3 | 3 |
| 28 | Permutation | PUSC | PUSC |
| 29 | N = # of Bins (If Band AMC) | n/a | n/a |
| 30 | M = # of Symbols (If Band AMC) | n/a | n/a |
| 31 |   | **DL** | **UL** | **DL** | **UL** |
| 32 | Data Sub-carriers/Sub-channel/Symbol | 24 | 16 | 24 | 12 |
| 33 | Data Sub-carriers per channel | 72 | 64 | 72 | 72 |
| 34 | Estimated number of OH Symbols | 7 | 4 | 7 | 4 |
| 35 | Total Data Symbols | 36 | 36 |
| 36 | DL/UL Data Symbols | 15 | 21 | 15 | 21 |
| 37 | UL/DL Symbol Ratio | 1.40 | 1.40 |
| 38 | Total OH Symbols (DL+UL+TR Gap) | 12 | 12 |
| 39 | **Peak & Cell Edge PHY Rates per Subchannel (Assume 1x1 MIMO for BS & SS) Same for UL and DL** |
| 40 | Peak kBytes/s/subchannel (64QAM-5/6) | 45.0 kB/s | 42.0 kB/s | 45.0 kB/s | 31.5 kB/s |
| 41 | Cell Edge kBytes/s/subchannel (QPSK-1/2) | 9.0 kB/s | 8.4 kB/s | 9.0 kB/s | 6.3 kB/s |
| 42  | **Average PHY Rate/Channel over coverage area for Excess Path Loss Factor, n ~ 4.3** |
| **Average Spectral Efficiency ~** | **2.0 bps/Hz** |
| 43 | Average kBytes/s/subchannel | 18.0 kB/s | 16.8 kB/s | 18.0 kB/s | 12.6 kB/s |
| 44 |  | **DL** | **UL** | **DL** | **UL** |
| 45 | Peak kBytes/s/Channel (64QAM-5/6) | 135.0 kB/s | 168.0 kB/s | 135.0 kB/s | 189.0 kB/s |
| 46 | Cell Edge kBytes/s/Channel (QPSK-1/2) | 27.0 kB/s | 33.6 kB/s | 27.0 kB/s | 37.8 kB/s |
| 47 | Average kBytes/s/Channel | 54.0 kB/s | 67.2 kB/s | 54.0 kB/s | 75.6 kB/s |
| 48 | Peak kbps per Channel | 1080 kbps | 1344 kbps | 1080 kbps | 1512 kbps |
| 49 | Cell Edge kbps per Channel | 216 kbps | 269 kbps | 216 kbps | 302 kbps |
| 50 | Average kbps per Channel | 432 kbps | 538 kbps | 432 kbps | 605 kbps |
| 51 | PHY DL + UL | 969.6 kbps | 1036.8 kbps |

# Potential Options for Support of <1.25 MHz Channels

In this section the various features that can be modified to enable support for channel BWs smaller than 1.25 MHz are considered. These modifications are evaluated with their impact on channel throughput, a key metric that must be considered with smaller channel BWs. A 1 MHz channel BW is used as a baseline for comparative purposes for each option. Each option or parameter set is numerically labeled from 1 to 12 and summarized in Table 3.

Note that Option 1 represents the simplest amendment to IEEE Std 802.16-2012 in support of a 1 MHz channel BW. We would only have to add a 1 MHz profile and stipulate that Optional PUSC in the UL be SHALL rather than optional. 64QAM with 5/6 coding in BOTH UL and DL would also have to be stipulated as SHALL requirements. Using this as a baseline for 1 MHz channels other feature modifications are considered and compared to Option 1 with respect to the UL + DL PHY Layer throughput.

**Table 3: Summary of feature options to be considered for enhancements to PHY Layer throughput**

| **Option** | **Description** | **IEEE 802.16-2012 Reference** |
| --- | --- | --- |
| **1** | Simply add a 1 MHz profile to the existing standard with Optional UL PUSC as in Column B) Table 2 by amending the clock frequency to 1.12 MHz. This approach theoretically can be extended to channel BWs to 100 kHz with further reduction to the clock frequency and/or the number of subchannels. This, by far is the simplest modification to the standard to support smaller channel BWs. | [1] 12.4, Table 12-20 |
| **2** | Change the sampling factor[[1]](#footnote-1) from 28/25 to 57/50, this will add 1 symbol | [1] 8.4.2.3 (OFDM Table 8-38) |
| **3** | With 28/25 sampling factor, adopt Band AMC permutation in DL and UL | [1] 8.4.8.1 , 6.3.17, Table 8-123 |
| **4** | With Band AMC, change sampling factor from 28/25 to 57/50 | [1] 8.4.2.3 (OFDM Table 8-38) |
| **5** | Change the sampling factor from 57/50 to 144/125 |
| **6, 7, 8, 9** | With 57/50 sampling factor, increase frame size from 5 ms to 10 ms to 15 ms to 20 ms to 25 ms | [1] 11.18.2 Table 11-62 |
| **10** | With 25 ms Frame size, reduce cyclic prefix from 1/8 to 1/16 | [1] 6.3.2.3.42, Table 6-160, 11.18.2, Table 11-62 |
| **11** | With PUSC as in #1 above, reduce cyclic prefix from 1/8 to 1/16 | [1] 6.3.2.3.42, Table 6-16011.18.2, Table 11-62 |
| **12** | With Band AMC as in #3 above, reduce cyclic prefix from 1/8 to 1/16 |

