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| Re: | IEEE 802.16s Project Discussion |
| Abstract | Provides an evaluation of two potential approaches for achieving channel BWs less than 1.25 MHz for Smart Grid Applications. This document expands on what has been discussed in past GRIDMAN Task Group meetings. |
| Purpose | Provides additional analysis on potential approaches and recommendations for further discussion  |
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**An Evaluation of Potential Solutions for Channel Bandwidths Less than 1.25 MHz for Smart Grid Applications**

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# Introduction

The lack of suitable spectrum has severely hampered attempts by utilities to deploy service-wide Smart Grid networks in the US. The potential to acquire 1 MHz blocks of spectrum in the 700 MHz band has gained widespread interest among utilities and has become a key driver for the development of solutions that will support channel bandwidths less than 1.25 MHz, the smallest channel BW currently supported by IEEE Std 802.16.

**Figure 1: Upper 700 MHz Band. Two ‘A Block’ 1 MHz channels are of interest to utilities**

Utilities would also very much like to have a solution that is standards-based and an amendment to IEEE Std. 802.16 appears to be the best alternative to achieve that goal. It is also reasonable to expect that WiMAX profiles based on 802.16 would quickly follow to address interoperability assurance. In consideration of the fact that small BW channels may become available in other frequency bands as well, both higher and lower, it is suggested that a standard that supports 1 MHz channels not be specific to 700 MHz but rather cover a wider range of spectrum alternatives. The VHF/UHF range of frequencies, spanning from 30 MHz to 3000 MHz has been suggested. Another upper limit that could be considered is 4940 MHz, the upper limit of the 4900-4940 MHz Public Safety band. This limit would also capture the 3650-3700 MHz portion of the recently defined 3550-3700 MHz CBRS (Citizens Broadband Radio Service) band, a frequency band currently used quite extensively for Smart Grid deployments. Nor should the channel BW options be limited to 1 MHz; having an 802.16-based solution to support channel BWs as low as 100 kHz would broaden deployment options for Smart Grid applications and increase the market potential.

A further consideration for this particular band is the availability of two 1 MHz channels. Clearly it would be desirable to have a TDD solution that supported multiple non-contiguous narrowband channels to take full advantage of the upper 700 MHz ‘A Block’ and other frequency bands for which non-contiguous small blocks of spectrum might be available.

For the purposes of this report 700 MHz will be the frequency used for any performance metric that is frequency dependent, most notably, range.

IEEE Std 802.16e-2009 already supports channel BWs down to 1.25 MHz using 128 Fast Fourier Transform (FFT). WiMAX profiles on the other hand, are only defined for channel BWs down to 3.5 MHz based on 512 FFT.

In reviewing different alternatives consistent for achieving channel BWs less than 1.25 MHz it is important to assess:

* Net channel capacity: This is the net throughput or ‘Good Put’ at the ‘Application Layer’ after accounting for all overhead factors. This particular metric can be considered the most important one given the limited channel BW.
* Number of sub-channels supported: This will impact the deployment flexibility with respect to frequency reuse and interference management
* Similarity to existing IEEE Std 802.16: To facilitate the timely development and ratification of an amendment to the current 802.16 standard, solutions closely aligned to the current standard would obviously gain broader acceptance.

Summary of Smart Grid Requirements
Since this work is directed towards an eventual amendment to IEEE Std 802.16, it is important to briefly review key Smart Grid requirements as they are quite different from broadband wireless access requirements, the original drivers for the 802.16 standard. Smart Grid requirements have been discussed in several venues referenced here: OpenSG[[1]](#endnote-1) , WiMAX Forum[[2]](#endnote-2) , SGIP PAP02 [Ref [[3]](#endnote-3)] , and Full Spectrum [Ref [[4]](#endnote-4)]. Focusing on requirements specific to Smart Grid applications can help identify features currently in IEEE Std 802.16 that may be relegated to a lower priority or perhaps dropped entirely for the purposes of facilitating a solution for channel bandwidths less than 1.25 MHz, and for reducing overhead to better optimize payload throughput or ‘Goodput’ with narrowband channels.

**Table 1: Requirements for Smart Grid Applications**

| **Feature** | **Smart Grid Requirement** | **Comments** |
| --- | --- | --- |
| UL/DL Traffic Ratio[[5]](#footnote-1) | Under normal conditions traffic will be predominantly in the UL direction, ranging from well over 10:1 in some higher density demographic venues to about 2:1 on low density rural areas 10:1 | Exceptions to this will be when it is necessary to download firmware updates in these cases DL will dominate.64QAM in UL should be a required feature, not optional |
| Duplex | TDD will ensure more efficient use of limited amount of spectrum due to degree of traffic asymmetry  | Can consider dropping FDD as a requirement |
| Average Packet Payload Size | Dominant traffic will be payloads from 60 to 300 Bytes | Exceptions for firmware DLs which can involve very large payloads requiring fragmentation |
| Mobility | A low priority requirement. Capability to support modest mobility is desirable, ≤ 30 km/hr perhaps. Nomadic support is mandatory. | Important to maintain the capability but opens the door for Band AMC permutation which is not considered as well-suited to mobility as PUSC. E.g. can reduce the velocity requirements, perhaps 30 km/hr or less  |
| BS to BS Handoff | Not necessary at high velocity, see above.  | Mandatory to support handoff to alternate BS in the event of equipment failure at primary BS within a specified time interval. |
| Services & QoS | Data – High priorityVideo – Necessary, but not highest priorityVoice –Low priority | Video will be primarily for critical infrastructure surveillance and disaster recovery situations. Sub-channel BW will determine quality. |
| Latency | Some SG use cases have stringent latency requirements and some SG subnetworks, such as AMI, will have a very high number of active end-points[[6]](#endnote-5) (actors) | Leads to a trade-off between large & small frame sizes. High numbers of end-points will add to queueing delays. Firmware DLs have modest latency requirements, but the need for fragmentation with very large payloads will add to latency  |
| Range | The service areas for utilities often encompass thousands of square miles in rural areas with few and widely spaced customers and utility infrastructure.  | Need provision for different TR gaps to match range requirements.Support for MIMO Matrix A (Tx Diversity) |
| Capacity Requirements | Generally low, but could be challenged in high density urban areas, due to channel BW limitation.Urbanized area deployments would tend to be ‘*capacity-constrained’* rather than ‘*range-constrained’.* | 64QAM with 5/6 coding in both UL and DL.MIMO Matrix B (Spatial Multiplexing)Reuse 1 will be desirable for high density venues |
| Channel Quality | With channel BWs less than 1.25 MHz, propagation characteristics it is reasonable to expect similar propagation over entire BW | Not necessary to have multiple channel quality detects, 1 is sufficient to support AAS |

# Assessing Key Performance Metrics and Supported Features

Before describing and providing an analysis of the various options that have been suggested, it is informative to describe the methodology used to estimate key performance attributes.

## Channel Capacity and Average Spectral Efficiency

To determine channel capacity for comparative purposes it is necessary to have a measure of the average spectral efficiency over the coverage area for a specific channel. Once arrived at, the average spectral efficiency can be used to determine:

1. Average data rate per data subcarrier (subcarrier BW will be a function of FFT)
2. Average PHY layer throughput per sub-channel which is dependent on the number of data subcarriers per sub-channel (total subcarriers per sub--channel minus pilot and null sub-carriers)
3. Average sector PHY throughput based on number of sub-channels per sector
4. Net application layer throughput or ‘Goodput’ is determined by subtracting the MAC OH and other higher layer packet OH from the PHY layer throughput. As shown later, this OH is dependent on the payload packet size and measures taken to reduce the impact of packet headers.

With adaptive modulation and coding (AMC), as is supported with IEEE Std 802.16 and WiMAX, the spectral efficiency varies from 5 bps/Hz with 64QAM and 5/6 coding for subscriber stations (SS) closest to the base station (BS) to the most robust 0.2 bps/Hz for QPSK with 1/2 coding and 6 repetitions for SSs at the edge of the cell coverage area. The modulation and coding scheme supported in any region of the coverage area is dependent on the signal to noise ratio (SNR) which is summarized in Table 1[[7]](#footnote-2).

**Table 2: Signal to Noise Ratio vs. Modulation and Coding Scheme**

| **Mod/Coding[[8]](#footnote-3)** | **Spectral Efficiency** | **Signal to Noise Ratio (SNR)** |
| --- | --- | --- |
| *QPSK 1/2 Rep 6* | *0.2 bps/Hz* | *-4.3 dB* |
| *QPSK 1/2 Rep 4* | *0.3 bps/Hz* | *-2.5 dB* |
| *QPSK 1/2 Rep 2* | *0.5 bps/Hz* | *0.5 dB* |
| QPSK 1/2 Rep 1 | 1.0 bps/Hz | 3.5 dB |
| QPSK ¾ | 1.5 bps/Hz | 6.8 dB |
| 16QAM ½ | 2.0 bps/Hz | 8.9 dB |
| 16QAM ¾ | 3.0 bps/Hz | 13.0 dB |
| 64QAM ½ | 3.0 bps/Hz | 13.9 dB |
| 64QAM 2/3 | 4.0 bps/Hz | 17.3 dB |
| 64QAM ¾ | 4.5 bps/Hz | 18.5 dB |
| 64QAM 5/6 | 5.0 bps/Hz | 20.3 dB |

The expected propagation path loss for the environment in question can be used to estimate the average spectral efficiency over the expected area of coverage. The path loss, PL, models the attenuation of the signal in terms of the fraction of the received power to the transmitted power measured at the respective antennas. The deterministic component of the path loss, PLd, is a function of the path distance, *d*, in meters between the transmitter and the receiver. Widely accepted models in the wireless propagation community predict an exponential attenuation as a function of distance according to a path loss exponent, *n*. In non-line of sight environments the degree of exponential fading increases after a certain breakpoint distance, *d1*.  The breakpoint path loss model below (shown on a dB scale) captures this relationship:



*PL0* = 20log10(2π*d0*/ *λ*); where *λ* = wavelength, *do*= 1 m, d1 is dependent on deployment conditions and is typically a value between 50 m and 200 m

Basically for a transmitting antenna at a reasonable height above ground we can expect free space path loss for the first 50 to 200 m before encountering the obstacles that would impede the signal in a non-line-of-sight (non-LoS) deployment. Section 5 in the above cited reference provides a more detailed description of the various path loss models that can be considered for Smart Grid deployments. For a ‘flat terrain with light tree density’, the ‘Modified Erceg-SUI’ model predicts an excess loss factor, *n* ~ 4.

