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Title	**Modulation and Equalization Criteria for 2-11 GHz Fixed Broadband Wireless Systems**	
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Re:	Invitation to Contribute IEEE802.16.3-00/09: solicitation of contributions on Evaluation Criteria for Key Characteristics of 802.16.3 Air Interface; issued 2000-07-28.	
Abstract	We give a brief survey of anti-multipath techniques and associated modulation (OFDM and single-carrier) formats, which are pertinent for 802.16.3 fixed broadband wireless systems. Careful modeling and evaluation of power amplifier nonlinearities and frequency offsets is important for evaluation of proposed PHY modulation formats. Because of the sensitivity of OFDM systems to these impairments, Single-carrier modulation schemes with reduced-complexity adaptive equalization strategies merit serious consideration.	
Purpose	Among the key characteristics of any 802.16.3 air interface standard are modulation and equalization. This document provides guidance and background on these topics for the evaluation of 802.16.3 PHY proposals.	
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Modulation and Equalization Criteria for 2-11 GHz Fixed Broadband Wireless Systems

David Falconer and Lek Ariyavisitakul

1. Introduction

802.16.3 systems will operate over NLOS (non-line of sight) links, serving residential and SOHO subscribers. Subscriber antennas may be less directive than in 802.16.1 (mm-wave LMDS) systems, because of the lower frequency antenna size and cost limitations, and perhaps because of a need for lower installation costs. Thus, multipath delay spread is expected to be larger than in 802.16.1 systems.

This raises the question of what types of anti-multipath measures are necessary, and consistent with low cost solutions. For example, is the use of OFDM advisable, as was adopted in 802.11a air interface, or is some form of QAM single-carrier modulation practical, combined with adaptive equalization at receivers?

This contribution includes a review of recent literature which sheds light on this question. We also point out the sensitivity of OFDM to nonlinear power amplifiers and frequency offsets, and the consequent need to evaluate any proposed PHY solution against these impairments. For convenience and brevity, the review is mostly organized in point form.

2. Multipath Channel Characteristics

- Existing 802.16.1 models and corresponding ways of dealing with multipath [Fal99a], [Fal99b] are not necessarily appropriate for 802.16.3.
- In [Erc99], multipath characteristics are described, based on 2 GHz measurements in suburban areas. Base antennas used in these measurements had 65° beamwidths; subscriber antennas were either omni or 32°. Up to 1 μs. delay spread[1] was observed for both omni and 32° subscriber antennas. Average delay profiles were roughly exponential, typically with a zero-delay LOS (line of sight) component.
- [Por00] reports measured rms delay spread for MMDS systems, for 53° base beamwidths and either 10° or omnidirectional subscriber antennas. For the directional subscriber antennas and NLOS paths, about 2% of the measured paths had rms delay spreads of over 2 μs.; the average was 0.14 μs. A 2 μs. rms delay spread could be equivalent to a channel impulse response spanning roughly 8-10 μs.
- These results imply that for single-carrier QAM-type or constant-envelope modulation, the impulse response duration typically spans up to about N or $2N$ symbols at a baud of N Megasymbols/s.

3. Anti-Multipath Approaches

- For 6 MHz wide channels in MMDS, the maximum symbol rate would be 5 to 6 Msymbols/s, so single-carrier (single-carrier) modulation, with a relatively simple decision feedback equalizer (DFE) with 5-10 taps would be adequate, assuming a maximum delay spread of about 1 μs.
- For some channels, and for wider bandwidths and higher bit rates, the multipath spans more bits. Modulation alternatives are (1) OFDM (orthogonal frequency division multiplexing); (2) single-carrier modulation with receiver equalization in the time domain; (3) single-carrier modulation with receiver equalization in the frequency domain.

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[1] "Delay spread" in this document does not refer to rms delay spread, but rather to the total time span of the measurable channel impulse response.

- Any of these anti-multipath approaches can be combined with antenna diversity at the transmitter and/or the receiver.

4. OFDM (Orthogonal Frequency Division Multiplexing)

- In conventional single-carrier modulation with time domain equalization, for a given bit rate, the hardware complexity is roughly proportional to the maximum expected delay spread. In OFDM, FFT (fast Fourier transform) processing is done at the transmitter and receiver to combat multipath, with a hardware complexity (measured approximately by number of multiplications per bit) which is roughly proportional to the logarithm of maximum delay spread [Cim85]. Thus OFDM appears to offer a better performance/complexity tradeoff than conventional single carrier modulation for large (>20 to 30 taps) multipath spread [McD96]. However OFDM has some disadvantages:

  (1) higher peak to average ratio than single-carrier, requiring transmitter power backoff and consequent link budget penalty [Van00]. Precoding measures can be applied [Cim00], [Tar00], but there is still a penalty with respect to single-carrier modulation with comparable bit rate.

  (2) OFDM is quite sensitive to frequency instability, phase noise and synchronization errors [Pol95].

