Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**[802.16.3 2G OFDM System for Broadband Wireless Access Development, Session #11 Presentation]**
Date Submitted	**[2001-01-16]**
Source(s)	[Dr. Robert M. Ward Jr] [SciCom, Inc.] [13863 Millards Ranch Lane] [Poway, Ca. 92064] Voice: [858.513.4326] Fax: [858.513.4326] mailto:[drbmward@ieee.org]
Re:	IEEE802.16.3-00/24 document. Response to “IEEE 802.16.3 Task Group Call for Contributions: Session #11”“Topic: Initial PHY Proposals”
Abstract	[The signal processing functionality for a 2nd Generation OFDM system is described.]
Purpose	[Proposed PHY system technology is described for consideration by 802.16.3 Task group in the development of its standard.]
Notice	This document has been prepared to assist IEEE 802.16. It is offered as a basis for discussion and is not binding on the contributing individual(s) or organization(s). The material in this document is subject to change in form and content after further study. The contributor(s) reserve(s) the right to add, amend or withdraw material contained herein.
Release	The contributor grants a free, irrevocable license to the IEEE to incorporate text contained in this contribution, and any modifications thereof, in the creation of an IEEE Standards publication; to copyright in the IEEE’s name any IEEE Standards publication even though it may include portions of this contribution; and at the IEEE’s sole discretion to permit others to reproduce in whole or in part the resulting IEEE Standards publication. The contributor also acknowledges and accepts that this contribution may be made public by IEEE 802.16.
Patent Policy and Procedures	The contributor is familiar with the IEEE 802.16 Patent Policy and Procedures (Version 1.0) <http://ieee802.org/16/ipr/patents/policy.html>, including the statement “IEEE standards may include the known use of patent(s), including patent applications, if there is technical justification in the opinion of the standards-developing committee and provided the IEEE receives assurance from the patent holder that it will license applicants under reasonable terms and conditions for the purpose of implementing the standard.” Early disclosure to the Working Group of patent information that might be relevant to the standard is essential to reduce the possibility for delays in the development process and increase the likelihood that the draft publication will be approved for publication. Please notify the Chair <mailto:r.b.marks@ieee.org> as early as possible, in written or electronic form, of any patents (granted or under application) that may cover technology that is under consideration by or has been approved by IEEE 802.16. The Chair will disclose this notification via the IEEE 802.16 web site <http://ieee802.org/16/ipr/patents/notices>.

2nd Generation OFDM Architecture for 802.16.3 Broadband Wireless Access

Dr. Robert M. Ward Jr.
SciCom, Inc.

Introduction

This contribution is a continuation of the proposal contained in Ref 2. The proposal described a PHY layer architecture employing OFDM modulation, concatenated coding and selectable parameters. Details of the design are presented along with discussions of performance trades and system advantages/disadvantages.

Relationship to prior standards

Design and performance considerations are drawn from several standard systems. These include:

- IEEE standards 802.11a and 802.14
- Digital Video Broadcast (DVB) standards DVB-Cable, DVB-Satellite, DVB-Terrestrial

The OFDM technology of the 802.11a is extended for increased multipath protection. Relatively invariant demodulator design can conceived based on the concepts presented herein to support multiple channel bandwidths. Concatenated coding technology employed in the DVB systems is used to strengthen the coding afforded in the 802.11a system.

Requirements

Tables 1 and 2 summarize key requirements assumed for this proposal. Table 1 is based upon the system document, Ref 1, whereas the second table concentrates on requirements that emerged from the November Task Group meeting.