## PUSC vs. Band AMC Permutation (Option 1 vs. 3)

Of all the features or attributes that can be modified in the IEEE standard, adopting Band AMC permutation in the DL and UL in lieu of PUSC permutation, as shown in Table 4, will have the greatest impact on throughput enhancement.

**Table 4: Band AMC permutation compared to PUSC with optional UL parameters**

|  |  | **1** | **3** |
| --- | --- | --- | --- |
|  | **Permutation** | **PUSC (Optional UL)** | **Band AMC** |
|  | **Channel BW** | **1.00 MHz** | **1.00 MHz** |
| 1 | FFT (Total Subcarriers) | 128 | 128 |
| 2 |   | DL | UL (opt) | DL | UL |
| 3 | DC Subcarriers | 1 | 1 | 1 | 1 |
| 4 | Guard Subcarriers - Left | 22 | 10 | 10 | 10 |
| 5 | Guard Subcarriers - Right | 21 | 9 | 9 | 9 |
| 6 | Used Subcarriers (DC + Pilots + Data) | 85 | 109 | 109 | 109 |
| 7 | Pilot Subcarriers | 12 | 36 | 12 | 12 |
| 8 | Data Subcarriers | 72 | 72 | 96 | 96 |
| 9 | Subchannels | 3 | 6 | 6 | 6 |
| 10 | Data Subcarriers per Subchannel | 24 | 12 | 16 | 16 |
| 11 | Pilot Subcarriers per Subchannel | 4 | 6 | 2 | 2 |
| 12 | Sampling Factor | 1 3/25  | 1 3/25  |
| 13 | Sampling Frequency | 1.12 MHz | 1.12 MHz |
| 14 | Subcarrier Spacing | 8.75 kHz | 8.75 kHz |
| 15 | Occupied BW (incl DC subcarrier) | 743.75 kHz | 953.75 kHz | 953.75 kHz | 953.75 kHz |
| 16 | Symbol Time - microsec | 114.29 us | 114.29 us |
| 17 | Guard Time (Cyclic Prefix) - microsec | 14.29 us | 14.29 us |
| 18 | Symbol Duration - microsec | 128.57 us | 128.57 us |
| 19 | Frame size - ms | 5 ms | 5 ms |
| 20 | Samples per Frame  | 5600.0 | 5600.0 |
| 21 | Frames per sec | 200.0 | 200.0 |
| 22 | # OFDMA Symbols per Frame | 38 | 38 |
| 23 | Symbols for TR-Gap | 1 | 1 |
| 24 | Net OFDMA Symbols per frame  | 37 | 37 |
| 25 | TTG+RTG Gap in microsec | 242.86 us | 242.86 us |
| 26 | Range Limit with 1 Symbol TR-Gap | 22.62 mi | 22.62 mi |
| 27 | TR-Gap Symbols for 40 mi range | 2 | 2 |
| 28 | Permutation | PUSC | AMC |
| 29 | N = # of Bins (If Band AMC) | n/a | 2 |
| 30 | M = # of Symbols (If Band AMC) | n/a | 3 |
| 31 |   | **DL** | **UL** | **DL** | **UL** |
| 32 | Data Sub-carriers/Sub-channel/Symbol | 24 | 12 | 16 | 16 |
| 33 | Data Sub-carriers per channel | 72 | 72 | 96 | 96 |
| 34 | Estimated number of OH Symbols | 7 | 4 | 7 | 4 |
| 35 | Total Data Symbols | 26 | 26 |
| 36 | DL/UL Data Symbols | 11 | 15 | 11 | 15 |
| 37 | UL/DL Symbol Ratio | 1.36 | 1.36 |
| 38 | Total OH Symbols (DL+UL+TR Gap) | 12 | 12 |
| 39 | **Peak & Cell Edge PHY Rates per Subchannel (Assume 1x1 MIMO for BS & SS)** |
| 40 | Peak kBytes/s/subchannel (64QAM-5/6) | 33.0 kB/s | 22.5 kB/s | 22.0 kB/s | 30.0 kB/s |  |  |  |  |
| 41 | Cell Edge kBytes/s/subchannel (QPSK-1/2) | 6.6 kB/s | 4.5 kB/s | 4.4 kB/s | 6.0 kB/s |  |  |  |  |
| 42 | **Average PHY rate assuming 2bps/Hz average spectral efficiency** |  |  |  |  |
| 43 | Average kBytes/s/subchannel | 13.2 kB/s | 9.0 kB/s | 8.8 kB/s | 12.0 kB/s |  |  |  |  |
| 44 | **Per channel peak, cell edge, and average PHY rate** |  |  |  |  |
| 45 | Peak kBytes/s/Channel (64QAM-5/6) | 99.0 kB/s | 135.0 kB/s | 132.0 kB/s | 180.0 kB/s |  |  |  |  |
| 46 | Cell Edge kBytes/s/Channel (QPSK-1/2) | 19.8 kB/s | 27.0 kB/s | 26.4 kB/s | 36.0 kB/s |  |  |  |  |
| 47 | Average kBytes/s/Channel | 39.6 kB/s | 54.0 kB/s | 52.8 kB/s | 72.0 kB/s |  |  |  |  |
| 48 | Peak kbps per Channel | 792 kbps | 1080 kbps | 1056 kbps | 1440 kbps |  |  |  |  |
| 49 | Cell Edge kbps per Channel | 158 kbps | 216 kbps | 211 kbps | 288 kbps |  |  |  |  |
| 50 | Average kbps per Channel | 317 kbps | 432 kbps | 422 kbps | 576 kbps |  |  |  |  |
| 51 | PHY DL + UL | 748.8 kbps | 998.4 kbps |  |  |  |  |
| 52 | kbps per data symbol | 28.8 | 38.4 |  |  |  |  |
| 53 | Per cent per data symbol | 3.85% | 3.85% |  |  |  |  |