  (3) The full potential performance of OFDM would be reached if bit rate and power were optimized for each frequency subchannel on each base-to-subscriber link (this would require feedback of channel information from receiver to transmitter). This is usually not done in radio systems, for reasons of complexity and because it is hard to accommodate broadcast infiormation. Some loss of performance results from the restriction to non-adaptive mode.

  (4) Because of the fixed power and bit rate on each subchannel, non-adaptive OFDM must be coded, to combat frequency-selective fading. Coding is optional for single-carrier systems.

  (5) FFT signal processing in OFDM systems is done on blocks which are at least 4 to 10 times longer than the maximum impulse response span. One or more blocks of this size are used for receiver training purposes, implying a somewhat larger training overhead than would be necessary for a single carrier system with time domain equalization.

  (6) The processing in OFDM of relatively long blocks of data at OFDM transmitters and receivers causes significantly larger total delays than in single carrier systems with time domain processing. This can be important for delay-sensitive services.

5. Single-carrier modulation with Time Domain Adaptive Equalizer Processing

- Single-carrier modulation alleviates power backoff and phase noise sensitivity problems, but the time domain complexity is proportional to delay spread in a conventional adaptive DFE (decision feedback equalizer) or linear equalizer.
- In general, a DFE yields better performance (lower mean squared error and bit error rate) than a linear equalizer for radio channels, in which multipath can cause severe nulls in channel frequency response (which would cause a severe noise enhancement problem for linear equalizers).
- Theoretically, a single-carrier DFE system offers the same anti-multipath and anti-noise capability as adaptive OFDM [Zer89].
- The minimum mean squared error (MMSE) adaptation criterion, which is relatively straightforward to implement, generally gives better performance than the zero-forcing criterion.
- Maximum likelihood sequence estimation (MLSE), sometimes called Viterbi equalization, is very effective, but is too complex for long impulse responses, unless the impulse response is truncated [Fal73], for example by a DFE forward filter [Mes74].

- A reduced-complexity (relative to a conventional DFE) time domain adaptive DFE for long impulse responses has been developed recently [Ari97]. It is summarized as follows:
    - First estimate the channel impulse response using training symbols or blind adaptation.
    - From the estimated response, determine a sampling time and DFE offset delay using a simple open loop timing criterion.
    - Use a long feedback filter, derived directly from the estimated channel response, to subtract prior decisions from the equalizer's input. The feedback filter's length would equal the span of the channel impulse response.
    - Use a short feedforward filter, operating at the symbol rate, to eliminate precursor ISI. The use of a long feedback filter (which operates on data symbols and can therefore avoid complex multiplies), and a short feedforward filter (which only does a small number of complex multiplies per input symbol) leads to significant complexity reduction.
    - Example [Ari97] for a ratio of (delay spread)/(symbol interval) of about 60: good performance with 5 forward taps, 60 feedback taps. This approach involved approximately 35 times fewer complex multiplies and 17 times fewer additions, than a comparable conventional DFE with a longer forward filter. The (larger) number of tap coefficients required for a conventional DFE, with or without additional space diversity, can be estimated from [Ari99].

6. Single-carrier modulation with Frequency Domain Adaptive Equalizer Processing

- Using single-carrier modulation and implementing a receiver equalizer in the frequency domain, by processing the FFT of the received signal [Sar95], [Ber95], [Kad97] has several potential advantages relative to time domain equalization and OFDM:
    - Use of single-carrier modulation reduces peak-to-average ratio and phase noise sensitivity problems of OFDM.
    - Frequency domain receiver processing has a similar complexity reduction advantage to that of OFDM: complexity is proportional to log of multipath spread.
    - Coding, while desirable, is not necessary for combating frequency selectivity, as it is in non-adaptive OFDM.
- Implementation of frequency domain adaptive equalization:
    - Usually, information is transmitted in blocks, to which a cyclic prefix is added to remove the effect of interblock interference [Cyl97], [Kad97], [Aue98], exactly the same as is done for OFDM systems. Overlap-save or overlap-add signal processing techniques could also be used to avoid the extra overhead of the cyclic prefix [Hay96], but they would substantially add to the complexity.
    - Linear equalization is just a form of linear filtering, which is done in the frequency domain on receiver input blocks, using FFT. An inverse FFT returns the equalized signal to the time domain prior to the detection of data symbols [Sar95], [Kad97]. Adaptation can be done with LMS (least mean square), or DMI (direct matrix inversion) techniques, analogous to adaptation of time domain equalizers [Hay96], [Cla98]. During its adaptation period, a frequency domain equalizer requires three FFT's or inverse FFT's [Cla98]; a comparable uncoded OFDM system requires two (one at the transmitter and one at the receiver).