Physical Channel capabilities	Service capabilities

• 2 to 11 Ghz Frequency Range
• Bidirectional communications
• Operate in multipath
• Support 50 km ranges
• Operate in multicell/sector topology
• Low BER
	• Capacity
	  • Up to 10 Mbps per user
	  • Aggregate data rate to support multiple users simultaneously
	• Scalable growth
	• Integrated Transport
	  • Voice, video, data
	  • Commensurate levels of QOS
	• Point to Multipoint Operation
	• Easy Access
	• Dedicated Bandwidth

Table 1: Summary 802.16.3 Network capabilities

Requirement	**Values**
Signal Bandwidths	1.5, 1.75, 3, 3.5, 6, 7, 8, 12, 14, 28 Mhz
Multipath Protection	10, 5, 2.5 5, 2.5, 1.25 μsec

Table 2: Additional requirements based on November 2000 Task Group 3 meeting

System Description

The 802.16.3 system is a multipoint wireless data network, consisting of basestations and subscriber stations in a (possibly overlapping) multicell topology. Ref 1 provides a wireless reference model and protocol reference layer model to describe access points, methods and network elements. The wireless and protocol models are used for this proposal and repeated here for convenience as Figure 1 and Figure 2. Subscriber stations communicate directly with basestations and vice versa. In the downstream direction, multiplexed traffic is transmitted by the base station, which serves as the radio supervisor of the cell. In the upstream direction, 802.16.3 protocols provide the means to multiplex traffic from multiple subscriber stations, resolve contention, and allocate capacity. The base station radio SHALL be P-MP, radiating its *downstream* signal with a shaped sector or adaptive array (spatial reuse) antenna achieving broad azimuthal beam width to “cover” a prospective number of subscribers. Channelized frequency plans and Time Domain Duplexing provide additional means to allocate coverage.