**Figure 2: Path loss at 700 MHz**

The following curves assumes a modulation and coding scheme (MCS) from 64QAM with 5/6 coding to QPSK with 1/2 coding and 2 repetitions (QPSK-1/4) for four different propagation conditions.



**Figure 3: Spectral efficiency vs. range relative to the maximum range denoted by ‘R’**

Putting this information in terms of the expected coverage area provides an assessment of the percentage of coverage area covered by each MCS. The dashed lines represent a curve intended to approximate the MCS over the entire coverage area. Taking the integral under the respective curves provides an estimate of the average spectral efficiency assuming a uniform distribution of subscriber stations with similar propagation characteristics throughout the coverage area.



**Figure 4: Spectral efficiency versus percentage of maximum coverage area**

It also assumed for this and future calculations that the same MCS is applicable to both DL and UL. 1x1 MIMO is also assumed. Taking the area under the respective curves we find:


**Figure 5: Average spectral efficiency for varied propagation conditions**

It must be noted that different path loss models will predict different path loss factors for varied propagation environments and varied relative antenna heights for the base and the subscriber station respectively. The Erceg-SUI model has been shown to be a fairly good predictor for suburban and rural areas in the 2 GHz range. For a relatively flat suburban area with light tree density, a moderately high BS antenna and a SS antenna in the 6-10 meter range a loss factor *n* ~ 4 is predicted by this model resulting in an average spectral efficiency of 1.80 bps/Hz. For a less propagation-friendly environment, hilly or heavy tree density or a more urbanized environment *n* will range between 4 and 5. For the analysis that follow I will use the value 2.0 bps/Hz which reflects an average rural or suburban environment. Note that this is equivalent to a MCS of 16QAM with 1/2 coding.

**Impact of MIMO:** As previously noted single input single output (SISO) antenna configuration is assumed. This is not intended to suggest that higher order MIMO antenna configurations would not be applicable, they would indeed be applicable and in many cases highly desirable to increase capacity and range or increased cell-edge availability.

## Permutation: PUSC vs Band AMC

The permutation choice will also have an impact on net channel capacity. Partially Used Sub-Channel (PUSC) is commonly used in today’s deployments since it is considered the best choice for mobile applications. A brief summary of the attributes commonly accepted for PUSC and AMC are:

* **PUSC**
	+ Asymmetric in downlink and uplink
	+ Frequency diversity
	+ Interference averaging
	+ Can support universal frequency reuse
	+ Best for mobility applications
* **AMC**
	+ Symmetric in downlink and uplink
	+ Frequency coherence for loading and beamforming
	+ Multiuser diversity
	+ No interference averaging
	+ Better for fixed and nomadic applications

All WiMAX profiles based on 802.16 require PUSC permutation for its support of mobility with AMC permutation designated as optional. Mobility however, is not a high priority for Smart Grid applications. It can also be argued that the frequency diversity and interference averaging benefits of PUSC are greatly mitigated with narrow BW channels. With respect to channel capacity, AMC offers a higher net PHY capacity, especially in the UL which, as has been noted earlier, is the dominant traffic direction for Smart Grid applications. This is summarized in the following table, which for reference includes values for a 5 MHz channel with a 512 FFT.

**Table 3: Comparing PUSC with AMC for capacity assuming a 28/25 sampling factor**

|  |  |  |  |
| --- | --- | --- | --- |
| **Channel BW** | **5 MHz** | **1.25 MHz** | **1 MHz (Projected)** |
| Sub-Carrier Spacing | 10.94 kHz | 10.94 kHz | 8.75 kHz |
| Total # of Subcarriers (FFT) | 512 | 128 | 128 |
| PUSC DL Data Sub-Carriers | 360 | 72 | 72 |
| PUSC UL Data Sub-Carriers | 272 (288 Optional) | 64 (72 Optional) | 64 (72 Optional) |
| AMC DL Data Sub-Carriers | 384 | 96 | 96 |
| AMC UL Data Sub-Carriers | 384 | 96 | 96 |
| **AMC DL Capacity Advantage** | **6.67 %** | **33.3 %** |
| **AMC UL Capacity Advantage** | **41.2 % (33.3 % w/Optional PUSC UL)** | **50.0 % (33.3 % w/Optional PUSC UL)** |

As the table indicates the throughput advantage of AMC over PUSC is considerable, especially so with the smaller channel BW. Tables 8-274 and 8-275 in the 802.16 standard [Ref [[9]](#endnote-6) ] describes optional UL parameters for PUSC which are also shown in the table. The optional parameters for UL PUSC uses the same number of pilots but reduces the guard null subcarriers to increase the number of data subcarriers. With the emphasis on UL capacity for Smart Grid networks, the optional UL parameters for PUSC may be adopted as mandatory in the development of a standard for channel BWs less than 1.25 MHz.

For a complete comparison between PUSC and Band AMC it is also necessary to consider interference management, support for advanced antenna systems, and mobility support and how applicable these attributes are for narrower BW channels as opposed to the wider BW channels specified for WiMAX. In the absence of further quantitative information, it is my view that both Band AMC and PUSC should be supported in an amendment to IEEE 802.16 for channel BWs less than 1.25 MHz.

## Frequency Reuse and Interference Margin

Frequency reuse and its impact on interference management is always an important consideration in a multicellular deployment. The limited number of sub-channels available with a single 1 MHz spectrum block presents limitations to the options for frequency reuse. The following illustration shows three potential reuse schemes. The numbers in the cell sectors refer to ‘sub-channel groups’. If for example there are 6 available sub-channels, each ‘sub-channel group’ comprises 2 sub-channels with (1, 3, 3) reuse. For deployment with reuse (3, 3, 3), at least 9 sub-channels would be required. Reuse (1, 3, 1) or what is commonly referred to as ‘reuse 1’ is supported by 802.16 by using fractional frequency reuse (FFR). With FFR the inner portion of any sector in the cell is supported with reuse 1 while the outer portion uses reuse 3. It has been suggested that PUSC due to its greater frequency diversity compared to Band AMC is better suited for reuse 1 than AMC [Ref [[10]](#endnote-7)]. An 802.16 working group document [Ref [[11]](#endnote-8)] ties PUSC with Reuse 1 but not to AMC. Nevertheless, for the purposes of this exercise it is assumed that reuse 1 can be supported with either PUSC or Band AMC, and that about one-half of the sector area can support reuse 1. The net sector or cell capacity gain therefore would be approximately two-times over reuse 3.



**Figure 6: Three potential reuse patterns in a multicellular deployment**

With (1, 3, 3)[[12]](#footnote-4) reuse there are three dominant interferer paths and under worse case conditions, (SS at the cell edge) the path length for the interfering signals is about twice that of the desired signal. Reuse (3, 3, 3) provides greater interference protection but requires 9 unique sub-channel groups which may not be realistic with a 1 MHz channel BW as it significantly reduces the sector capacity. With fractional frequency reuse (1, 3, 1) there is a greater number of potential interferers, thus necessitating higher interference margin, especially in environments that are more propagation friendly.

**Table 4: Reuse and Interference Margin**

|  | **Propagation Environment** |
| --- | --- |
|  |  ***n* = 2** | ***n* = 3** | ***n* = 4** | ***n* = 5** |
| **Reuse** | **Applicable Interference Margin** |
| (1,3,3) | ~3.5 dB | ~2.5 dB | ~2 dB | ~1.5 dB |
| (3,3,3) | < 1 dB | < 0.25 dB | < 0.1 dB | < 0.1 dB |
| (1,3,1) | ~5 dB | ~2.5 dB | ~2 dB | ~1.5 dB |
| Approximately 50 % of sector will support (1,3,1) reuse the remaining area will have effective reuse of (1, 3, 3) |

As the table indicates, a more conservative reuse as with (3, 3, 3) requires less interference margin which subsequently translates to greater range potential. The tradeoff is lower capacity per sector.

With respect to interference margin there will also be some differences between PUSC and Band AMC permutations. The frequency diversity of PUSC would make it less susceptible to CCI, especially with reuse (1, 3, 1). I have not however, found any good analysis, simulations, or actual field results comparing the two permutation approaches from the standpoint of interference. This perhaps, is due to the fact that, up to now, broadband mobility support has been the highest priority for WiMAX/802.16 deployments and with PUSC having a clear advantage for broadband mobile applications, little attention has been paid to Band AMC.

## Higher Layer Overhead

 Minimizing overhead contributions will be key to achieving a net channel capacity sufficient to meet Smart Grid requirements with channel bandwidths limited to 1.25 MHz or less. PHY layer contributions; frame OH, DL and UL MAP, coding, etc., will be discussed in a review of the OFDMA parameters for the specific alternatives for sub-1.25 MHz channels. From an application perspective however, higher level overhead factors must be taken into account as well. Payloads for most Smart Grid use cases are quite small while the various headers remain fixed. The impact of this overhead can be significant. The following figure shows the various sources of overhead (OH) for the MAC and higher layers. Bear in mind that the MAC ‘payload’ may include additional sub-headers and multiple Service Data Units (SDUs) or SDU fragments. These sub-headers include; grant management sub-header, fragmentation sub-header, and packing sub-header. In any case the diagram should help highlight the importance of these higher OH factors.