**Key takeaways from Table 4, PUSC vs. Band AMC:**

* Changing the permutation from PUSC to Band AMC increases the number of data subcarriers for 72 to 96 for a 33.3 % increase in the PHY rate.
* Line 53 provides a measure of the PHY Layer throughput gain that can be achieved with measures taken to reduce the number of overhead symbols or, alternatively the reduction in throughput for any additional TR-Gap symbols required to support a longer range. DL + UL + TR-Gap is assumed to be 12 symbols for this and the following tables.

## Cyclic Prefix Modification (Option 3 vs. 12)

The standard specifies a cyclic prefix of 1/8 for performance to control inter-symbol-interference (ISI), thus relegating a considerable portion of the symbol duration to overhead. Reducing this overhead with a 1/16 cyclic prefix adds 3 symbols per 5 ms frame and increases the throughput by 11.5 %. Note that other values between 1/8 and 1/16 can also be considered.

**Table 5: Parameters for 1/8 versus 1/16 cyclic prefix**

|  |  | **3** | **12**  |
| --- | --- | --- | --- |
|  | **Permutation** | **Band AMC** | **Band AMC** |
|  | **Channel BW** | **1.00 MHz** | **1.00 MHz** |
| 1 | FFT (Total Subcarriers) | 128 | 128 |
| 2 |   | DL | UL | DL | UL |
| 3 | DC Subcarriers | 1 | 1 | 1 | 1 |
| 4 | Guard Subcarriers - Left | 10 | 10 | 10 | 10 |
| 5 | Guard Subcarriers - Right | 9 | 9 | 9 | 9 |
| 6 | Used Subcarriers (DC + Pilots + Data) | 109 | 109 | 109 | 109 |
| 7 | Pilot Subcarriers | 12 | 12 | 12 | 12 |
| 8 | Data Subcarriers | 96 | 96 | 96 | 96 |
| 9 | Subchannels | 6 | 6 | 6 | 6 |
| 10 | Data Subcarriers per Subchannel | 16 | 16 | 16 | 16 |
| 11 | Pilot Subcarriers per Subchannel | 2 | 2 | 2 | 2 |
| 12 | Sampling Factor | 28/25  | 28/25  |
| 13 | Sampling Frequency | 1.12 MHz | 1.12 MHz |
| 14 | Subcarrier Spacing | 8.75 kHz | 8.75 kHz |
| 15 | Occupied BW (incl DC subcarrier) | 953.75 kHz | 953.75 kHz | 953.75 kHz | 953.75 kHz |
| 16 | Symbol Time - microsec | 114.29 us | 114.29 us |
| 17 | Guard Time (Cyclic Prefix) - microsec | 14.29 us | 7.14 us |
| 18 | Symbol Duration - microsec | 128.57 us | 121.43 us |
| 19 | Frame size - ms | 5 ms | 5 ms |
| 20 | Samples per Frame  | 5600.0 | 5600.0 |
| 21 | Frames per sec | 200.0 | 200.0 |
| 22 | # OFDMA Symbols per Frame | 38 | 41 |
| 23 | Symbols for TR-Gap | 1 | 1 |
| 24 | Net OFDMA Symbols per frame  | 37 | 40 |
| 25 | TTG+RTG Gap in microsec | 242.86 us | 142.86 us |
| 26 | Range Limit with 1 Symbol TR-Gap | 22.62 mi | 13.31 mi |
| 27 | TR-Gap Symbols for 40 mi range | 2 | 4 |
| 28 | Permutation | AMC | AMC |
| 29 | N = # of Bins (If Band AMC) | 2 | 2 |
| 30 | M = # of Symbols (If Band AMC) | 3 | 3 |
| 31 |   | **DL** | **UL** | **DL** | **UL** |
| 32 | Data Sub-carriers/Sub-channel/Symbol | 16 | 16 | 16 | 16 |
| 33 | Data Sub-carriers per channel | 96 | 96 | 96 | 96 |
| 34 | Estimated number of OH Symbols | 7 | 4 | 7 | 4 |
| 35 | Total Data Symbols | 26 | 29 |
| 36 | DL/UL Data Symbols | 11 | 15 | 12 | 17 |
| 37 | UL/DL Symbol Ratio | 1.36 | 1.42 |
| 38 | Total OH Symbols (DL+UL+TR Gap) | 12 | 12 |
| 39 | **Peak & Cell Edge PHY Rates per Subchannel (Assume 1x1 MIMO for BS & SS)** |   |   |   |   |
| 40 | Peak kBytes/s/subchannel (64QAM-5/6) | 22.0 kB/s | 30.0 kB/s | 24.0 kB/s | 34.0 kB/s |  |  |  |  |  |
| 41 | Cell Edge kBytes/s/subchannel (QPSK-1/2) | 4.4 kB/s | 6.0 kB/s | 4.8 kB/s | 6.8 kB/s |  |  |  |  |  |
| 42 | **Average PHY rate assuming 2bps/Hz average spectral efficiency** |  |  |  |  |  |
| 43 | Average kbytes/s/subchannel | 8.8 kB/s | 12.0 kB/s | 9.6 kB/s | 13.6 kB/s |  |  |  |  |  |
| 44 | **Per channel peak, cell edge, and average PHY rate**  |  |  |  |  |  |
| 45 | Peak kBytes/s/Channel (64QAM-5/6) | 132.0 kB/s | 180.0 kB/s | 144.0 kB/s | 204.0 kB/s |  |  |  |  |  |
| 46 | Cell Edge kBytes/s/Channel (QPSK-1/2) | 26.4 kB/s | 36.0 kB/s | 28.8 kB/s | 40.8 kB/s |  |  |  |  |  |
| 47 | Average kbytes/s/Channel | 52.8 kB/s | 72.0 kB/s | 57.6 kB/s | 81.6 kB/s |  |  |  |  |  |
| 48 | Peak kbps per Channel | 1056 kbps | 1440 kbps | 1152 kbps | 1632 kbps |  |  |  |  |  |
| 49 | Cell Edge kbps per Channel | 211 kbps | 288 kbps | 230 kbps | 326 kbps |  |  |  |  |  |
| 50 | Average kbps per Channel | 422 kbps | 576 kbps | 461 kbps | 653 kbps |  |  |  |  |  |
| 51 | PHY DL + UL | 998.4 kbps | 1113.6 kbps |  |  |  |  |  |
| 52 | kbps per data symbol | 38.4 | 38.4 |  |  |  |  |  |
| 53 | Per cent per data symbol | 3.85% | 3.45% |  |  |  |  |  |

## Increased Frame Size Options (Options 4, 6, 9)

Frame sizes of 5, 10, 15, 20, and 25 ms have been analyzed but only 5, 10, and 25 ms are shown for illustrative purposes in the following table. Details for all options are shown Appendix 1.