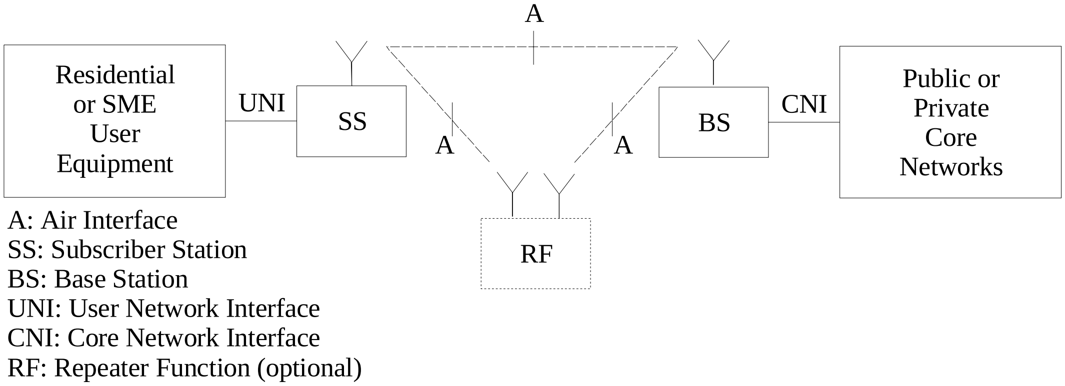

Figure 1: Wireless Reference Model

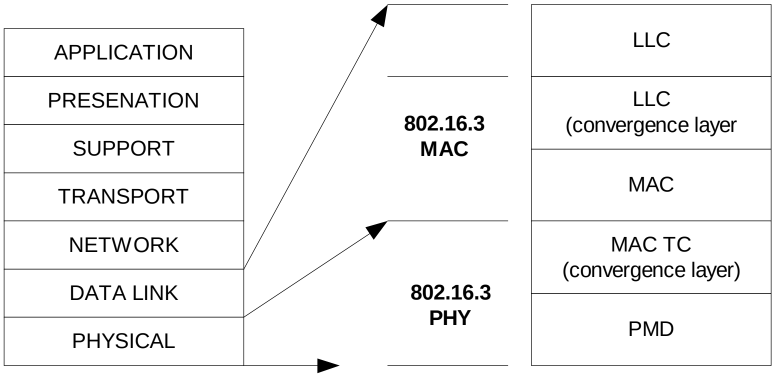

Figure 2: 802.16.3 protocol architecture

System Operation and Data Framing

Within one cell, either FDM or TDD can be used to distinguish the downlink and uplink. Partitioning of the radio resources by the radio supervisor can be made depending on traffic load. Figure 3 illustrates a data framing hierarchy for the phy layer to accomplish this partitioning. The concept described will assume a single channel frequency with downstream and upstream time allotments. OFDM is used for both the downstream and upstream links. The basestation uses the super frame layer to partition the downstream and upstream to suit the traffic load. This could be asymmetric (e.g. more downstream time allotted) or symmetric. Assume F1 is down and F2 is the uplink return. Guard time, not shown, between the end of F1 and the start of F2 is provided to accommodate worst case propagation delays to avoid transmission overlap. The basestation broadcasts on F1, using a Frame preamble for initial synchronization. The frame consists of n segments (S). Each segment uses a specific OFDM configuration (e.g modulation type, symbol duration, etc, segment or fine preamble as required). A popular ordering scheme would be for lower ordered constellations (e.g BPSK) to be transmitted as early segments in the frame, and higher ordered constellations (e.g. 64 QAM) for the later segments. A disadvantaged subscriber station can thus receive its data early on in the segment, before potentially losing synchronization. This also provides an easy method to offer near in users having the luxury of higher system margins the best data rates, while still providing far out users reliable (but lower rate) communications. Note in each segment layer there are n OFDM symbols (O). Data multiplexing on the downstream can managed using the separate OFDM symbols as time slots, as well as using subcarrier multiplexing within each OFDM symbol. This can be particularly valuable on the uplink, supporting a subscriber with poor link margin. Interleaving of users across the subcarriers is also recommended as this will provide maximum frequency diversity against frequency selective fades.

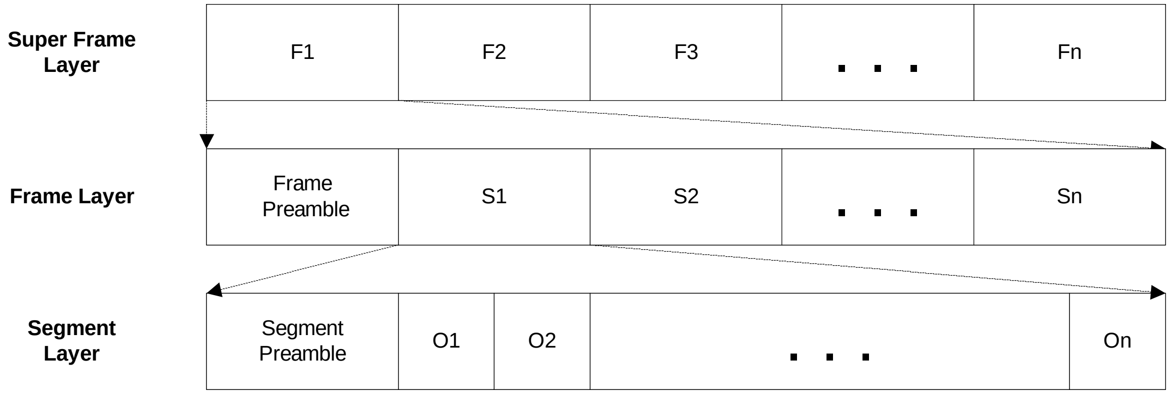

Figure 3: Data Framing Notion

Frame and optionally segment preambles will be used on the downlink for synchronizing the subscriber stations to the basestation. On uplink, frame and segment preambles may not be necessary, depending on the synchronization methodology. Subscriber stations will synchronize to the basestation via the downlink. Using the channel estimates of the downlink, predistortion of the uplink signal could eliminate or minimize the need for uplink Frame/Segment layer preambles. Minimal preamble overhead on the uplink can have significant transmission efficiency for data consisting of primarily small packets (e.g Acks).

Lastly, a special segment of the downlink and uplink frames could be utilized for system access. This serves as a special time slot on which initial ranging/synchronization would be performed.

Phy Layer Trades and Signal Processing

FLEXIBLE FFT SIZING

The choice of the FFT size (e.g. the active symbol duration) for an OFDM system is driven by two larger considerations, each with many 2nd layer trade issues. The first consideration is multipath protection and the second is data transmission efficiency.