**Figure 7: Contributors to Higher Layer Overhead (OH)**

Ignoring MAC Payload sub-headers, the OH contributions are as follows:

* IP Header: IPv4 = 20 Bytes, IPv6 = 40 Bytes
* UDP (User Datagram Protocol) = 8 Bytes, TCP (Transmission Control Protocol) = 20 Bytes
* MAC: 10 Bytes total (MAC Header = 6 Bytes, CRC Footer (Cyclic Redundancy Check) = 4 Bytes)
* Total higher level OH: 38 to 70 Bytes, % OH depends on payload size

The following table provides an OH summary for various payloads from 64 Bytes to 1900 Bytes.

**Table 5: MAC and Higher Layer OH**

| **Payload** | **UDP/IPv4** | **UDP/IPv6** | **TCP/IPv4** | **TCP/IPv6** |
| --- | --- | --- | --- | --- |
| 64 Bytes | 30.9 % | 43.4 % | 39.0 % | 48.9 % |
| 200 Bytes | 12.8 % | 19.8 % | 17.2 % | 23.6 % |
| 1000 Bytes | 3.2 % | 5.1 % | 4.3 % | 6.2 % |
| 1900 Bytes | 1.9 % | 3.0 % | 2.6 % | 3.6 % |

An IP packet packing protocol similar to Mikro Tik Packet Packer Protocol (M3P) can be used to group smaller packets into packets averaging 1000 to 1500 Bytes. Combined with Packet Header Suppression (PHS), upper layer OH should be able to be kept to a tolerable range of under 6 %.

## Link Budget and Range

For suburban and rural environments, the Erceg-SUI model[[13]](#endnote-9) has gained wide acceptance as a suitable path loss model. Although the model was derived based on field tests in the 2000 MHz range, subsequent modifications proposed with respect to the frequency dependence of the model, described in SGIP-PAP02[[14]](#endnote-10), has extended the frequency range over which it can be considered applicable (further details are included in Appendix I).

For path loss analysis, the Erceg-SUI model defines 3 terrain types with the following characteristics and respective path loss factor, *n*, as shown.

* Type A Terrain: Hilly with moderate to heavy tree density, *n*=4.7
* Type B Terrain: Hilly with light tree density or flat with medium to heavy tree density, *n*=4.26
* Type C Terrain: Flat with light tree density, *n*= 4.0



**Figure 8: Range Projection versus Link Budget at 700 MHz-**

The Link budget, in most cases, will be limited by uplink system gain. With fixed services being a higher priority use case, subscriber stations, especially those at or near the cell edge, will not have the same EIRP constraints that typically prevail for mobile applications.

The following table provides some link budget estimates for two typical deployment scenarios[[15]](#footnote-5) assuming (2x2) MIMO at the base station.

**Table 6: Projected Link Budget for a 157.5 kHz and 52.5 kHz Sub-Channel BW Respectively[[16]](#footnote-6)**

| **Parameter** | **DL** | **UL** | **DL** | **UL** |
| --- | --- | --- | --- | --- |
| Tx Power (Watts) | 10.0 W | 1.0 W | 10.0 W | 2.0 W |
| Tx Power (dBm) | 40.0 dBm | 30.0 dBm | 40.0 dBm | 33.0 dBm |
| Tx Antenna Gain | 15.0 dBi | 12.0 dBi | 15.0 dBi | 12.0 dBi |
| Number of Tx Antennas | 2 | 1 | 2 | 1 |
| Cable Loss | 1.0 dB | 1.0 dB | 1.0 dB | 1.0 dB |
| Tx Diversity Gain | 3.0 dB | 0.0 dB | 3.0 dB | 0.0 dB |
| EIRP | 57.0 dBm | 42.0 dBm | 57.0 dBm | 45.0 dBm |
| Rx Antenna Gain | 12.0 dBi | 15.0 dBi | 12.0 dBi | 15.0 dBi |
| # Rx Antennas | 1 | 2 | 1 | 2 |
| Rx Diversity Gain | 0.0 dB | 3.0 dB | 0.0 dB | 3.0 dB |
| Rx Noise Figure | 5.0 dB | 4.0 dB | 5.0 dB | 4.0 dB |
| (AWGN) Thermal Noise | -174.0 dBm/Hz | -174.0 dBm/Hz | -174.0 dBm/Hz | -174.0 dBm/Hz |
| Required S/N QPSK-1/4  | 0.5 dB | 0.5 dB | 0.5 dB | 0.5 dB |
| Sub-Channel BW | 157.5 kHz | 157.5 kHz | 52.5 kHz | 52.5 kHz |
| Rx Sensitivity/Sub-channel | -116.5 dBm | -117.5 dBm | -121.3 dBm | -122.3 dBm |
| **System Gain** | **185.5 dB** | **177.5 dB** | **190.3 dB** | **185.3 dB** |
| Fade Margin (Fast Fade & Log Normal) | 8.0 dB | 8.0 dB | 8.0 dB | 8.0 dB |
| Interference Margin | 2.0 dB | 2.0 dB | 2.0 dB | 2.0 dB |
| Penetration Loss | 0.0 dB | 0.0 dB | 0.0 dB | 0.0 dB |
| **Total Margins** | **10.0 dB** | **10.0 dB** | **10.0 dB** | **10.0 dB** |
| **Link Budget** | **175.5 dB** | **167.5 dB** | **180.3 dB** | **175.3 dB** |

Based on the above, 40 miles range would be attainable in propagation-friendly environments such as Type C Terrain but limited to approximately 20 miles in a Type A terrain.

In addition to the link budget, for TDD deployments the TR gap will have to be adjusted to a value consistent with the range objective. The following table shows the roundtrip delay for a range from 5 miles to 50 miles with an assessment for the regions where different ranges may be applicable.

**Table 7: TTG/RTG Gap to meet specific range objective**

| **Where applicable ….** | **Range Objective** | **Roundtrip Delay** |
| --- | --- | --- |
| Typical for urbanized areas | 5.0 mi | 8.0 km | 53.7 μs |
| Typical for average suburban area | 10.0 mi | 16.1 km | 107.4 μs |
| Average rural area | 20.0 mi | 32.2 km | 214.7 μs |
| Goal for low density rural areas  | 40.0 mi | 64.4 km | 429.4 μs |
| Not likely unless Point-to-Point LoS | 50.0 mi | 80.5 km | 536.8 μs |

## Latency

Latency or delay is another key performance metric that will be important for many Smart Grid use cases and will have to be considered in assessing the trade-offs between the net channel throughput and the end-to-end delay, when evaluating the parameters necessary to achieve channel bandwidths less than 1.25 MHz.

There are four key components to the end-to-end delay or latency in a wireless packet-based network:

1. **Propagation Delay:** The propagation time is 3.34 microseconds per kilometer (5.37 μs/mi) and for terrestrial networks, even with multiple HARQ retransmissions, will not be a significant contributor to latency. There may be exceptions with multiple links but generally should be small enough to ignore.
2. **Processing Delay:** This describes the time to process packet headers, routing functions, security, link error control, mobility management, transfer of network packets into frames, etc. From an IEEE Std 802.16 perspective we only need to be concerned with the functionality of the Data Link or MAC layer and not layers 3 and above.
3. **Transmission Delay:** This component is tied to the net channel or sub-channel capacity, basically how many bytes per second net of channel overhead or ‘Goodput’.
4. **Queuing (or scheduling delay) Delay**: This component will come into play as the traffic loading on the channel or sub-channel approaches its capacity. Under these congested conditions multiple packets will be competing for access to a limited resource and there is a distinct probability that any given packet will or will not gain access to the link within a specific time interval. The resulting delay in this scenario will generally be the dominant contributor to the end-to-end latency. QoS and priority levels will play a key role in ensuring that latency-sensitive traffic has a higher probability of gaining access to the congested channel. This topic was discussed extensively in SGIP-PAP02[[17]](#endnote-11) and models suggested for assessing the probability of meeting specific latency requirements.

In a lightly loaded channel, i.e. not congested, latency will be directly related to Frame Size. The DL latency, independent of QoS type, will generally take 2 frames [Ref [[18]](#endnote-12)][[19]](#footnote-7) with a possible worst case scenario taking up to 4 frames[[20]](#footnote-8). The end-to-end UL latency is dependent on service type and would be as low as 2 frames for Unsolicited Grant Service (UGS) and up to 9 frames[[21]](#footnote-9) for BE and nrt service flow types.

An Analysis of Potential Solutions for Channel BWs Less than 1.25 MHz

Discussions within the IEEE 802.16 working group regarding the approaches that could or should be considered to achieve channel bandwidths less than 1.25 MHz began in early 2015 and continued in following working group meetings in 2015 and the Atlanta meeting in January 2016. A PAR was finally approved at the Macau meeting in March 2016. In the aforementioned meetings, two alternative approaches for narrowband channels have been discussed and, of course, now with an approved PAR, can serve as a basis for more detailed discussion subsequently leading to a consensus view on the preferred solution(s) and identification on what modifications are required to IEEE Std 802.16 to support the preferred solution(s).

The two alternative approaches can be broadly characterized as follows:

* **Alternative 1: 128 FFT with Band AMC permutation** [Ref [[22]](#endnote-13)]
* **Alternative 2: 512 FFT with PUSC permutation** [Ref [[23]](#endnote-14)]

At the Atlanta meeting, in Jan 2016, both of the above solutions were briefly reviewed with additional details based on an early analysis by this author [Ref [[24]](#endnote-15)]. The following pages are intended to provide further details on these two alternative approaches. The expanded details are based on; a) conversations and e-mails with proponents and\or entities that initially suggested the respective alternative, 1 or 2, b) my own understanding of the tradeoffs based on my experience and familiarity with WiMAX and IEEE Std 803.16 and, c) discussions with others with known expertise of the 802.16 standard.

In the discussion that follows, I have attached the name of the entity that originally suggested the respective alternative for narrowband channels, Full Spectrum Inc. for ‘Alternative 1’, and Runcom for ‘Alternative 2’. The intent is to provide a more complete description of these two alternatives, with the information that is currently available to help kick-start the discussions going forward. I have also taken the liberty of offering some variations on these two alternatives for consideration in the ongoing GRIDMAB Task Group discussions.