**Table 6: Impact of Frame Size, 5 ms, 10 ms, and 25 ms with 57/50 sampling factor**

|  |  | **4** | **6** | **9** |
| --- | --- | --- | --- | --- |
|  | **Permutation** | **Band AMC** | **Band AMC** | **Band AMC** |
|  | **Channel BW** | **1.00 MHz** | **1.00 MHz** | **1.00 MHz** |
| 1 | FFT (Total Subcarriers) | 128 | 128 | 128 |
| 2 |   | DL | UL | DL | UL | DL | UL |
| 3 | DC Subcarriers | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | Guard Subcarriers - Left | 10 | 10 | 10 | 10 | 10 | 10 |
| 5 | Guard Subcarriers - Right | 9 | 9 | 9 | 9 | 9 | 9 |
| 6 | Used Subcarriers (DC+Pilots+Data) | 109 | 109 | 109 | 109 | 109 | 109 |
| 7 | Pilot Subcarriers | 12 | 12 | 12 | 12 | 12 | 12 |
| 8 | Data Subcarriers | 96 | 96 | 96 | 96 | 96 | 96 |
| 9 | Subchannels | 6 | 6 | 6 | 6 | 6 | 6 |
| 10 | Data Subcarriers per Subchannel | 16 | 16 | 16 | 16 | 16 | 16 |
| 11 | Pilot Subcarriers per Subchannel | 2 | 2 | 2 | 2 | 2 | 2 |
| 12 | Sampling Factor | 57/50  | 57/50  | 57/50  |
| 13 | Sampling Frequency | 1.14 MHz | 1.14 MHz | 1.14 MHz |
| 14 | Subcarrier Spacing | 8.91 kHz | 8.91 kHz | 8.91 kHz |
| 15 | Occupied BW (incl DC subcarrier) | 970.78 kHz | 970.78 kHz | 970.78 kHz | 970.78 kHz | 970.78 kHz | 970.78 kHz |
| 16 | Symbol Time - microsec | 112.28 us | 112.28 us | 112.28 us |
| 17 | Guard Time (Cyclic Prefix) - microsec | 14.04 us | 14.04 us | 14.04 us |
| 18 | Symbol Duration - microsec | 126.32 us | 126.32 us | 126.32 us |
| 19 | Frame size - ms | 5 ms | 10 ms | 25 ms |
| 20 | Samples per Frame  | 5700.0 | 11400.0 | 28500.0 |
| 21 | Frames per sec | 200.0 | 100.0 | 40.0 |
| 22 | # OFDMA Symbols per Frame | 39 | 79 | 197 |
| 23 | Symbols for TR-Gap | 1 | 1 | 1 |
| 24 | Net OFDMA Symbols per frame  | 38 | 78 | 196 |
| 25 | TTG+RTG Gap in microsec | 200.00 us | 147.37 us | 242.11 us |
| 26 | Range Limit with 1 Symbol TR-Gap | 18.63 mi | 13.73 mi | 22.55 mi |
| 27 | TR-Gap Symbols for 40 mi range | 3 | 3 | 2 |
| 28 | Permutation | AMC | AMC | AMC |
| 29 | N = # of Bins (If Band AMC) | 2 | 2 | 2 |
| 30 | M = # of Symbols (If Band AMC) | 3 | 3 | 3 |
| 31 |   | **DL** | **UL** | **DL** | **UL** | **DL** | **UL** |
| 32 | Data Sub-carriers/Sub-channel/Symbol | 16 | 16 | 16 | 16 | 16 | 16 |
| 33 | Data Sub-carriers per channel | 96 | 96 | 96 | 96 | 96 | 96 |