Multipath protection will be discussed first, as it is expected to be a significant factor in the performance of the 802.16.3 network. For the OFDM system, introduction of a guard, or cyclic prefix is made to lessen the impact of multipath (it does not eliminate it). Thus the guard length must be chosen to support the multipath protection desired. A definition of protection required is necessary also, as it is modulation dependent. Obviously QPSK is more tolerant to multipath than 64 QAM. The desired frequency diversity (e.g. the degrees of freedom across the frequency band) also drives the FFT size. If supported by the coherence bandwidth of the channel, then to achieve more diversity, longer FFTs may be used. Thus the FFT size and channel bandwidth determine the subcarrier spacing. More robustness against frequency offsets is provided by larger subcarrier spacings. For similar performance, it would be desireable to maintain similar subcarrier spacing for different channel bandwidths. Lastly, the deployment scenario forces the FFT size issue. As there will inevitably be an infinite number of deployment scenarios (various configurations of antenna, sectorization, …, and differing environments), no single choice will be best. Choosing too large an FFT size could penalize the system, whereas too small may make the network under perform.

Efficient data transmission must also be considered in the choice of the FFT size. A long guard time is directly responsible for higher overhead. Longer OFDM symbol duration causes less flexibility in the data access management described earlier. Synchronization (frequency and timing) will also be impacted by the choice. While the synchronization issues are not trivial, system transmission efficiencies is considered the more important issue by this author. Thus, for larger FFT sizes, guard overhead can be tailored by making this a selectable parameter.

Experience with 802.11a multipath design will be used to support the recommended OFDM symbol design. The 802.11a system parameters are: 20 Mhz channelization, 64 point FFT, 4 µsec symbol duration, 25 % guard relative to active FFT symbol, 54 Mbps when rate ¾ coded. Restricting the FFT size to 64 points for similarity to 802.11a (note the shaded grey row) and designing for the bandwidths cited earlier leads to **Error! Reference source not found.**. While the FFT size remained constant for the various bandwidths, nothing else did. Changing subcarrier spacing leads to different performance and many symbol durations suggest more mac/phy management interaction.

Channel BW (Mhz)	Sample BW (Mhz)	Sample Period (nsec)	FFTsize	Subcarrier Spacing (khz)	No. of Active Subcarriers	Symbol Duration with 25% guard (usec)
1.5	2.5	400	64	39.0625	32	32
1.75	2.5	400	64	39.0625	38	32
3	5	200	64	78.125	32	16
3.5	5	200	64	78.125	38	16
6	10	100	64	156.25	32	8
7	10	100	64	156.25	38	8
8	10	100	64	156.25	43	8
12	20	50	64	312.5	32	4
14	20	50	64	312.5	38	4
16	20	50	64	312.5	52	4
28	32	31.25	64	500	47	2.5

Table 3: 64 Point FFT Design

Development of the 802.11a standard relied on a very demanding NLOS multipath model. It is not Ricean and causes a very diffuse signal of many multipath rays. In the 54 Mbps, 64 QAM mode, very good performance can be achieved, even in presence of peak multipath in excess by 50% of the guard caused by this model. This leads to the following estimate of multipath protection vs FFT length. To meet the 10 μsec multipath protection requirement, a 512 point FFT can be used, with a ¼ guard length. This can be seen parametrically from Figure 4. For FFTsizes (64, 128, 256, 512, 1024) and a common 20 Mhz sample rate, the total symbol duration, guard plus FFT, is graphed. The 802.11a system is shown for the ¼ guard length and FFT size of 64.