## Alternative 1: 128 FFT with Band AMC, initially suggested by Full Spectrum[[25]](#footnote-10)

Full Spectrum Inc. uploaded an alternative solution [Ref [[26]](#endnote-16)] to support a 1 MHz channel BW, or less, for Smart Grid networks. The discussion that follows includes information in addition to what was contributed, based on discussions with Full Spectrum staff[[27]](#footnote-11), material received after the meeting and information from their website.

It is important to note that Full Spectrum has been delivering and has extensive deployments in frequency bands below 1000 MHz with channel BWs less than 1.25 MHz. The product solutions known as FullMAX use a fast Fourier transform (FFT) of 128 and TDD duplexing. Full Spectrum has also taken overhead (OH) reduction measures to help enhance net throughput.

The following tables provide OFDMA details about the Full Spectrum alternative for a channel bandwidth of 1.0 MHz. The FullMAX options span a frame size from 5 ms to 25 ms.

**Table 8a: FullMAX OFDMA Parameters and PHY Data Rate per Slot**

**Explanatory notes for Table 6a:**

* Columns: All of the columns assume AMC permutation, the columns denoted by ‘a’ represent AMC with 2 Bins over 3 symbols, and those denoted by ‘b’, AMC with 1 Bin over 6 symbols resulting in 6 or 12 sub-channels respectively. 5, 10, 20, 25 ms frame sizes are shown in the table. FullMAX also supports 12.5 ms frame sizes which is not shown in the table
* Row numbers in red highlighted in gray are values from information originally submitted to IEEE, other rows provide additional details
* Row 14: For comparative purposes the TR gap is selected to be 1 symbol for all variations even though it may not be sufficient to support a 40 mi range
* Row 17: Shows the supported range with a single symbol for the TR-Gap
* Row 18: Shows the required number of symbols to support a range ≥ 40 miles (64.4 km) which would generally only be applicable in propagation-friendly environments.
* Rows 32 and 33: The DL and UL data symbols are selected to provide an uplink bias to the direction of traffic in the order 1.5 to 1.7 to 1, a value typical for a Smart Grid deployment.
* Rows 40 and 41: Shows the peak and cell-edge rate per slot for the PHY layer
* Row 43: Shows the ‘average’ rate per slot based on a coverage area with a path loss factor, n ~4.3, applicable for a ‘Type B’ suburban environment as defined by the Erceg-SUI path loss model.

The following table provides the anticipated UL and DL PHY rate per sector and per cell for reuse (1, 3, 3) and reuse (1, 3, 1). Note that the reuse 1 benefit over reuse 3 is assumed to be 2x, not 3x to account for fractional frequency reuse in the outer portions of the coverage area for interference management in a multi-cellular deployment.

**Table 8B: FullMAX PHY Rate per Sector and per Cell for Reuse (1, 3, 3) and (1, 3, 1)** 

The following figure summarizes the FullMAX data rates per cell at the PHY layer in graphical form for reuse (1, 3, 3) and reuse (1, 3, 1).



**Figure 9: UL & DL PHY Data Rate for Full Spectrum Solution for Reuse (1, 3, 3) and (1, 3, 1)**

### PHY Rate at Cell Edge and Deployment Considerations

In the above table and charts we show a cell edge PHY rate based on an estimated average spectral efficiency of 2.0 bps/Hz, a value arrived at using the approach described earlier for a coverage area with propagation conditions consistent with a path loss factor, *n* ~ 4.3.

It is important to note that the range is define by a link budget which, in turn, has a defined fade margin estimated to ensure a specific availability, typically 99 % or higher. That said, the cell-edge PHY rate would only be experienced 1 % of the time, the same can be said for the ‘Average’ PHY rate. Whereas 99 % of the time the cell-edge and average data rates would be somewhat higher.

It is also important to remember that the average spectral efficiency used in the table above assumes similar propagation characteristics over the entire coverage area and uniformly distributed end-points or subscriber stations with similar Tx and Rx characteristics. For a mobile network where emphasis is on DL traffic and mobile handheld subscriber stations that have limited EIRP due to lower antenna gain and lower TX power, the link budget and range is typically limited by the UL system gain. In a deployment for Smart Grid applications however, UL traffic is dominant and end-points are predominantly fixed rather than mobile or portable. Therefore, in a typical deployment, options can be considered to further enhance the UL channel capacity from the estimated values shown in the above tables. Namely:

* End-points at the cell edge or in other weak signal areas within the coverage area can be limited to a single sub-channel rather than 2 or 4 sub-channels. This increases the UL power spectral density (PSD) by 3 or 6 dB respectively.
* Fixed end-point devices in high path loss locations can be configured with higher EIRP by using a higher gain antenna and/or higher power Tx amplifier and end-point antennas can be mounted higher above ground level for lower path loss.

There will still be some isolated cases where higher Tx powers would not be applicable. These might be portable devices used by a mobile workforce that under certain conditions will be required to connect to the Smart Grid network. In these cases, EIRP will be constrained by human safety exposure considerations, low omnidirectional antenna gain, and battery limitations.

### Goodput for FullMAX Solution

With respect to channel capacity, what is of greatest interest is the available throughput at the application layer not the PHY Layer. The ‘Goodput’ is defined as the effective capacity at the application layer and, as described earlier, the upper layer OH can be considerable for small sized payloads that are typical for a Smart Grid network, approaching 40% or more with packets less than 100 bytes. With packet packing and payload header suppression (PHS) the upper OH should be manageable with levels of 6% or less. This value is assumed in the following table.

**Table 8C: Application Layer Throughput (aka Goodput) with PHS and Packet Packing**

### Other Attributes for Full Spectrum Alternative

These include:

* The Full Spectrum alternative includes several options for reducing MAP overhead (OH) as described in their March 23, 2015 submission with further updates in a February 25, 2016 submission [Ref [[28]](#endnote-17)]
* Preamble On or OFF: When OFF, GPS can be used for synchronization, preamble OFF frees up a symbol that can be used for data
* Multi-channel operation with non-contiguous small BW channels
* In addition to Band AMC, PUSC can also supported
* Measures to enhance UL system gain and thus UL throughput as described earlier for subscriber stations located in locations with high path loss
* QoS: The Full Spectrum alternative supports; Unsolicited Grant Service (UGS), real time Polling service (rtPs), non-real time Polling service (nrtPs), and Best Effort (BE). Within the same scheduling type, FullMAX offers 7 priority levels. *Note: This will be a key attribute when the sub-channel is in a congested state.*

**Table 8D: Bytes per Slot for Different Modulation and Coding Schemes**

|  |  |  |
| --- | --- | --- |
| **Modulation Coding Scheme** | **Spectral Efficiency** | **# Bytes per Slot** |
| **QPSK-1/2 2 Repetitions** | 0.5 bps/Hz | 3 bytes/slot |
| **QPSK-1/2** | 1.0 bps/Hz | 6 bytes/slot |
| **QPSK-3/4** | 1.5 bps/Hz | 9 bytes/slot |
| **16QAM-1/2** | 2.0 bps/Hz | 12 bytes/slot |
| **16QAM-3/4** | 3.0 bps/Hz | 18 bytes/slot |
| **64QAM-2/3** | 4.0 bps/Hz | 24 bytes/slot |
| **64QAM-3/4** | 4.5 bps/Hz | 27 bytes/slot |
| **64QAM-5/6** | 5.0 bps/Hz | 30 bytes/slot |

### Possible Variation on Solution Suggested by Full Spectrum

One variation that may warrant further discussion in the development of an amendment to IEEE Std 802.16 is an adjustment (or perhaps an option) to the sampling factor, from 28/25 to 57/50. This change increases the clock frequency from 1.12 kHz to 1.14 kHz thus increasing the subcarrier spacing for a 1 MHz channel BW from 8.75 kHz to 8.91 kHz and the occupied spectrum from 945.000 kHz to 961.875 kHz. Depending on the frame size, it also adds 1 to 3 symbols per frame. These added symbols can be used for an increased TR gap to support an increased range or for added channel capacity. It should be noted that 57/50, was originally specified [Ref [[29]](#endnote-18)] in IEEE Std 802.16 for channel BWs that are a multiple of 2 MHz.

Full Spectrum has provided the following response related to increasing the clock frequency to 1.14 kHz:

* *Suggested that 1.14 MHz sampling clock does add capacity but a couple of issues need to be considered: Support of the applicable FCC Spectrum Mask (e.g., FCC Part 27   for the Upper 700 MHz A Block): the additional spectrum used (961.875 kHz instead of 945.000 KHz) may make it more difficult to pass FCC at the same TX power level.*
* *FullMAX currently require the number of samples per frame to be an integer multiple of 140. If we follow this rule with 1.14 MHz sampling clock, we are unable to align the frame size with the currently supported frame durations. New frame durations can be easily added but TDD frame synchronization at the BS currently requires the number of TDD frames per second to be an integer. This is because the TDD frame at the BS is synchronized to a 1 PPS signal derived from a GPS module. The integer number of frames per second requirement could be relaxed if we modify our TDD frame synchronization scheme to be done every configurable number of seconds and not necessarily at every second.*

FCC Part 27 is in the Appendix of this document to facilitate further analysis of a 1.14 kHz clock rate versus 1.12 kHz.

## Alternative 2: 512 FFT with PUSC initially suggested by Runcom[[30]](#footnote-12)

Runcom offered an alternative solution for 1 MHz channels at the March, 2015 IEEE 802.16 Working Group Meeting. The ODMA parameters for the Runcom alternative is summarized in the following table which has been excerpted from the Runcom IEEE submission[[31]](#endnote-19) . This alternative has as its starting point a 5 MHz channel BW with a sampling frequency of 5.60 MHz. Dividing the sampling frequency by two to 2.80 MHz with an increased frame size of 10 ms provides a 2.5 MHz channel BW with a sub-carrier spacing of 5.47 kHz comprising 15 sub-channels in the DL and 18 sub-channels[[32]](#footnote-13) in the UL with PUSC permutation. To scale to a 1 MHz channel BW an RF filter is employed to pass a reduced number of sub-carriers, 169, and a reduced number of sub-channels, in this case, 6 in the DL and 7 in the UL. The increased frame size maintains the total number of symbols at 48.