| 34 | Estimated number of OH Symbols | 7 | 4 | 7 | 4 | 7 | 4 |
| 35 | Total Data Symbols | 27 | 67 | 185 |
| 36 | DL/UL Data Symbols | 12 | 15 | 28 | 39 | 77 | 108 |
| 37 | UL/DL Symbol Ratio | 1.25 | 1.39 | 1.40 |
| 38 | Total OH Symbols (DL+UL+TR Gap) | 12 | 12 | 12 |
| 39 | **Peak & Cell Edge PHY Rates per Subchannel (Assume 1x1 MIMO for BS & SS) Same for UL and DL** |
| 40 | Peak kBytes/s/subchannel (64QAM-5/6) | 24.0 kB/s | 30.0 kB/s | 28.0 kB/s | 39.0 kB/s | 30.8 kB/s | 43.2 kB/s |  |  |  |  |  |
| 41 | Cell Edge kBytes/s/subchannel (QPSK-1/2) | 4.8 kB/s | 6.0 kB/s | 5.6 kB/s | 7.8 kB/s | 6.2 kB/s | 8.6 kB/s |  |  |  |  |  |
| 42 | **Average PHY rate assuming 2bps/Hz average spectral efficiency** |  |  |  |  |  |
| 43 | Average kBytes/s/subchannel | 9.6 kB/s | 12.0 kB/s | 11.2 kB/s | 15.6 kB/s | 12.3 kB/s | 17.3 kB/s |  |  |  |  |  |
| 44 | **Per channel peak, cell edge, and average PHY rate** |  |  |  |  |  |
| 45 | Peak kBytes/s/Channel (64QAM-5/6) | 144.0 kB/s | 180.0 kB/s | 168.0 kB/s | 234.0 kB/s | 184.8 kB/s | 259.2 kB/s |  |  |  |  |  |
| 46 | Cell Edge kBytes/s/Channel (QPSK-1/2) | 28.8 kB/s | 36.0 kB/s | 33.6 kB/s | 46.8 kB/s | 37.0 kB/s | 51.8 kB/s |  |  |  |  |  |
| 47 | Average kBytes/s/Channel | 57.6 kB/s | 72.0 kB/s | 67.2 kB/s | 93.6 kB/s | 73.9 kB/s | 103.7 kB/s |  |  |  |  |  |
| 48 | Peak kbps per Channel | 1152 kbps | 1440 kbps | 1344 kbps | 1872 kbps | 1478 kbps | 2074 kbps |  |  |  |  |  |
| 49 | Cell Edge kbps per Channel | 230 kbps | 288 kbps | 269 kbps | 374 kbps | 296 kbps | 415 kbps |  |  |  |  |  |
| 50 | Average kbps per Channel | 461 kbps | 576 kbps | 538 kbps | 749 kbps | 591 kbps | 829 kbps |  |  |  |  |  |
| 51 | PHY DL + UL | 1036.8 kbps | 1286.4 kbps | 1420.8 kbps |  |  |  |  |  |
| 52 | kbps per data symbol | 38.4 | 19.2 | 7.68 |  |  |  |  |  |
| 53 | Per cent per data symbol | 3.70% | 1.49% | 0.54% |  |  |  |  |  |

## Sampling Factor Variations (Options 3, 4, and 5)

The Sampling Factor multiplied by the channel BW defines the Clock Frequency. Increasing the sampling factor and hence the clock frequency increases the subcarrier spacing for some improvement in inter-carrier-interference (ICI) but with a corresponding increase in occupied BW. The increased occupied BW may lead to a greater challenge in meeting out-of-band-emission (OOBE) requirements.

