

Update on CE-OFDM Waveforms For Use on HF Channels

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Presentation Overview



- OFDM Waveform
- CE-OFDM Waveform
- RF Power Amplifiers
- System Models
- Performance
- Summary

- OFDM
 - Orthogonal Frequency Division Multiplexing
 - An OFDM frame is created by transmitting data using N orthogonal tones in parallel
 - Addition of a guard-time removes inter-frame interference
 - Coherent Modulation
 - Equalizer in frequency domain becomes a single complex tap per OFDM tone
 - Differential Modulation
 - No equalizer required
 - IFFT (TX) and FFT (RX) are very efficient signal processing blocks that can be used to generate and demodulate OFDM
 - Can use complex modulations
 - 2-PSK, 4-PSK, 8-PSK, 16-QAM

- Disadvantage of OFDM
 - High Peak-power to Average-power Ratio (PAR)
 - Worst case - $10 \log_{10}(N)$
 - Typical – 10-14 dB for $N > 16$
 - Requires very linear power amplifier (PA)
 - Class A or Class A-B
 - Distortion and spectral re-growth caused by PA
 - For some applications (i.e. handheld devices, battery powered), Class C amplifiers desired ??

OFDM Waveform Parameters

	OFDM
Frame Size (samples)	256 (i.e. FFT Size)
Number of Data Tones	64
Guard Time (samples)	32
Sample Rate (samples per second)	9600
Frame Time (ms)	30
First Tone Location	8
Tone-to-Tone Bandwidth (Hz)	2400
Modulation	2-PSK, 4-PSK, 8-PSK, 16-QAM
FEC	Rate 1/2 k=7
APBO*	6 dB
Clip Level	6 dB

*APBO is the Average Power Backoff into PA

- Constant Envelope Orthogonal Frequency Division Multiplexing (CE-OFDM)
 - Exploit some of the ideas used in OFDM
 - Phase modulate a carrier with a time-domain waveform similar to OFDM
 - Constraints imposed by phase modulation
 - One-dimensional modulation
 - M-ary Pulse-amplitude modulation (M-PAM)
 $\pm 1, \pm 3, \dots, \pm(M - 1)$
 - Real-valued message signals (i.e. sub-carriers)
 - Half-wave cosines
 - Half-wave sines
 - Full-Wave cosines and sines
 - Cyclic prefix (guard-time) allows the use of a frequency-domain equalizer prior to phase demodulation

- 64 Sub-Carriers, 2-PAM modulation (-1, 1 symbols), $C_N = \text{square root of } (2.0/64.0)$, T_B is CE-OFDM frame time (not including guard time), $h = \text{modulation index}$

$$q_k(t) = \begin{cases} \cos(\pi kt / T_B), 0 \leq t \leq T_B \\ 0, \text{otherwise} \end{cases} \quad (1)$$

$$\phi(t) = \phi_i + 2\pi h C_N \sum_{k=1}^N I_{i,k} q_k(t - iT_B), iT_B \leq t \leq (i+1)T_B$$