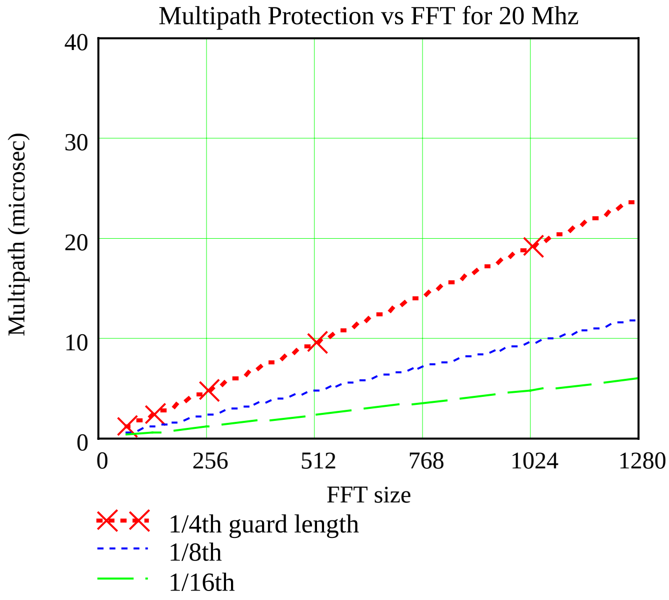

Figure 4: Estimating FFT size vs Multipath Protection for 20 Mhz channel

8X/4X Design

Relaxing the constraint to have a 64 point FFT or any Fixed point FFT leads to an 8X/4X design, as shown below. The 8X system is relative to the 802.11a system. It has a guard of 6.4 μsec, thus affording approximately 8 times as much multipath protection, with the anticipation that 10 μsec protection may be achieved. The grey row shows that the peak rate of 802.11a can still be maintained. Allowing the flexible FFT size, makes many other system parameters consistent: similar symbol duration, guard length, and subcarrier spacing, while still providing for all of the channel bandwidths. The 4X system, reduces the parameters by factor of two. The product of active subcarriers and subcarrier spacing is the occupied bandwidth within the channel bandwidth. For simplicity the same scaling as 802.11a (52/64) was used.

Channel BW (Mhz)	Sample BW (Mhz)	Sample Period (nsec)	FFT size	Subcarrier Spacing (khz)	No. of Active Subcarriers	Guard % of active FFT symbol duration	Guard (usec)	Symbol Duration (usec)	64 QAM (bits per subcarrier)	Rate 3/4 coded capacity (Mbps)
1.5	2.5	400	64	39.0625	32	25%	6.4	32	6	3.94
1.75	2.5	400	64	39.0625	37	25%	6.4	32	6	4.64
3	5	200	128	39.0625	63	25%	6.4	32	6	7.73
3.5	5	200	128	39.0625	73	25%	6.4	32	6	9.14
6	10	100	256	39.0625	125	25%	6.4	32	6	15.33
7	10	100	256	39.0625	146	25%	6.4	32	6	18.28
8	10	100	256	39.0625	167	25%	6.4	32	6	21.23
12	20	50	512	39.0625	250	25%	6.4	32	6	30.66
14	20	50	512	39.0625	292	25%	6.4	32	6	36.56
16	20	50	512	39.0625	410	25%	6.4	32	6	53.16
28	40	25	1024	39.0625	583	25%	6.4	32	6	72.98

Table 4: **8X**

Channel BW (Mhz)	Sample BW (Mhz)	Sample Period (nsec)	FFT size	Subcarrier Spacing (khz)	No. of Active Subcarriers	Guard % of active FFT symbol duration	Guard (usec)	Symbol Duration (usec)	64 QAM (bits per subcarrier)	Rate 3/4 coded capacity (Mbps)
1.5	5	200	64	78.125	16	25%	3.2	16	6	3.38
1.75	5	200	64	78.125	19	25%	3.2	16	6	4.22
3	5	200	64	78.125	32	25%	3.2	16	6	7.88
3.5	5	200	64	78.125	37	25%	3.2	16	6	9.28
6	10	100	128	78.125	63	25%	3.2	16	6	15.47
7	10	100	128	78.125	73	25%	3.2	16	6	18.28
8	10	100	128	78.125	84	25%	3.2	16	6	21.38
12	20	50	256	78.125	125	25%	3.2	16	6	30.66
14	20	50	256	78.125	146	25%	3.2	16	6	36.56
16	20	50	256	78.125	205	25%	3.2	16	6	53.16
28	40	25	512	78.125	292	25%	3.2	16	6	73.13

Table 5: **4X**

Two OFDM symbol durations are provided, 16 and 32 μsec, with 25% guard lengths 3.2 and 6.4 μsec respectively. To suit varying deployment scenarios, the guard length can be selected by including factors of 1/8 and 1/16 allowing customization down to 800 nsec, equivalent to 802.11a.