**Table 7: Impact of sampling factor modification from 28/25 to 57/50 to 144/125**

|  |  | **3** | **4** | **5** |
| --- | --- | --- | --- | --- |
|  | **Permutation** | **Band AMC** | **Band AMC** | **Band AMC** |
|  | **Channel BW** | **1.00 MHz** | **1.00 MHz** | **1.00 MHz** |
| 1 | FFT (Total Subcarriers) | 128 | 128 | 128 |
| 2 |   | DL | UL | DL | UL | DL | UL |
| 3 | DC Subcarriers | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | Guard Subcarriers - Left | 10 | 10 | 10 | 10 | 10 | 10 |
| 5 | Guard Subcarriers - Right | 9 | 9 | 9 | 9 | 9 | 9 |
| 6 | Used Subcarriers (DC+Pilots+Data) | 109 | 109 | 109 | 109 | 109 | 109 |
| 7 | Pilot Subcarriers | 12 | 12 | 12 | 12 | 12 | 12 |
| 8 | Data Subcarriers | 96 | 96 | 96 | 96 | 96 | 96 |
| 9 | Subchannels | 6 | 6 | 6 | 6 | 6 | 6 |
| 10 | Data Subcarriers per Subchannel | 16 | 16 | 16 | 16 | 16 | 16 |
| 11 | Pilot Subcarriers per Subchannel | 2 | 2 | 2 | 2 | 2 | 2 |
| 12 | Sampling Factor | 28/25  | 57/50  | 144/125 |
| 13 | Sampling Frequency | 1.12 MHz | 1.14 MHz | 1.15 MHz |
| 14 | Subcarrier Spacing | 8.75 kHz | 8.91 kHz | 9.00 kHz |
| 15 | Occupied BW (incl DC subcarrier) | 953.75 kHz | 953.75 kHz | 970.78 kHz | 970.78 kHz | 981.00 kHz | 981.00 kHz |
| 16 | Symbol Time - microsec | 114.29 us | 112.28 us | 111.11 us |
| 17 | Guard Time (Cyclic Prefix) - microsec | 14.29 us | 14.04 us | 13.89 us |
| 18 | Symbol Duration - microsec | 128.57 us | 126.32 us | 125.00 us |
| 19 | Frame size - ms | 5 ms | 5 ms | 5 ms |
| 20 | Samples per Frame  | 5600.0 | 5700.0 | 5760.0 |
| 21 | Frames per sec | 200.0 | 200.0 | 200.0 |
| 22 | # OFDMA Symbols per Frame | 38 | 39 | 40 |
| 23 | Symbols for TR-Gap | 1 | 1 | 1 |
| 24 | Net OFDMA Symbols per frame  | 37 | 38 | 39 |
| 25 | TTG+RTG Gap in microsec | 242.86 us | 200.00 us | 125.00 us |
| 26 | Range Limit with 1 Symbol TR-Gap | 22.62 mi | 18.63 mi | 11.64 mi |
| 27 | TR-Gap Symbols for 40 mi range | 2 | 3 | 4 |
| 28 | Permutation | AMC | AMC | AMC |
| 29 | N = # of Bins (If Band AMC) | 2 | 2 | 2 |
| 30 | M = # of Symbols (If Band AMC) | 3 | 3 | 3 |
| 31 |   | **DL** | **UL** | **DL** | **UL** | **DL** | **UL** |
| 32 | Data Sub-carriers/Sub-channel/Symbol | 16 | 16 | 16 | 16 | 16 | 16 |
| 33 | Data Sub-carriers per channel | 96 | 96 | 96 | 96 | 96 | 96 |
| 34 | Estimated number of OH Symbols | 7 | 4 | 7 | 4 | 7 | 4 |
| 35 | Total Data Symbols | 26 | 27 | 28 |
| 36 | DL/UL Data Symbols | 11 | 15 | 12 | 15 | 12 | 16 |
| 37 | UL/DL Symbol Ratio | 1.36 | 1.25 | 1.33 |
| 38 | Total OH Symbols (DL+UL+TR Gap) | 12 | 12 | 12 |
| 39 | **Peak & Cell Edge PHY Rates per Subchannel (Assume 1x1 MIMO for BS & SS) Same for UL and DL** |
| 40 | Peak kBytes/s/subchannel (64QAM-5/6) | 22.0 kB/s | 30.0 kB/s | 24.0 kB/s | 30.0 kB/s | 24.0 kB/s | 32.0 kB/s |  |  |  |  |  |
| 41 | Cell Edge kBytes/s/subchannel (QPSK-1/2) | 4.4 kB/s | 6.0 kB/s | 4.8 kB/s | 6.0 kB/s | 4.8 kB/s | 6.4 kB/s |  |  |  |  |  |
| 42 | **Average PHY rate assuming 2bps/Hz average spectral efficiency** |  |  |  |  |  |
| 43 | Average kBytes/s/subchannel | 8.8 kB/s | 12.0 kB/s | 9.6 kB/s | 12.0 kB/s | 9.6 kB/s | 12.8 kB/s |  |  |  |  |  |
| 44 | **Per channel peak, cell edge, and average PHY rate** |  |  |  |  |  |
| 45 | Peak kBytes/s/Channel (64QAM-5/6) | 132.0 kB/s | 180.0 kB/s | 144.0 kB/s | 180.0 kB/s | 144.0 kB/s | 192.0 kB/s |  |  |  |  |  |
| 46 | Cell Edge kBytes/s/Channel (QPSK-1/2) | 26.4 kB/s | 36.0 kB/s | 28.8 kB/s | 36.0 kB/s | 28.8 kB/s | 38.4 kB/s |  |  |  |  |  |
| 47 | Average kBytes/s/Channel | 52.8 kB/s | 72.0 kB/s | 57.6 kB/s | 72.0 kB/s | 57.6 kB/s | 76.8 kB/s |  |  |  |  |  |
| 48 | Peak kbps per Channel | 1056 kbps | 1440 kbps | 1152 kbps | 1440 kbps | 1152 kbps | 1536 kbps |  |  |  |  |  |
| 49 | Cell Edge kbps per Channel | 211 kbps | 288 kbps | 230 kbps | 288 kbps | 230 kbps | 307 kbps |  |  |  |  |  |
| 50 | Average kbps per Channel | 422 kbps | 576 kbps | 461 kbps | 576 kbps | 461 kbps | 614 kbps |  |  |  |  |  |
| 51 | PHY DL + UL | 998.4 kbps | 1036.8 kbps | 1075.2 kbps |  |  |  |  |  |
| 52 | kbps per data symbol | 38.4 | 38.4 | 38.4 |  |  |  |  |  |
| 53 | Per cent per data symbol | 3.85% | 3.70% | 3.57% |  |  |  |  |  |