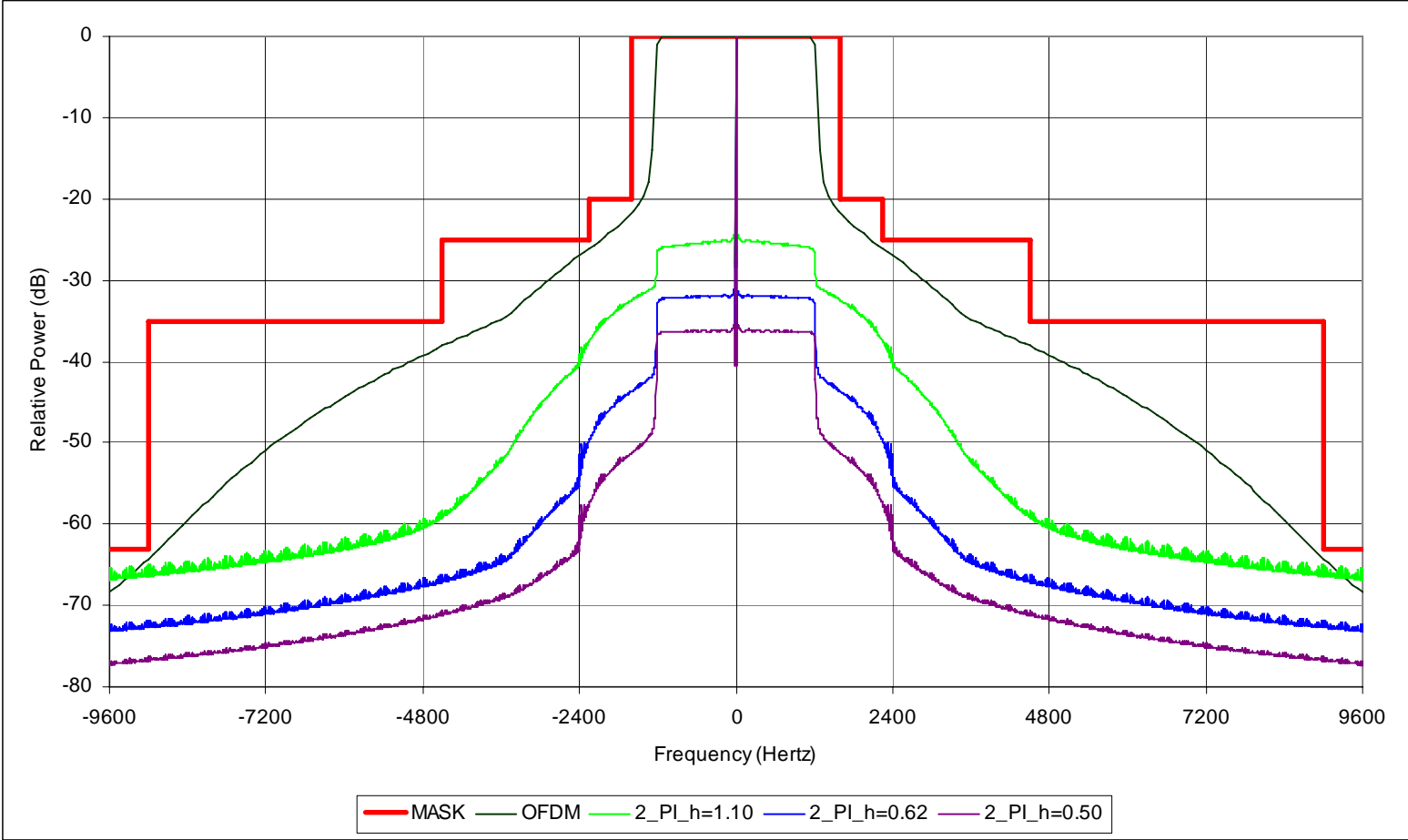
$$s(t) = A e^{j\phi(t)} \quad (2)$$

CE-OFDM Waveform Parameters

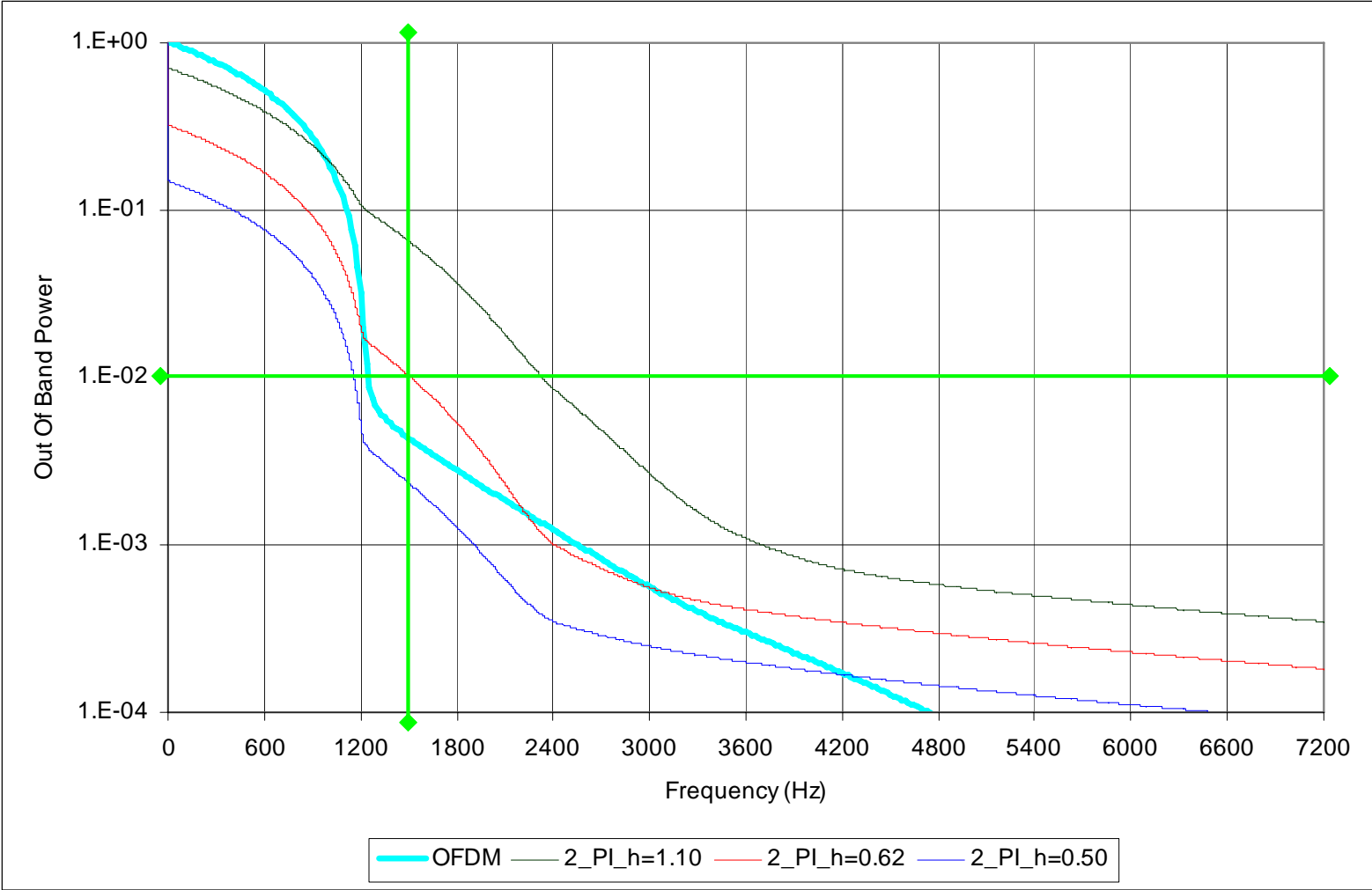
	CE-OFDM
Frame Size (samples)	1024
Number of Data Tones	64
Guard Time (samples)	128
Sample Rate (samples per second)	38400
Frame Time (ms)	30
First Tone Location	-
Tone-to-Tone Bandwidth (Hz)	-
Modulation	2-PAM, 4-PAM, 8-PAM, 16-PAM
FEC	Rate 1/2 k=7
Modulation Index	$h=0.62/TWO_PI$

- Radio Frequency (RF) Power Amplifier (PA)
 - Typically peak-power limited
 - PAs deviate from ideal ones in region where maximum input/output power levels are approached
 - Produce non-linear behavior
 - Amplitude distortion
 - Phase distortion
 - Spectral re-growth
 - Most systems constrain the out-of-band power emissions by defining a spectral mask and a percent power bandwidth