FEC

802.11a relies on standard convolutional coding as shown in Figure 5. A standard rate = ½ , constraint length K = 7 encoding combined with rate 2/3rd and ¾ puncturing is specified. It is bit interleaved per OFDM symbol, mitigating frequency selective error effects. The decoding is synchronized and flushed according to PDU structure. Left to design are the trellis depth and quantization. Lastly, a CRC provides a pass or fail metric on the decoded packet.

Performance is standard. In AWGN only, good coding gain is achieved, and maximum data rates can be easily supported with an efficient core. In multipath, depending on the nature, error bursts can occur causing multiple subcarrier QAM symbol errors per OFDM symbol. The convolutional decoder can be expected to eliminate errors to a certain degree, on the order of less than 2 to 3 x 10^{-3} BER. However, error bursts must not exceed constraint length & trellis depth design capabilities (two to three QAM symbol errors per OFDM symbol) for complete elimination of the errors.

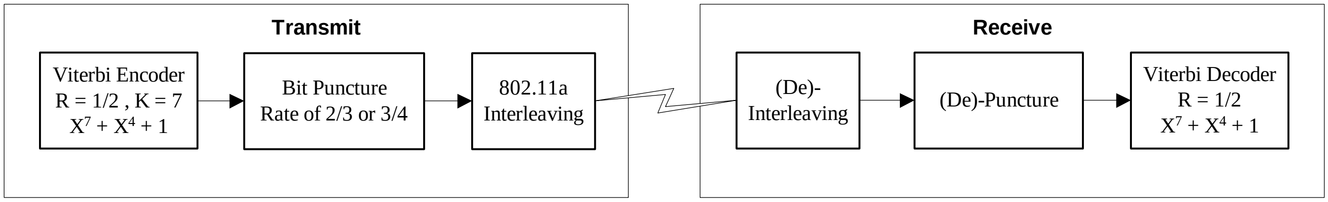

Figure 5: 802.11a Convolutional Coding system

The basic proposal of the earlier contribution combines Reed Solomon coding as the outer code and convolutional as the inner code. The same convolutional coding (rate ½, constraint length $k = 7$) with puncturing (½ , 2/3 , ¾ , 5/6 , 7/8) is suggested. Interleaving is employed in convolutiona/Reed Solomon concatenated systems. In DVB systems, an interleaver of $I = 12$ depth is used to spread burst error effects prior to Reed Solomon decoding. The 802.11a system uses interleaving after convolutional encoding. Simulation results have demonstrated that applying a Reed Solomon decoder immediately after the 802.11a decoder with a few symbol error capability can recover many of packets which would fail the final CRC check.

For flexibility, the Reed Solomon block coding is made programmable. Both the length of the Reed Solomon codeword (n) and the length of the parity symbols ($2t = n-k$) is made selectable. This allows matching the phy layer framing and the desired coding strength. Existing technology for RS(n,k,t): $0 < n \le 255$; $0 < 2t \le 38$ allow for efficient decoders. Reed Solomon with erasure capabilities can also be easily implemented to improve decoding performance. The selection of the maximum error correction capability remains open at this time pending further evaluation of multipath channel and interleaving options.

QAM

801.11a utilizes BPSK, QPSK, 16 and 64 QAM as the underlying signal constellation mappings. A single constellation choice is signaled for each packet, and remains fixed. Using the framing and segmentation layer concept offered earlier, constellation choices can vary for consecutive OFDM symbols. For the symbol durations explored, use of adaptive constellations within one symbol may or may not be useful on the down link. However, for the more limited uplink, employment of OFDMA and adaptive modulation for users on different subcarriers could prove useful. Thus data framing/segmentation would support this feature. This proposal includes 32 and 128 QAM constellations as additional modes for greater flexibility and performance.