  - Decision feedback equalization (DFE) gives better performance for frequency-selective radio channels than does linear equalization. In conventional DFE equalizers, symbol-by-symbol data symbol decisions are made, filtered, and immediately fed back to remove their interference effect from subsequently detected symbols. Because of the delay inherent in the block FFT signal processing, this immediate filtered decision feedback cannot be done in a frequency domain DFE, which uses frequency domain filtering of the fed-back signal. [Ber95] describes a version of a frequency domain DFE, which feeds decisions back after a certain delay. However the effect of this delay on the equalizer's performance over a wide range of radio channel responses is unclear.
  - An alternative frequency domain DFE approach, which avoids the abovementioned feedback delay problem would be to use frequency domain filtering only for the forward filter part of the DFE, and use conventional transversal filtering for the feedback part. The transversal feedback filter is relatively simple in any case, since it does not require complex multiplies, and it could be made as short or long as is required for adequate performance. In a sense this is an inverse approach to that advocated in [Ari97], in that here the forward filter of the DFE is long, and its complexity is reduced by implementation in the frequency domain, while the feedback filter length may be moderate. This approach could also be used to limit possible DFE error propagation problems, or to implement MLSE equalization with a suitable truncated impulse response [Fal73], [Mes74]. Such a DFE system would train, using frequency domain processing to compute forward equalize parameters and a small matrix inversion to compute the time domain feedback taps.
  - Frequency domain equalization can be combined with spatial processing to provide interference suppression and diversity [Cla98].

7. Comparisons

- [Cyl97] compares uncoded adaptive OFDM (where the bit rate, signal constellation and power of each OFDM subchannel is optimized for the overall frequency selective channel), uncoded non-adaptive OFDM, and single-carrier modulation with adaptive linear equalization. Simulations were done using measured radio channel responses with ratios of (delay spread)/(bit interval) up to about 25. Adaptive OFDM outperformed the other systems, but non-adaptive OFDM had the worst performance, especially at high SNR.
- [Aue98] compares coded linearly equalized single-carrier modulation with coded non-adaptive OFDM on the basis of the cutoff rate random coding bound for two-ray Rayleigh fading channels. Both systems had similar performance at low to moderate code rates, while the coded linearly equalized single-carrier modulation system exhibited better performance at higher code rates.
- The above results for single-carrier modulation assumed *linear equalization*. For radio channels with severe multipath, decision feedback equalization will substantially outperform linear equalization, as pointed out earlier.
- Complexity comparisons:
  - [McD96] compares the complexity (measured by numbers of real multiplies required per second) for uncoded, nonadaptive OFDM and conventional single-carrier modulation with time domain DFE equalization approaches. The comparison was done for bit rates up to 100 Mb/s and dispersive channels with delay spreads up to about 10 times the symbol rate (FFT sizes of up to 256 were considered for the OFDM approach and feedback filter lengths of up to 10 symbols were considered for the conventional DFE approach, for example). For the highest bit rates the OFDM system complexity (not including the complexity of coding, decoding and

synchronization components) was typically on the order of 10% of that of the conventional single-carrier/DFE approach.

- Note however that if frequency domain DFE processing were done, the equalization complexity of the single-carrier/DFE approach would be roughly equivalent to that of the OFDM approach. An analysis of the complexity of the combined frequency- and time-domain training of the DFE receiver mentioned above indicates a number of complex multiplies per data symbol of on the order of $(3/2) \log_2 M + B$, where M is the FFT block size (typically 4 to 10 times the maximum impulse response span), and B is the (small) number of feedback taps. A comparable figure for OFDM, including transmitter and receiver FFT processing, is about $\log_2 M$.
- Furthermore, the evaluation of complexity in the simplified approach in [Ari97] indicates that this approach for time domain DFE equalization for single-carrier modulation could have comparable or even less complexity than the OFDM approach for high bit rates and severely dispersive channels.

8. Conclusions

Fixed wireless access systems providing high bit rate access to residential and small-business subscribers in non-LOS environments may be subject to severe time dispersion, spanning many bit intervals. For symbol rate of 6 Msymbols/s or less, and with the maximum delay spreads of about 1 μs reported in [Erc99], single-carrier modulation with relatively simple decision feedback equalization would seem to offer the best performance/complexity tradeoff. For higher bandwidths and bit rates, or more severe multipath dispersion, modulation and equalization strategies based on OFDM could be considered. However, OFDM is very sensitive to power amplifier nonlinearities and frequency offsets. Single-carrier modulation, using either reduced complexity time-domain equalization, or frequency domain equalization at the receiver, should also be seriously considered, since it has less sensitivity to transmitter nonlinearities and to phase noise than does OFDM, its complexity may be comparable or less, and its performance may be equal or better than that of non-adaptive OFDM. In any case it is important to evaluate any proposed PHY air interface solution against appropriate models of nonlinearity and frequency instability.

Furthermore, single carrier techniques can be easily combined with MIMO (multiple-input, multiple-output) techniques, in which both transmitting and receiving ends use arrays of antenna elements; MIMO techniques can potentially achieve enormous spectral efficiencies (bit/s/Hz), limited only by the number of antenna elements which can be practically implemented [Fos99]. This, in turn, relieves the delay spread issues, since the desired bit rate is achieved without increasing the symbol rate.

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