Power Spectrum



Out-Of-Band Power



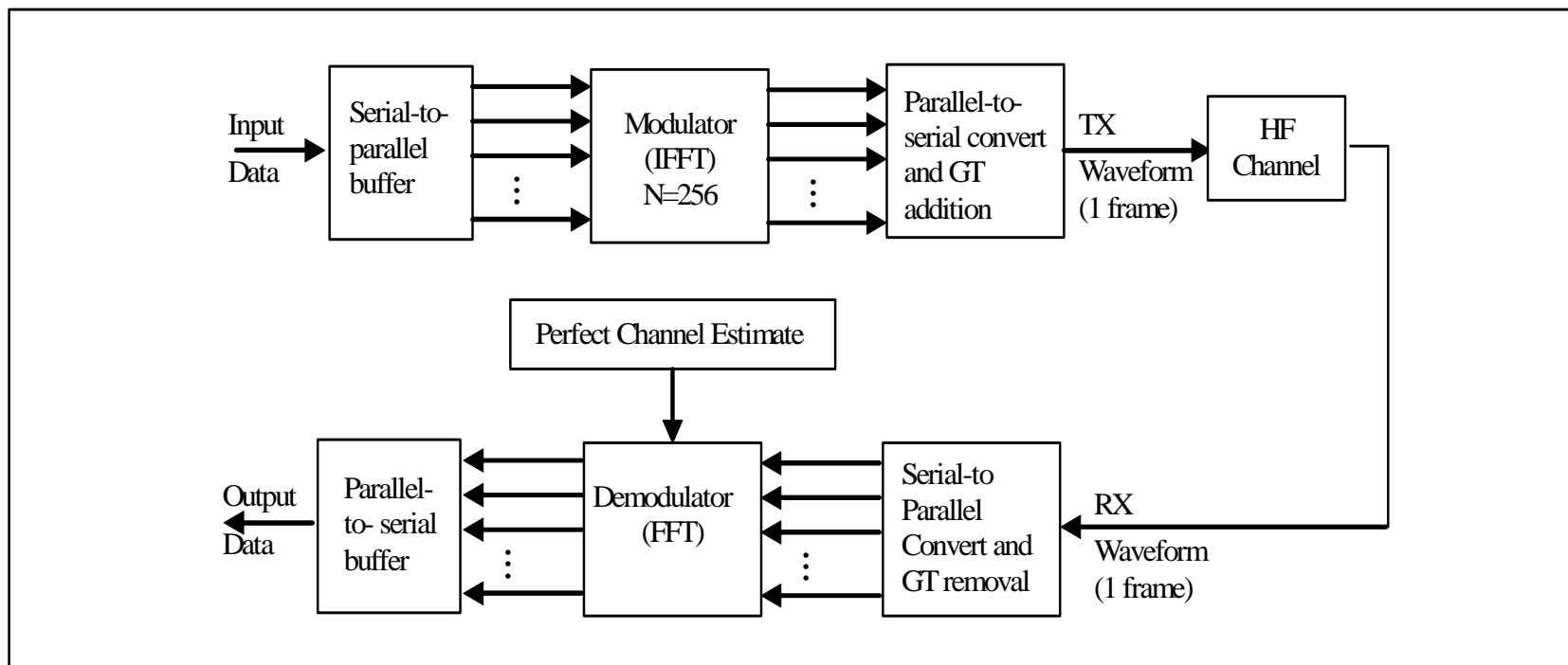
Percent Power Bandwidths

	99.00 % (Hertz)	99.90 % (Hertz)	99.99 % (Hertz)
OFDM	2475	5100	9488
2_PI_h=1.10	4664	7399	28453
2_PI_h=0.80	3792	5944	25458
2_PI_h=0.62	3028	4816	21551
2_PI_h=0.60	2910	4713	20960
2_PI_h=0.50	2407	4312	17461
2_PI_h=0.40	2316	3811	13094

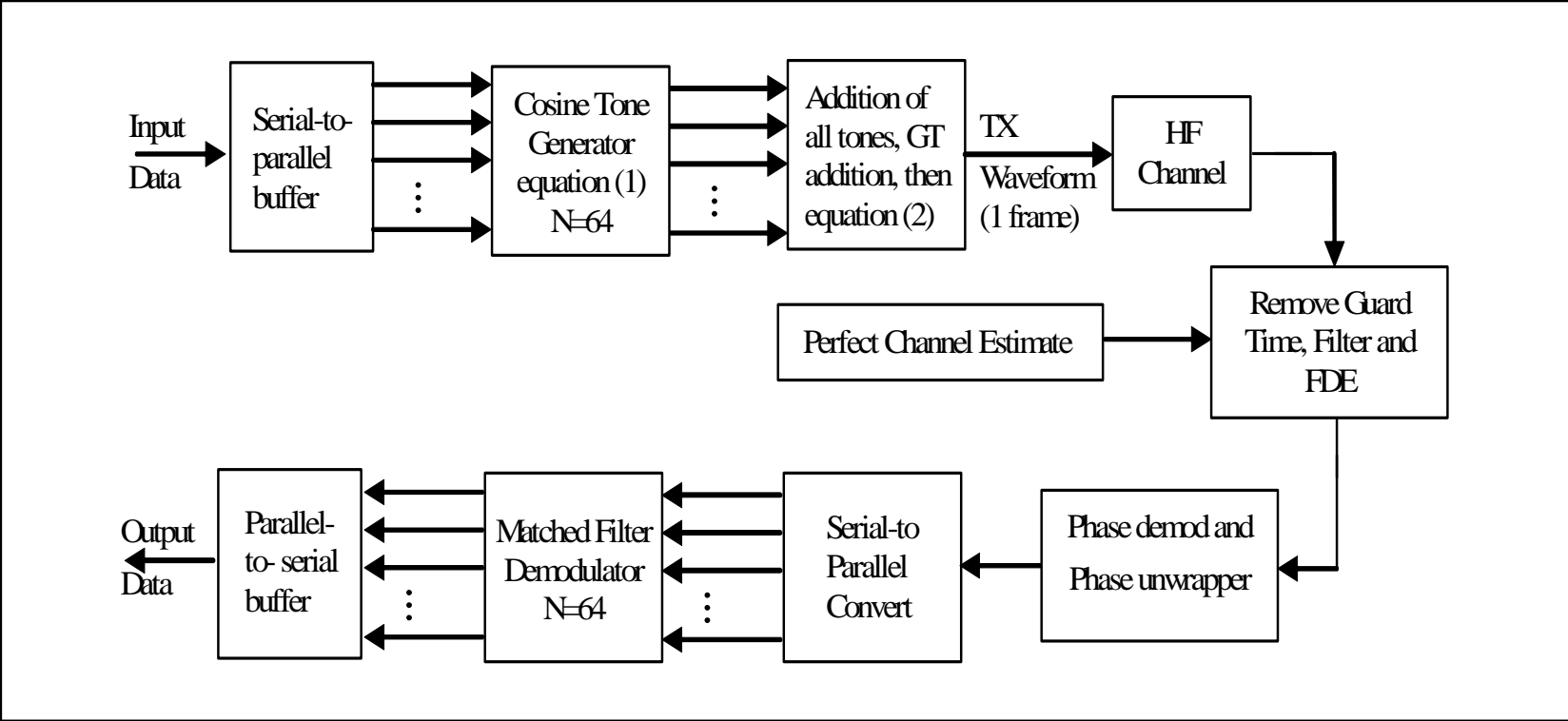
For OFDM, backing off the PA by 6 dB reduces actual on-air average transmitted power by 6 dB