# Comparative Summary of all Considered Options

The following table provides a summary of all considered feature options with a projection of the anticipated PHY Layer throughput. Note that column H lists potential tradeoffs that may or may not need to be considered. Column I provides the specific paragraph in IEEE Std 802.16-2012 that relates to the specific feature being considered for each option.

**Table 8: Summary of all considered options**

| **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **I** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Options** | **Channel BW** | **Description** | **DL+UL PHY** | **∆ % Ref** | **∆ % Increm.** | **%/OH Symbol** | **Tradeoff** | **Reference** |
| Baseline | **1.25 MHz** | **128 FFT, PUSC, 64QAM-5/6 in UL & DL, 5 ms frame size, 1/8 cyclic prefix, 28/25 sampling factor** | **969.6 kbps** | **Ref** |   | 2.78% |   | [1] 8.4.6.1.2.1, 64-QAM 8.1.1 |
| 1.25 MHz | As above w/Optional UL PUSC  | 1036.8 kbps | 6.93% |   | 2.78% | Reduced UL guard-band | [1] 8.4.6.2.5, Table 8-275 |
| 1 | **1.00 MHz** | **As above (optional UL PUSC) with 1 MHz profile** | **748.8 kbps** | **Ref** |   | 3.85% | >ICI Compared to 1.25 MHz | [1] 12.4, Table 12-20 |
| 2 | 1.00 MHz | Sampling factor 28/25 to 57/50 | 777.6 kbps | 3.85% |   | 3.70% | >BW, <ICI | [1] 8.4.2.3 (OFDM Table 8-38) |
| 3 | 1.00 MHz | Band AMC (2 bins), 28/25 Sampling factor, 5 ms frame | 998.4 kbps | 33.3% |   | 3.85% | Less robust, mobility support | [1] 8.4.8.1 , 6.3.17, Table 8-123 |
| 4 | 1.00 MHz | Band AMC (2 bins), 57/50 Sampling factor, 5 ms frame | 1036.8 kbps | 38.5% | 3.85% | 3.70% | >BW, <ICI | [1] 8.4.2.3 (OFDM Table 8-38) |
| 5 | 1.00 MHz | Band AMC (2 bins), 144/125 Sampling factor, 5 ms frame | 1075.2 kbps | 43.6% | 3.70% | 3.57% | >BW, <ICI | [1] 8.4.2.3 (OFDM Table 8-38) |
| 6 | 1.00 MHz | As #4 above with 10 ms frame size, 57/50 Sampling factor | 1286.4 kbps | 71.8% | 24.1% | 1.49% | >latency | [1] 11.18.2, Table 11-62 |
| 7 | 1.00 MHz | As #6 above with 15 ms frame size, 57/50 Sampling factor | 1356.8 kbps | 81.2% | 5.5% | 0.94% | >latency |
| 8 | 1.00 MHz | As #7 above with 20 ms frame size, Sampling factor | 1401.6 kbps | 87.2% | 3.3% | 0.68% | >latency |
| 9 | 1.00 MHz | As #8 above with 25 ms frame size, Sampling factor | 1420.8 kbps | 89.7% | 1.4% | 0.54% | >latency |
| 10 | 1.00 MHz | As #9 above with reduced cyclic prefix from 1/8 to 1/16 | 1513.0 kbps | 102.1% | 6.5% | 0.51% | Delay spread robustness, i.e. >ISI | [1] 6.3.2.3.42, Table 6-160, 11.18.2, Table 11-62 |
| 11 | 1.00 MHz | As #1 above with reduced cyclic prefix (cp) from 1/8 to 1/16 | 835.2 kbps | 11.5% | vs. #1 |   | 3.45% | Delay spread robustness, i.e. >ISI | [1] 6.3.2.3.42, Table 6-160, 11.18.2, Table 11-62 |
| 12 | 1.00 MHz | As #3 above with reduced cyclic prefix (cp) from 1/8 to 1/16 | 1113.6 kbps | 11.5% | vs. #3 |   | 3.45% | Delay spread robustness, i.e. >ISI |