The MAP would only allocate data to the subcarriers within the desired 6 DL sub-channels and 7 UL sub-channels. Similarly, as per Runcom, the preamble would be scaled by 40 % rather than using the entire 2.5 MHz BW.

 **Table 9: Runcom Suggested Alternative for 1 MHz Channels**

|  |  |
| --- | --- |
| **Nominal Channel Bandwidth** | **1 MHz** |
| Sampling factor | 28/25 |
| Sampling frequency (MHz) | 2.8 |
| FFT size | 512 |
| Subcarrier spacing (kHz) | 5.47 |
| Subchannels | 6 DL |
| Actual Bandwidth (centered on nominal channel) | 918.75 kHz DL |
| Frame Size | 10 ms |
| Useful symbol time (µs) | 182.86 |
| For CP ratio = 1/8 | OFDMA symbol time (µs) | 205.72 |
| FDD | OFDMA Symbols per 10 ms frame | n/a |
| Idle time (µs) | n/a |
| TDD | TR Gap Symbols | 1 |
| OFDMA Symbols per 10 ms frame | 47 |
| TTG + RTG (µs) | 331.42 |

A variation on the Runcom alternative was received via e-mails and discussions on a telephone call[[33]](#footnote-14). For this alternative solution the clock or sampling rate is reduced by a factor of 5 and the frame rate increased to 25 ms compared to a 5 MHz channel BW. The reduced clock frequency reduces the subcarrier spacing to 2.19 kHz. The number of DL sub-channels is maintained at 15 and the UL sub-channels at 18. With the 25 ms frame size, the number of symbols is maintained at 48.

In the discussions that follow I have used the designations; Runcom-10 or RC-10 for the 1/2 sampling clock solution and Runcom-25 or RC-25 for the 1/5 sampling clock solution.

### Runcom 1/2 Clock Solution (Runcom-10 or RC-10)

Before providing further details on the OFDMA parameters and anticipated channel data rates for the two Runcom approaches, it is important to share my understanding of Runcom-10. With a 2.5 MHz channel BW as a starting point with an FFT of 512 and PUSC, there would be 15 DL sub-channels, each comprising 24 data subcarriers and 4 pilot subcarriers per symbol, generated from a total of 420 used subcarriers as shown in the following table. Due to the frequency diversity of PUSC, each of the subcarriers in each sub-channel would span, on average, a frequency range of approximately 2000 kHz. Simply passing this through a 1 MHz wide filter would result in 15 sub-channels each with a reduced number of data and pilot sub-channels, not 6 sub-channels as shown in the preceding table.

This alternative, in my view, would entail a permutation scheme which could be similar to PUSC but differ somewhat from IEEE Std. 802.16. With the Runcom suggested solution, 169 sub-carriers (168 used for pilots and data and 1 DC subcarrier) of the 512 total sub-carriers would fall within a 924 kHz bandwidth. The permutation scheme via the MAP would then allocate data and pilot subcarriers only to the 168 selected subcarriers within the 924 kHz bandwidth. All other sub-carriers would be unused, they would effectively be null subcarriers. The 168 **used** subcarriers would be sufficient to support 6 DL sub-channels with 28 subcarriers per sub-channel (24 data subcarriers and 4 pilots per sub-channel). The following table provides a summary of my understanding of this approach. The appendix includes a further description of a DL PUSC sub-carrier allocation.

**Table 10: Runcom 1/2 Clock Solution (RC-10) Compared to IEEE Std. 802.16**

|  | **Downlink Subcarrier Allocations - PUSC** | **IEEE Std 802.16** | **Runcom-10 (1/2 Clock Rate)** |
| --- | --- | --- | --- |
| 1 | Channel BW | 2.50 MHz | 1.00 MHz |
| 2 | FFT | 512 | 512 |
| 3 | Sampling Frequency | 2.80 MHz | 2.80 MHz |
| 4 | Subcarrier Spacing | 5.47 kHz | 5.47 kHz |
| 5 | Number of DC Subcarriers | 1 | 1 |
| 6 | Number of Guard Subcarriers Left | 46 | 46 |
| 7 | ***Additional Guard (null) Subcarriers Left*** | n/a | **126** |
| 8 | Number of Guard Subcarriers Right | 45 | 45 |
| 9 | ***Additional Guard (null) Subcarriers Right*** | n/a | **126** |
| 10 | Number of Used Subcarriers (including DC subcarrier) | 421 | **169** |
| 11 | Null subcarriers plus Used subcarriers | 512 | 512 |
| 12 | Occupied BW (including DC subcarrier #256) | 2302.3 kHz | 924.2 kHz |
| 13 | Pilot + Data Subcarriers | 420 | **168** |
| 14 | # Sub-channels (24 Data + 4 Pilots per sub-channel) | 15 | 6 |
| 15 | Based on IEEE Std 802.16 sub-channels cover:  Minimum frequency span of | 1870 kHz |   |
| 16 | Maximum frequency span of | 2193 kHz | 924.2 kHz |
| 17 | Average frequency span of | 2036 kHz |   |

### Why PUSC over AMC?

As pointed out earlier, PUSC is considered to have an advantage in robustness due to the pseudo-random data sub-carrier frequency diversity relative to the contiguous alignment of data sub-carriers with Band AMC. Driven by mobility requirements and interference management PUSC has been used extensively in deployments over the past several years. The additional pilots with PUSC has also proven useful for beamforming. With this application focus, the WiMAX Forum profiles do not include Band AMC. Further, since the emphasis up to now has been focused on meeting broadband DL traffic requirements, the relatively small Band AMC benefit in the DL direction, 6.67 %, for a 5 MHz channel BW and 512 FFT, is almost entirely offset by the other propagation and coverage benefits offered by PUSC.

In the UL however, Band AMC has a more significant capacity benefit over PUSC. For a data subcarrier efficiency benefit greater than 30 %, Band AMC permutation should be considered a high priority deployment option for applications that are UL-centric, such as Smart Grid. Additionally, mobility is a low priority for this application.

In my estimation, in addition to an UL capacity advantage, Band AMC would also be a more straightforward approach for the implementation of the Runcom-10 alternative. With Band AMC, a filter to pass only the inner 163 subcarriers out of the 512 total subcarriers would support 9 sub-channels in the DL and 9 sub-channels in the UL in an occupied bandwidth of 886.14 kHz.

### OFDMA Parameters and Channel Capacity for Runcom Alternatives

The following table, which includes parameters for a 5 MHz and 2.5 MHz channel BW for reference purposes, provides a more detailed view of the Runcom approach with additional details including projections on PHY data rate. As described earlier the nomenclature RUNCOM-10 (or RC-10) denotes the first alternative with 1/2 clock rate and 10 ms frame size and RUNCOM-25 (or RC-25) denotes the second alternative with 1/5 clock rate and 25 ms frame size.

**Table 11A: Runcom OFDMA Parameters for Suggested Solutions** 

**Explanatory notes for Table 10A:**

* Column 1: This column simply restates the parameters submitted to the IEEE in March 2015. The values in red were received at a later date[[34]](#footnote-15)
* Row 14: The TR gap is maintained at 1 for comparative purposes even though it does not ensure a 40 mile range for RC-10, a desirable goal for many Smart Grid applications in rural environments
* Rows 17, 18: Shows the achievable range with a 1 symbol TR gap in row 17 and in row 18, the necessary symbols for a 40 mile range.
* Row 33: Without having more specific estimates from Runcom, I have selected conservative values for DL and UL OH symbols. This can be updated with more details from Runcom regarding measures taken to reduce MAP and preamble OH.
* Rows 35: Number of DL and UL symbols were selected to provide an PHY UL/DL data ratio of approximately 1.6

The PHY data rate for RUNCOM-10 and RUNCOM-25 are summarized in the following table. The last row in the table shows the resulting UL to DL data ratio resulting from the UL/DL symbol ratio of 1.92 used in the previous table.

**Table 11B: Runcom PHY Rate per Sector and per Cell** 

Runcom has elected to adopt the optional UL PUSC parameters per IEEE Std 802.16-2012, the details of which are shown in the following table for informative purposes. This optional approach enables support for 18 sub-channels in the UL as opposed to 17 sub-channels.

**Table 12: Optional UL PUSC Parameters IEEE Std 802.16**

|  | **Runcom****Optional PUSC UL for 512 FFT, per 8.4.6.2.5** **Table 8-274** | **UL per IEEE Std 802.16 8.4.6.1.2.1** |
| --- | --- | --- |
| # UL of Sub-Channels | 18 | 17 |
| Data sub-carriers per symbol | 288 | 272 |
| Pilot sub-carriers per symbol | 144 | 136 |
| Data + Pilot sun-carriers | 432 | 408 |
| DC sub-carrier | 1 | 1 |
| Left null sub-carriers | 40 | 52 |
| right null sub-carriers | 39 | 51 |
| **Total number sub-carriers** | **512** | **512** |

The following figure shows the estimated PHY rate for the Runcom suggested solutions graphically for reuse (1, 3, 3) and (1, 3, 1).



**Figure 11: UL & DL data rates for RC-10 and RC-25 for UL/DL symbol ratio of ~1.9**

### Other Considerations for the Runcom Alternative[[35]](#footnote-16)

* Permutation: Although PUSC is suggested, Band AMC can be programmed as well
* FFT: 128 FFT rather than 512 FFT can be implemented with some software adaptation
* Runcom has indicated that it does not anticipate any phase noise issues with 2.19 kHz subcarrier spacing
* Although not specifically discussed, it can be assumed that packet packing and PHS can be supported with the Runcom solution to ensure that the MAC and higher layer OH are kept to a reasonable value of 6% or less.

### Runcom Variations – Band AMC vs. PUSC

Since Band AMC permutation can also be supported by Runcom, I have done further analysis to assess the benefits of this approach versus PUSC permutation. The results are shown in Figure 12.