For performance testing, CE-OFDM will use 2_PI_h=0.62

OFDM System Model

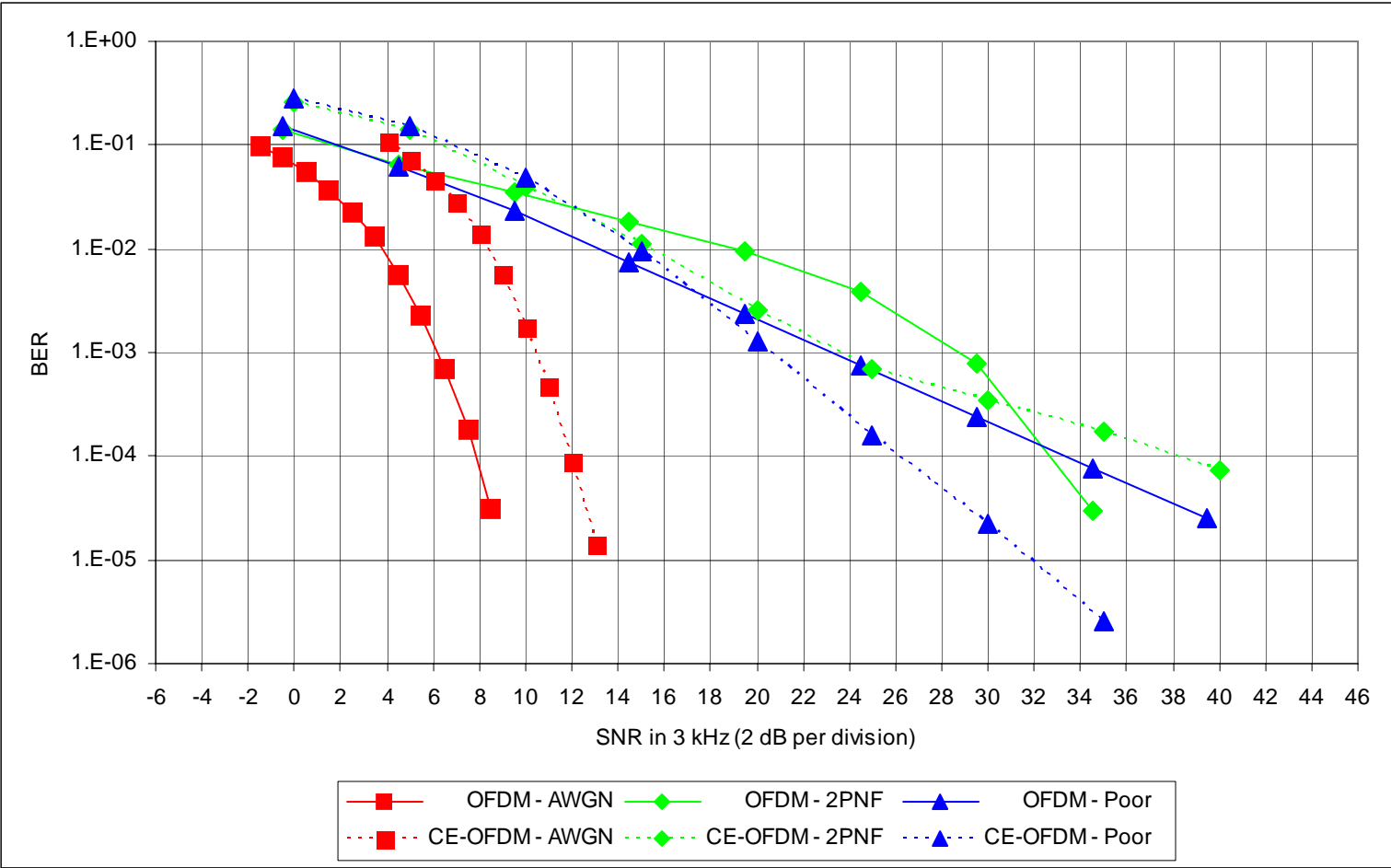


CE-OFDM System Model

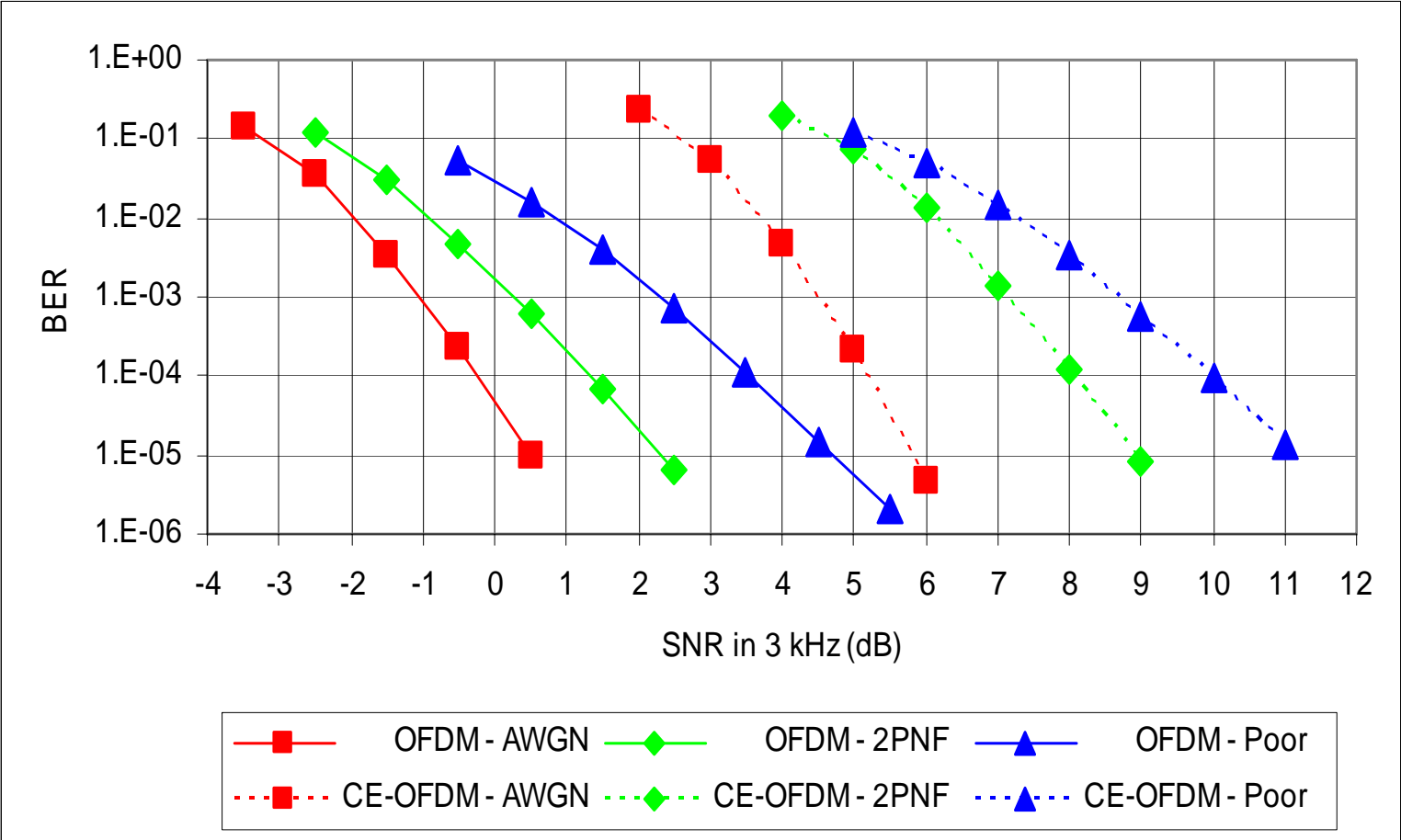


- Channels used for BER performance testing
 - AWGN channel (label = AWGN)
 - Non-Fading multipath channel (label = 2PNF)
 - 2 equal power paths
 - 2 ms apart
 - HF Channel (label = Poor)
 - ITU Mid-Latitude Disturbed Channel
 - 2 equal power paths
 - Each path fades independently with a 1 Hz fade rate
 - 2 ms apart