## Quantifying the PHY Layer Throughput Benefits

**Table 9: Summary of throughput enhancements for specific feature modifications**

| **Baseline: 1 MHz channel BW, 128 FFT with PUSC in DL and optional UL PUSC, with 28/25 sampling factor, and 5 ms frame size** |
| --- |
| **Feature or Attribute** | **Change or Modification** | **Notes** | **Throughput Impact****Relative to baseline** |
| Permutation | PUSC to Band AMC |  | +33.3% |
| Frame Size | Increase from 5 ms to 10 ms | Must balance with increased latency | +24.1% |
|  | to 15ms, 20ms, & 25ms | Subsequent increases will incur considerable additional latency | An additional gain of; +5.5%, 3.3%, 1.4% respectively |
| Cyclic Prefix | Reduce from 1/8 to 1/16 | Symbol OH is reduced from >11% to <6% | +11.5% |
| Sampling Factor | 28/25 to 57/50 to 144/125 | Adds 1 data symbol for each step increase from 28/25 | +3.85% and +3.70% respectively |
| Reducing Overhead | Assumptions in previous examples are: 7 DL + 4 UL + 1 TR-Gap = 12 OH symbols | 11 UL + DL OH symbols represents ~28% OH for a 5 ms frame | +3.57% to +3.85% per symbol for 5 ms frame size, reduces to ~1.5% for 10ms frame and <1% for larger frame sizes |

## Tradeoffs to Consider

The following figures help to quantify some of the tradeoffs that may need further study in discussions related to specific feature modifications that are recommended to support channel BWs less than 1.25 MHz and ultimately down to 100 kHz BW.

**Figure 2 Left:** *Shows UL + DL PHY throughput for 5, 10, 15, 20, and 25ms frame sizes,* **Right:** *Shows minimal frame dependent UL latency for unsolicited grant service for same 5 frames sizes*

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**Figure 3 Left:**  *Throughput and occupied BW for 1 MHz channel BW for sampling factors of 28/25, 57/50, and 144/125; corresponding to a subcarrier spacing of 1.12kHz, 1.14kHz, and 1.15kHz respectively,* **Right:** *Shows expected inter-carrier interference as a function of subcarrier spacing. Channel BWs down to 100 kHz will result in a subcarrier spacing in the order of 3.5 kHz.*

# References

[1] IEEE Std 802.16-2012, IEEE Standard for Air Interface for Broadband Wireless Access Systems, August 2012

[2] 16-16-0034-02-000s, IEEE 802.16s Draft System Requirements Document, <https://mentor.ieee.org/802.16/dcn/16/16-16-0034-02-000s-draft-p802-16s-system-requirements-document-srd.docx>

[3] 16-16-0037-02-000, An Evaluation of Alternatives for 1 MHz Channels, <https://mentor.ieee.org/802.16/dcn/16/16-16-0037-02-000s-evaluation-of-alternatives-for-1-nhz-channels.docx>

# Appendix I: Detailed OFDMA parameters for all 12 considered feature modifications



1. The sampling factor times the channel BW determines the ***Clock Frequency***, the only restriction provided in the standard is that the resulting clock frequency result in an integer number of samples per frame. This metric is shown in line 20 in the applicable tables. [↑](#footnote-ref-1)