**Figure 12: A comparison of Band AMC and PUSC permutations for the two Runcom alternatives**

The net channel capacity benefit for Runcom-10 with AMC is a little over 10 % and for Runcom-25, the benefit is more than 15 %. As Runcom points out, some of the capacity benefit may be offset with the lower robustness of Band AMC with respect to interference management, but in this author’s opinion, Band AMC is a permutation option that deserves further consideration for this approach.

## Comparing the Full Spectrum and Runcom Alternatives and Other Considerations

### PHY Rate Comparison

The following graph provides a comparison of the Full Spectrum and Runcom alternative solutions as originally suggested. For the purposes of comparison the UL and DL PHY rates are combined to remove variations in UL/DL ratios. I have also adjusted the DL and UL OH symbols for the Runcom approach to be the same as those for FullMAX on the assumption that similar MAP and preamble OH reduction schemes would apply similarly to either solution.

F**igure 12: Comparing Runcom & Full Spectrum Alternatives**

For the same reuse and frame size, the FullMAX approach shows a higher throughput than the Runcom approach, driven primarily by the higher subcarrier efficiency of AMC over PUSC permutation.

The following table provides a more direct PHY rate comparison of the Full Spectrum and Runcom alternatives, with a (1, 3, 3) reuse. Both provide increased throughput for a 25 ms frame size over a 10 ms frame size. The Full Spectrum solution with Band AMC and 128 FFT exhibits a considerable throughput benefit over The Runcom solution with PUSC and 512 FFT.

**Table 13: Comparison of Cell UL+DL PHY Rate for Full Spectrum and Runcom Alternatives**

|  | **10 ms Frame Size** | **25 ms Frame Size** | **25 ms Frame vs. 10 ms Frame** |
| --- | --- | --- | --- |
| **FullMAX w/AMC 2 Bins/3 Symbols, Reuse (1,3,3), w/7 DL & 0 UL OH Symbols** | 1325 kbps/cell | 1428 kbps/cell | +7.8% |
| **Runcom w/PUSC, Reuse (1,3,3), w/7 DL OH & 0 UL OH Symbols** | 986 kbps/cell | 1002 kbps/cell | +1.7% |
| **FM AMC vs. RC PUSC** | +34.4% | +42.5% |  |

For completeness with the comparison between the two approaches it is important to look at them both with the same permutation. This helps to more truly assess the implication of FFT 128 versus FFT 512. This comparison is shown in the following figure for reuse (1, 3, 3).

**Figure 13: Comparison of FullMAX and Runcom solutions with the same permutation scheme (AMC)**

The relative improvement for a 25 ms frame size compared to a 10 ms frame size is similar for both the Full Spectrum and Runcom solutions. The analysis also shows a significant throughput advantage of almost 20 % for 128 FFT over 512 FFT as shown in the following table.

**Table 14: Comparison of FullMAX and Runcom with Band AMC Permutation**

|  | **10 ms Frame Size** | **25 ms Frame Size** | **25 ms Frame Size vs. 10 ms Frame Size** |
| --- | --- | --- | --- |
| **FullMAX w/AMC 2 Bins/3 Symbols, Reuse (1,3,3), 128 FFTUL + DL PHY Rate**  | **1325 kbps** (w/27 DL & 42 UL Data Symbols) | **1428 kbps**(w/72 DL & 114 UL Data Symbols | **7.8%** |
| **Runcom w/AMC 2 Bins/3 Symbols, Reuse (1,3,3), 512 FFTUL + DL PHY Rate** | **1123 kbps**(w/15 DL & 24 UL Data Symbols) | **1198 kbps**(w/15 DL & 24 UL Data Symbols) | **6.7%** |
| **FM AMC 128 FFT vs. RC AMC 512 FFT** | **17.9%** | **19.2%** |  |

### Subcarrier Spacing

A more significant difference between the two alternatives lies with the FFT and subsequently the subcarrier spacing. Although mobility is not a high priority requirement for Smart Grid networks, it cannot be ruled out as a longer term requirement. Mobility combined with multipath can contribute to Doppler Spread which in turn can lead to inter-carrier interference [Ref [[36]](#endnote-20)]. For simplicity just looking at the Doppler shift for a single path can be instructive. In the following figure, the graph on the left shows the Doppler shift in Hertz for different relative velocities between the BS and the SS for carrier frequencies from 500 MHz to 4900 MHz. The graph on the right shows the percentage effect on the subcarrier frequency for a velocity of 100 km/hr for a subcarrier spacing from 10.94 kHz to 2.19 kHz. Using 10.94 kHz as a reference we can assume a value in the range of 3.5 % to 4 % is acceptable to support mobility up to 100 km/hr. This would indicate that a 2.19 kHz subcarrier spacing would support 100 km/hr for carrier frequencies up to 1000 MHz and subsequently 30 km/hr for carrier frequencies up to 3000 MHz.



**Figure 14: Doppler Shift with Mobility**

A further consideration with respect to the sub-carrier spacing is the potential for channel bandwidths less than 1 MHz. Although 1 MHz channel BW to fit block A in the 700 MHz band has been a key driver for this activity, the potential for other small blocks of spectrum less than 1MHz should not be ignored, especially in the lower frequency bands. Smaller channel sizes also offer more flexibility for frequency reuse and opens more opportunities for sharing blocks of spectrum between operators.

The following table shows the resulting subcarrier spacing for channel sizes down to 0.25 MHz for a 128 and 512 FFT and two different sampling factors. It should be noted that this may not be the only approach for achieving a smaller channel bandwidth. In this case the sub-carrier spacing is simply:

The *Channel BW* times the *Sampling Factor* divided by the *FFT* or alternatively the *Clock Frequency* divided by the *FFT*.

**Table 15: Subcarrier Spacing for Varied Channel Sizes**

| **Channel BW** | **1.0 MHz** | **0.75 MHz** | **0.50 MHz** | **0.25 MHz** |
| --- | --- | --- | --- | --- |
| **128 FFT with 28/25 Sampling Factor & AMC** |
| SC Spacing | 8.75 kHz | 6.56 kHz | 4.38 kHz | 2.19 kHz |
| Occupied BW | 945.00 kHz | 708.75 kHz | 472.50 kHz | 236.25 kHz |
| **128 FFT with 57/50 Sampling Factor & AMC** |
| SC Spacing | 8.91 kHz | 6.68 kHz | 4.45 kHz | 2.23 kHz |
| Occupied BW | 961.88 kHz | 721.41 kHz | 480.94 kHz | 240.47 kHz |
| **512 FFT with 28/25 Sampling Factor & AMC** |
| SC Spacing | 2.19 kHz | 1.64 kHz | 1.09 kHz | 0.55 kHz |
| Occupied BW | 945 kHz | 709 kHz | 473 kHz | 236 kHz |
| **512 FFT with 57/50 Sampling Factor & AMC** |
| SC Spacing | 2.23 kHz | 1.67 kHz | 1.11 kHz | 0.56 kHz |
| Occupied BW | 961.88 kHz | 721.41 kHz | 480.94 kHz | 240.47 kHz |

The following graph shows the estimated inter-carrier interference (ICI) due to Doppler spread for varied subcarrier spacing, ranging from 10.94 kHz to 1.09 kHz. The ICI projections are based on the model described in the cited reference[[37]](#endnote-21).



**Figure 15: Worse case projection for inter-carrier interference (ICI) due to Doppler spread**

In reviewing the above curves it is important to note that the threshold signal to noise ratio for 64QAM-5/6 is about 21 dB and alternatively, about 15 dB for 16QAM-3/4. The point being that inter-carrier interference due to Doppler spread can have a significant negative impact on channel capacity in frequency bands above ~700 MHz for a 1.09 kHz spacing and above ~1500 MHz for a 2.19 kHz sub-carrier spacing. The above curves suggest that, for a narrowband channel solution suitable for frequencies up to 4000 MHz, the subcarrier spacing should exceed ~5 kHz.

Another approach, offered by Full Spectrum [Ref [[38]](#endnote-22)], for smaller bandwidth channels is summarized in the following table[[39]](#footnote-17). This approach, based 128 FFT, either selects specific sub-channels or adjusts the sampling clock to achieve a channel BW as low as 100 kHz with a subcarrier spacing of 3.50 kHz.

**Table 16: Summary of Full Spectrum Parameters for Smaller Channel BW**

| **Channel BW** | **1.00 MHz** | **0.50 MHz** | **0.25 MHz** | **0.125 MHz** | **0.100 MHz** |
| --- | --- | --- | --- | --- | --- |
| Sampling Frequency | 1.12 MHz | 1.12 MHz | 1.12 MHz | 0.560 MHz | 0.448 MHz |
| FFT | 128 | 128 | 128 | 128 | 128 |
| Sub-Carrier Spacing  | 8.75 kHz | 8.75 kHz | 8.75 kHz | 4.38 kHz | 3.50 kHz |
| AMC | 2 x 3 | 1 x 6 | 2 x 3 | 1 x 6 | 1 x 6 | 1 x 6 | 1 x 6 |
| # of Sub-Channels | 6 | 12 | 3 | 6 | 3 | 3 | 3 |
| Sub-Channel BW | 157.5 kHz | 78.75 kHz | 157.5 kHz | 78.75 kHz | 78.75 kHz | 39.38 kHz | 31.50 kHz |
| Occupied BW | 945.00 kHz | 472.50 kHz | 236.25 kHz | 118.13 kHz | 94.50 kHz |

### Mini-Sub-Channel Benefit

In assessing the trade-offs of subcarrier spacing it is also important to note the advantages of smaller bandwidth sub-channels. With a higher power spectral density (PSD) and lower noise floor a reduction in sub-channel BW can have a favorable impact on the UL link budget leading to greater range.

### Frame Size

Between the two suggested alternatives, frame sizes from 5 ms to 25 ms have been shown; 5, 10, 20, and 25 ms for FullMAX and 10 and 25 ms for Runcom. At a high level, the trade-offs are:

* Larger frame size: Lower OH leading to higher throughput but, with higher latency
* Smaller frame size: Lower latency but with reduced throughput and increased potential for fragmentation with large payloads

The following figure based on the FullMAX options with AMC (2 bins x 3 symbols) provides a more quantitative perspective on the relative tradeoffs between throughput and latency. As the curve on the left shows, the relative percentage throughput gain diminishes with larger frame sizes whereas the contribution to the UL delay, shown on the right is significant. Increasing the frame size from 10 ms to 25 ms provides less than 8 % additional throughput with a 2.5 times increase in the frame dependent delay.