Uncoded OFDM and CE-OFDM Waveforms (2-PSK, 2133.33 bps)



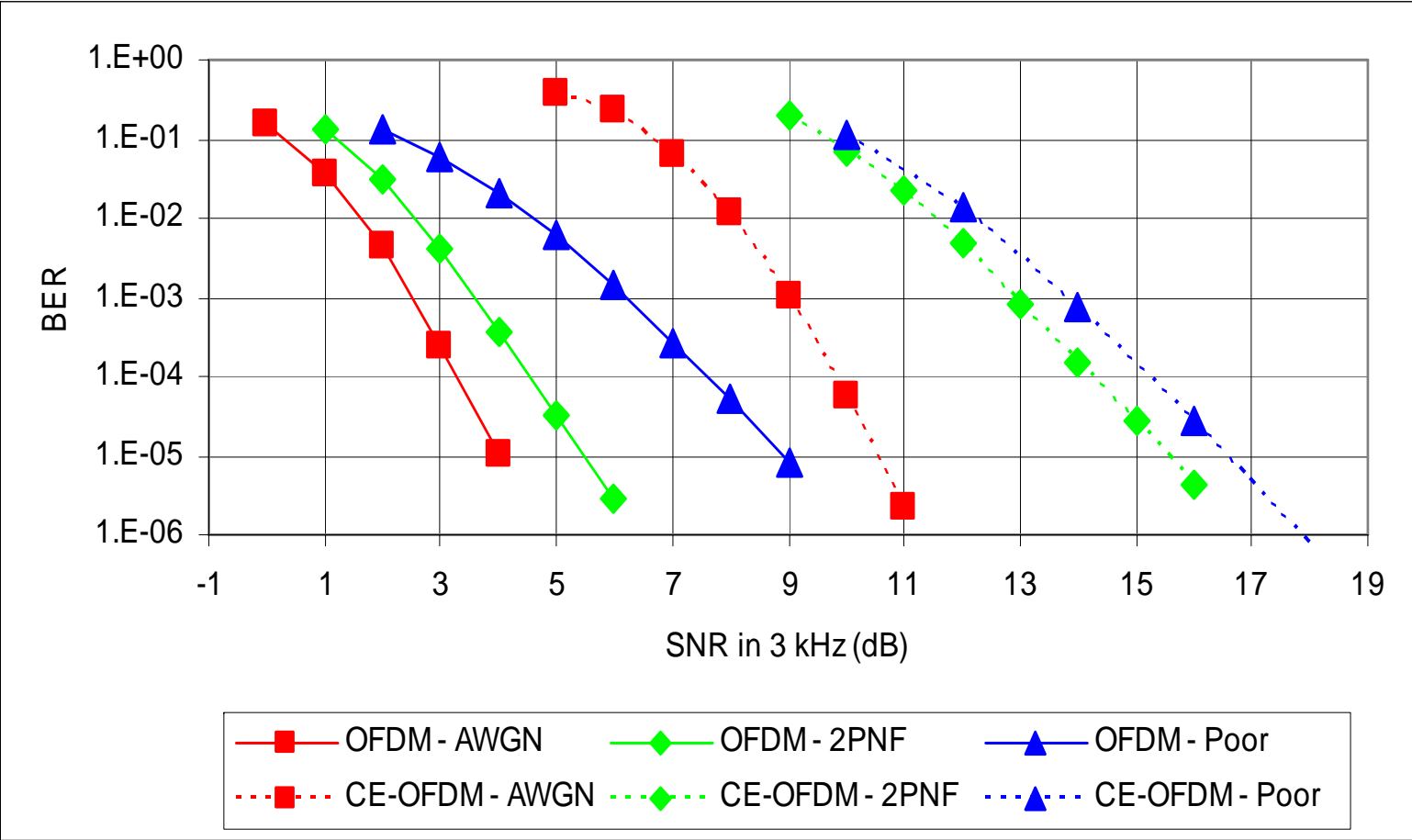
Rate 1/2 2-PSK OFDM and CE-OFDM Waveforms (1067 bps)