Both 32 and 128 QAM are utilized successfully in European cable systems to effectively raise capacity. Theory indicates that a 6db margin between 16 and 64 QAM. 32 QAM splits that difference, while 128 QAM requires 3 db more than 64 QAM. Thus in applications where 64 QAM is not achieveable, 32 QAM offers a compromise to gain 25% more basic capacity over 16 QAM. 128 QAM offers 17% capacity increase over 64 QAM. Cable systems experience slightly longer acquisition times with these non square constellations, depicted in Figure 6. However, an OFDM system does not experience the longer acquisition penalty, as initial synchronization is not dependent on the constellation within the data part of the phy layer frame. An additional benefit of using these additional constellations is the increased robustness of smaller constellations to multipath.

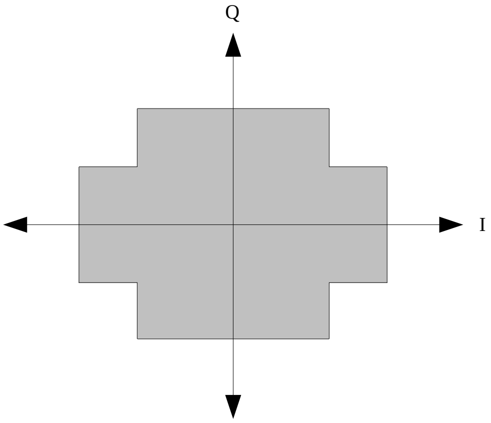

Figure 6: Non square constellation

Evaluation

The criteria of the evaluation table in the call for contribution have been satisfied. Flexibility of key parameters as outlined in this contribution permit the system to optimize performance, both in terms of system capacity and robustness. Complexity is on the same order as 802.11a systems and 802.16.1, Ref 3. The phy layer contained herein is also designed to be compatible with the anticipated 802.16.3 MAC functionality.

Item	Comments
1. Meets Systems Requirements	Yes. OFDM based proposal for bi-directional communications in 2 – 11 Ghz with capabilities to support system capacity and reliability needs. 8x and 4x scalable design were describe, which provide similar data capacities to 802.11a, support varying channel bandwidths, and afford greater multipath protection.
2. Channel Spectrum efficiency	Very Efficient. Gross bit rates in excess of 802.11a were presented. OFDM technology with underlying multimode QAM supports higher spectrum efficiency. Concatenated RS-convolutional coding with selectable coding rates to afford best match to channel needs.
3. Simplicity of implementation	Moderately simple. Utilizes proven technologies in current implementations. Signal design supports consistent radio front end designs, expected to be the cost driver for both basestations and subscriber stations, for different deployment scenarios. Also, inherent mode flexibility allows tailoring implementation to meet specific cost/performance criteria.
4. Spectrum Resource Flexibility	Uses spectrum flexibly. Supports TDD/FDD, Hybrid channel access methodologies. A wide variety of system configurations was presented, supporting different data rates and offering similar performance.
5. Spectrum Resource Flexibility	Flexibility is good. Standard interfaces of the network topology and protocol access points are planned.
6. System Spectrum Efficiency	Up to 128 QAM is recommended, providing 7 bits/subcarrier. The use of consistent subcarrier spacing across channels and data framing techniques lends itself to efficient utilization of the system capacity. Channelized operation is provided for, supporting frequency reuse. TDD operation was described for uplink/downlink operation in single frequency channels.
7. Protocol Interface Complexity	Supports the standard 802.16.3 interfaces required.

8. Reference System Gain	Allows optimization of System Gain as OFDM technology supports frequency selective gain and via coding technique.
9. Robustness to Interference	Moderate. Reducing QAM mode for longer range diminishes interference outside immediate cell.
10. Robustness to Channel Impairments	OFDM is inherently designed to mitigate multipath. Preamble can be designed to support antenna diversity.
11. Robustness to radio impairments	Linearity is required due to use of higher order constellations. OFDM provides an integrating gain for synchronization.
12. Support of advanced antenna techniques	Not specifically addressed by this proposal. However, does not prohibit.
13. Prior Standards	Supports standards based operation.

References

Ref 1: 802.16.3-00/02r4, Functional Requirements for the 802.16.3 Interoperability Standard
Ref 2: 802.16.3 2G OFDM System for Broadband Wireless Access Development 802163c-00_38.pdf
Ref 3: 802.16.1-00/01 Air Interface for Fixed Broadband Wireless Access Systems