**Figure 16: a) (left) Shows relative throughput gain for increased frame size while, b) (right) shows frame dependent delay versus throughput gain.**

# WiMAX/IEEE 802.16 Compliant Chips (SOC)

Inquiries have been submitted to three companies that offer IEEE 802.16 and/or WiMAX compliant chips with the goal of determining the capabilities and limitations of chips that are commercially available. The goal being, to determine if any of the available chips can be configured or programmed to support channel BWs less than 1.25 MHz. The chip suppliers queried were:

* GCT Semiconductor, San Jose, California, USA, <http://www.gctsemi.com/>
* Intel Corporation, Santa Clara, California, USA, <http://www.intel.com/>
* Sequans Communications, Colombes, FRANCE, <http://www.sequans.com/>

The six questions asked and responses received or surmised from other sources[[40]](#footnote-18) are summarized in the following table.

**Table 17: WiMAX or IEEE 802.16 Compliant ASIC Suppliers**

| **Questions** | **GCT Semiconductor** | **Intel Corporation** | **Sequans** |
| --- | --- | --- | --- |
| 1. Will your 802.16/WiMAX chip support 128 FFT?
 | GDM7225: 1024 FFT | No | No, only supports 512 FFT |
| 1. Whatever the FFT, will the chip(s) support different clock rate (sampling factors)?
 |  |  |  |
| 1. Will the chip support Band AMC as well as PUSC?
 |  | Probably not | Probably not |
| 1. Is the chip configured in such that would prevent operation in the 700 MHz band or any other frequency band below or above 1 GHz?
 | 700 MHz OK | Yes, that appears to be the case | Yes, configured for specific bands that **do not include** the 700 MHz band |
| 1. If any, what are the frequency limitations?
 | GDM7243M: 700 to 2700 MHzGDM7225: 2.3-2.7 GHz | Offer WiFi/WiMAX Dual mode chips at 2.3 & 2.5 GHz | SQN1210/1220: 2.3-2.4, 2.5-2.7, & 3.3-3.8 GHz |
| 1. Are there any other constraints that would prevent operation in a 1 MHz channel BW with either 512 or 128 FFT?
 |  |  |  |
| Available Chip Products | GDM7225GDM7243M |  | SQN5120 Dual mode LTE/WiMAX |
| Company Response | No formal response received as of 2/29/16 | “Intel not very active (with WiMAX)”“…performance of 128 FFT … low due to overhead of signaling …” | “We do not support 1 MHz channel and have no way to support except by developing a new chip” |

Evidenced by the response of the above chip suppliers there appears to be little interest in devoting the engineering effort to design and develop a SOC or ASIC specifically for this application. Unfortunately the anticipated limited market size for a narrow-band WiMAX/IEEE 802.16 based solution is not considered sufficient to support the time and effort required. The best alternative going forward is a ‘Software Defined Radio’ (SDR) approach using FPGAs or a low cost general purpose processor.

Fortunately SG applications are not driven by the need for the lowest power dissipation, smallest possible size, and lowest cost; benefits generally provided by an ASIC approach in support of small handheld mobile devices. The ‘FPGA’ or ‘general purpose processor’ approach, on the other hand, provides the opportunity for ‘feature tweaks’ with simple and straightforward downloads. And as for power dissipation, size, and costs; the key goal at this point is having a solution that enables utilities and related industries to gain cost-effective access to limited spectrum that would otherwise go unused. Although these other factors are important, what is most important at this point is gaining access to spectrum.

# Validating Alternative Solutions for BWs Less than 1.25 MHz

As the effort to develop an IEEE 802.16s Amendment to IEEE Std 802.16-2012 proceeds it will be necessary, at some point, to validate suggested modifications and or additions to the existing standard to facilitate the implementation of channel BWs less than 1.25 MHz. Several simulation models have been identified for WiMAX [Ref [[41]](#endnote-23)], many of which would be applicable for this project. The Electric Power Research Institute (EPRI) has simulation modeling capability in their laboratory and, given its ties to the utilities community, may be the best place to carry out this activity.

# Summary and Recommendations for Further Discussion

Approaches for achieving channel BWs less than 1.25 MHz have been suggested by two companies and have been discussed in this document; one based on 128 FFT with Band AMC permutation with frame sizes from 5 ms to 25 ms, suggested by Full Spectrum and the second based on 512 FFT with PUSC permutation with a 1/2 clock rate and 10 ms frame size and 1/5 clock rate and 25 ms frame size, suggested by Runcom. For best spectrum utilization TDD is the preferred duplexing method with configurable UL to DL ratios to conform to a traffic bias in either the UL or DL direction.

In assessing the suggested alternatives for narrow bandwidth applications, net channel throughput, aka Goodput, has been used as the key metric for comparative purposes with a focus on requirements specific to Smart Grid networks. Hopefully, this document can provide a good starting point for the development of an amendment to IEEE Std 802.16-2012 by the GRIDMAN Task Group to support channel BWs less than 1.25 MHz. Key areas to address in this ongoing effort are:

* Frequency Range of Interest: Although emphasis for this effort is appropriately focused in the bands below 1000 MHz, higher bands should not be precluded since small amounts of spectrum could materialize anywhere. In this document I have suggested 30 MHz to 4940 MHz, the upper end determined by the 4900-4940 MHz public safety band.
* Channel BW Range: The initial goal has been stated simply as less than 1.25 MHz with no specific lower limit suggested and with 1.0 MHz to fit the ‘Upper 700 MHz A Block’ being a key focus. Channel BWs as small as 100 kHz has been suggested in this document with potential parameters shown in Table 16.
* Multi-(Non-contiguous) Channel Support: A utility may gain access to more than 1 narrowband block of spectrum, both ‘Block A’ channels in the 700 MHz band for example. This scenario may occur in other bands as well.
* 128 FFT or 512 FFT: My estimates indicate a throughput advantage of almost 20 % for 128 FFT over 512 FFT. Unless there are other benefits to having closer subcarrier spacing that I have missed, 128 FFT would be the preferred choice. Additionally, from an IEEE Std 802.16 perspective 128 FFT would be an obvious choice since it is already in the standard for 1.25 MHz.
* Band AMC vs PUSC Permutation: Band AMC has a clear throughput advantage from the standpoint of subcarrier utilization efficiency. And since mobility support is not considered a priority use case for Smart Grid applications, Band AMC would obviously be a first choice. What deserves further discussion however, is the relative benefits of PUSC with respect to interference management. Runcom has indicated a throughput/coverage advantage with PUSC that offsets the advantage of the pilot to data subcarrier advantage of Band AMC. Unfortunately I have not been able to find any quantitative comparative analysis of the two approaches, especially for narrowband channels where the frequency diversity advantage of PUSC is greatly diminished. Going forward, mobility, at least to some degree, should not be ruled out entirely as a longer term requirement for Smart Grid and consideration should also be given to the potential for smaller channel BWs for applications other than Smart Grid where mobility support may be a higher priority. That said, in the absence of any detailed information on how well Band AMC supports mobility, an amendment to IEEE Std 802.16 should, in my opinion, support both Band AMC and PUSC.
* Subcarrier Spacing Trade-offs: Doppler spread and ICI, vs. mini-sub-channels for better range and what level of mobility should be supported. Even though mobility is not a priority for Smart Grid it may be longer term but certainly not necessary to go to 100 km/hr. Also may want to consider applications other than Smart Grid for a larger market opportunity. This discussion ties to PUSC vs. AMC as well.
* DL and UL MAP OH: With the limited channel BW, reduction in symbol OH will be essential to ensure adequate channel throughput. Full Spectrum has provided OH reduction steps in their March 13, 2015 submission xiii with updates provided February 25, 2016 [Ref xiv]. Although I have not seen details, Runcom has also indicated that they would be taking steps for OH reduction as well.
* Frame Size and Latency: The relationship between ‘frame size and throughput’ and ‘frame size and latency’ has been described. Questions for further discussion are: Is it necessary to go as high as 25 ms with a large increase in delay? Or is 10 ms sufficient for a reasonable tradeoff between throughput and delay?
* Queuing or Scheduling Delay: With a narrowband channel and a high number of remotes, characteristic of many Smart Grid subnetworks, there will be an increased likelihood of channel congestion during peak busy periods. Multiple priority levels will be important for each QoS level to ensure mission-critical payloads have timely access to the network.
* Requirement for packet packing (SDUs): Packet packing will be essential to minimize higher level OH with small payloads, which will be dominant with Smart Grid UL data traffic.
* 57/50 vs. 28/25 Sampling Factor: An increase in clock rate from 1.12 MHz to 1.14 MHz adds up to 3 symbols per frame for a 20 ms frame size. These added symbols can be used for increased TR gap to support greater range or for added channel throughput.
* Reuse (1, 3, 3), Reuse (1, 3, 1) and Fractional Frequency Reuse (FFR): FFR with reuse 1 is an important feature for added sector and cell capacity. I have assumed a similar benefit of 2x sector throughput increase for either PUSC or Band AMC. My intuition is that PUSC might be somewhat better than Band AMC due to the greater diversity of data subcarriers, but have not been able to find any quantitative comparisons. Perhaps PUSC offers a bit more than 2x and Band AMC a bit less than 2x improvement. This is certainly worth further discussion to see if there is a consensus value. In any case, reuse 1 with FFR will provide a significant increase in sector throughput and, in my view, should be supported.
* MIMO Support: Whereas polarization diversity can be an effective means for de-correlating 2x2 MIMO arrays, support for higher order MIMO in the bands below 1000 MHz would require multi-wavelength spacing (2 meters or more at 700 MHz[[42]](#footnote-19)) to achieve maximum performance.
* Beamforming: Similar challenges exist for beamforming in the lower frequency bands. An array of several antennas spaced at 1/2 wavelength can be a deployment challenge in the lower frequency bands. Beamforming may require additional pilot subcarriers to implement thus requiring PUSC permutation.

Hopefully this paper and the above recommended discussion points will help to focus and facilitate the ongoing work of the GRIDMAN Task Group of the [IEEE 802.16 Working Group](http://wirelessman.org) in their development of an IEEE 802.16s Amendment for operation in channel bandwidths up to 1.25 MHz in accordance the [Project Authorization Request (PAR)](http://doc.wirelessman.org/16-16-0012-03) endorsed by the IEEE 802 Sponsor at the Macau meeting in March 2016 [Ref [[43]](#endnote-24)].

# Acknowledgements

My thanks to Menashe Shahar, CTO, and Guy Simpson, COO of Full Spectrum and to Zion Haddad, CEO of Runcom for responding to my questions and sharing more details beyond their respective submissions to the IEEE GRIDMAN Task Group.

# Appendix I: Erceg-SUI Path Loss Model for Extended Frequency Range

**Source of following is NISTIR 7761 Rev. 1, Sections 5.2.1.3.5 and 5.2.1.3.9**

**Erceg-SUI Path Loss Model (original):**

PLdB = 20log10(4π *d0*/*λ*) + 10(*a*-*b*\**Th* + *c*/*Th*)\*log10(*d*/ *d0*) + 6log10(*f*/2000) –*X*log10(*Rh*/2)

where:

*Th* = base station antenna height in meters,

*Rh* = terminal or subscriber station antenna height in meters,

*d0* = 100 meters,

*λ* =wavelengthin meters,

*f* in MHz, and

*d* in meters.

The remaining parameters are terrain dependent and defined and defined as below.

Erceg-SUI path loss model, parameters for different terrain types

| **Parameter** | **Terrain Type A** | **Terrain Type B** | **Terrain Type C** |
| --- | --- | --- | --- |
| *a* | 4.6 | 4.0 | 3.6 |
| *b* | 0.0075 | 0.0065 | 0.005 |
| *c* | 12.6 | 17.1 | 20 |
| *X* | 10.8 | 10.8 | 0 |

The proposed modification is as follows:

* The term, **6 log10(*f*/2000),** is modified[[44]](#footnote-20) to: **6(1 + *ak*/*Th*) log10(*f*/2000)**.

**Modified Erceg-SUI Path Loss Model):**

PLdB = 20log10(4π *d0*/*λ*)+10(*a*-*bTh*+*c*/*Th*)log10(*d*/ *d0*) + 6(1 + *ak*/*Th*) log10(*f*/2000) - *X*log10(*Rh*/2)

Where:

Recommended value for *k =* 4

# Appendix II: 47 CFR Part 27.53 Emission Limits

|  |
| --- |
|  |
| (c) For operations in the 746-758 MHz band and the 776-788 MHz band, the power of any emission outside the licensee's frequency band(s) of operation shall be attenuated below the transmitter power (P) within the licensed band(s) of operation, measured in watts, in accordance with the following: |
| (1) On any frequency outside the 746-758 MHz band, the power of any emission shall be attenuated outside the band below the transmitter power (P) by at least 43 + 10 log (P) dB; |
| (2) On any frequency outside the 776-788 MHz band, the power of any emission shall be attenuated outside the band below the transmitter power (P) by at least 43 + 10 log (P) dB; |
| (3) On all frequencies between 763-775 MHz and 793-805 MHz, by a factor not less than 76 + 10 log (P) dB in a 6.25 kHz band segment, for base and fixed stations; |
| (4) On all frequencies between 763-775 MHz and 793-805 MHz, by a factor not less than 65 + 10 log (P) dB in a 6.25 kHz band segment, for mobile and portable stations; |
| (5) Compliance with the provisions of paragraphs (c)(1) and (c)(2) of this section is based on the use of measurement instrumentation employing a resolution bandwidth of 100 kHz or greater. However, in the 100 kHz bands immediately outside and adjacent to the frequency block, a resolution bandwidth of at least 30 kHz may be employed; |
| (6) Compliance with the provisions of paragraphs (c)(3) and (c)(4) of this section is based on the use of measurement instrumentation such that the reading taken with any resolution bandwidth setting should be adjusted to indicate spectral energy in a 6.25 kHz segment. |
| (d) [Reserved] |
| (e) For operations in the 775-776 MHz and 805-806 MHz bands, transmitters must comply with either paragraphs (d)(1) through (5) of this section or the ACP emission limitations set forth in paragraphs (d)(6) to (d)(9) of this section. |
| (1) On all frequencies between 758-775 MHz and 788-805 MHz, the power of any emission outside the licensee's frequency bands of operation shall be attenuated below the transmitter power (P) within the licensed band(s) of operation, measured in watts, by a factor not less than 76 + 10 log (P) dB in a 6.25 kHz band segment, for base and fixed stations; |
| (2) On all frequencies between 758-775 MHz and 788-805 MHz, the power of any emission outside the licensee's frequency bands of operation shall be attenuated below the transmitter power (P) within the licensed band(s) of operation, measured in watts, by a factor not less than 65 + 10 log (P) dB in a 6.25 kHz band segment, for mobile and portable stations; |
| (3) On any frequency outside the 775-776 MHz and 805-806 MHz bands, the power of any emission shall be attenuated outside the band below the transmitter power (P) within the licensed band(s) of operation, measured in watts, by at least 43 + 10 log (P) dB; |
| (4) Compliance with the provisions of paragraphs (e)(1) and (e)(2) of this section is based on the use of measurement instrumentation such that the reading taken with any resolution bandwidth setting should be adjusted to indicate spectral energy in a 6.25 kHz segment; |
| (5) Compliance with the provisions of paragraph (e)(3) of this section is based on the use of measurement instrumentation employing a resolution bandwidth of 100 kHz or greater. However, in the 100 kHz bands immediately outside and adjacent to the frequency block, a resolution bandwidth of at least 30 kHz may be employed. |
| (6) The adjacent channel power (ACP) requirements for transmitters designed for various channel sizes are shown in the following tables. Mobile station requirements apply to handheld, car mounted and control station units. The tables specify a value for the ACP as a function of the displacement from the channel center frequency and measurement bandwidth. In the following tables, “(s)” indicates a swept measurement may be used. |

# Appendix III: PUSC with 512 FFT

Ref: IEEE Std 802.16-2012 8.4.6.1.2.1.1 DL sub-channels subcarrier allocation in PUSC

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2. WiMAX Forum® System Profile Requirements for Smart Grid Applications Requirements for WiGRID DRAFT-T31-002-R010v02-A, Working Group Draft Specification, (2014-04-16) [↑](#endnote-ref-2)
3. SGIP-PAP02: NISTIR 7761 Rev. 1: NIST Smart Grid Interoperability Panel Priority Action Plan 2: Guidelines for Assessing Wireless Standards for Smart Grid Applications [↑](#endnote-ref-3)
4. DCN 16-15-0033-00-Gcon, “Technical requirements for a Point to Multipoint Broadband Wireless System Operating in a 1 MHz wide channel” [↑](#endnote-ref-4)
5. With requirements for synchronization in a multi-cell deployment, ‘adaptive TDD’ is not a viable option. That said, the UL to DL ratio would generally be set to facilitate UL traffic bias, which occurs most of the time, without negatively impacting less frequent firmware DL requirements. WiGRID requirements currently specify an UL to DL symbol ratio up to 1.75 to 1. [↑](#footnote-ref-1)
6. SGIP-PAP02: NISTIR 7761 Rev.1, Sections 5.2.7 & 6.1, Have extensive discussion on latency and suggested queueing models for analysis [↑](#endnote-ref-5)
7. These SNR values are based on a threshold BER of 10-3 and were arrived at from discussions with Intel engineers for earlier papers. Other sources may differ due to minor degree due to varied initial assumptions, what is important however, is the approach not the exact values. [↑](#footnote-ref-2)
8. Multiple repetitions, shown in italics, is a supported feature but may not be applicable for narrow BW channels [↑](#footnote-ref-3)
9. IEEE Std 802.16-2012, IEEE Standard for Air Interface for Broadband Wireless Access Systems, August 2012 [↑](#endnote-ref-6)
10. Achieving Frequency Reuse 1 in WiMAX Networks with Beamforming Masood Maqbool, Marceau Coupechoux and Philippe Godlewski TELECOM ParisTech & CNRS LTCI, Paris France Véronique Capdevielle Alcatel-Lucent Bell Labs, Paris France [↑](#endnote-ref-7)
11. IEEE C802.16e-05/162, IEEE 802.16 Broadband Wireless Access Working Group, 2005-03-09 [↑](#endnote-ref-8)
12. The nomenclature (N, S, K), where N=Cells per cluster, S=Sectors per cell, and K=Number of sub-channel groups [↑](#footnote-ref-4)
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19. ‘FullMAX Latency’ document received from Menashe Shahar, also stated in Siemens document, “Understanding Latency” [↑](#footnote-ref-7)
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24. IEEE 802.16-16-0011-00-Gcon, IEEE 802.16 Broadband Wireless Access Working Group <<http://ieee802.org/16>>, An Evaluation of Alternative Solutions for 1 MHz Channels for Smart Grid Applications, uploaded 27 Jan 2016 [↑](#endnote-ref-15)
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30. <http://www.runcom.com> [↑](#footnote-ref-12)
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32. Note that 18 sub-channels in the UL differs from IEEE Std 802.16 that specifies 17 UL sub-channels for PUSC with an FFT of 512. [↑](#footnote-ref-13)
33. I had the opportunity to discuss the Runcom solution with Zion Haddad, Runcom CEO, on Jan 7, 2016. [↑](#footnote-ref-14)
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35. Further information received from Runcom discussion and e-mails [↑](#footnote-ref-16)
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44. This modification was arrived at after discussions with Vinko Erceg, one of the principal investigators involved with the testing and derivation of the Erceg-SUI path loss model. [↑](#footnote-ref-20)