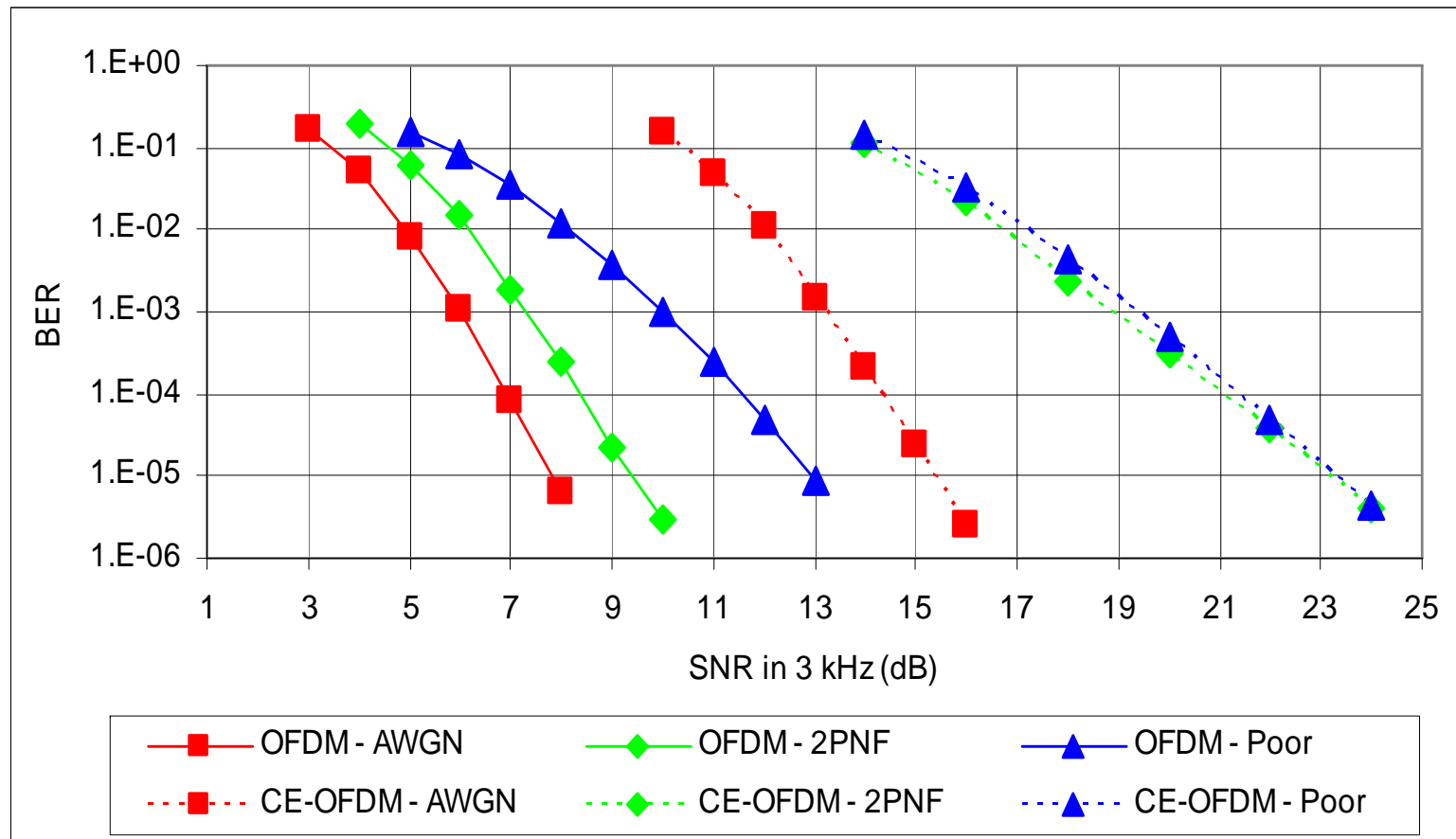
- Based purely on SNR
 - Uncoded @ BER = 10^{-4}
 - OFDM 4 dB better on AWGN
 - OFDM 5 dB better on 2PNF
 - CE-OFDM 7 dB better on Poor
 - Coded @ BER = 10^{-5}
 - OFDM 5.3 dB better on AWGN
 - OFDM 6.7 dB better on 2PNF
 - OFDM 10.2 dB better on Poor

- Based on SNR + Average Power Backoff (APBO)
 - Uncoded @ BER = 10^{-4}
 - CE-OFDM 2 dB better on AWGN
 - CE-OFDM 1 dB better on 2PNF
 - CE-OFDM 13 dB better on Poor
 - Coded @ BER = 10^{-5}
 - CE-OFDM 0.7 dB better on AWGN
 - OFDM 0.7 dB better on 2PNF
 - OFDM 4.2 dB better on Poor

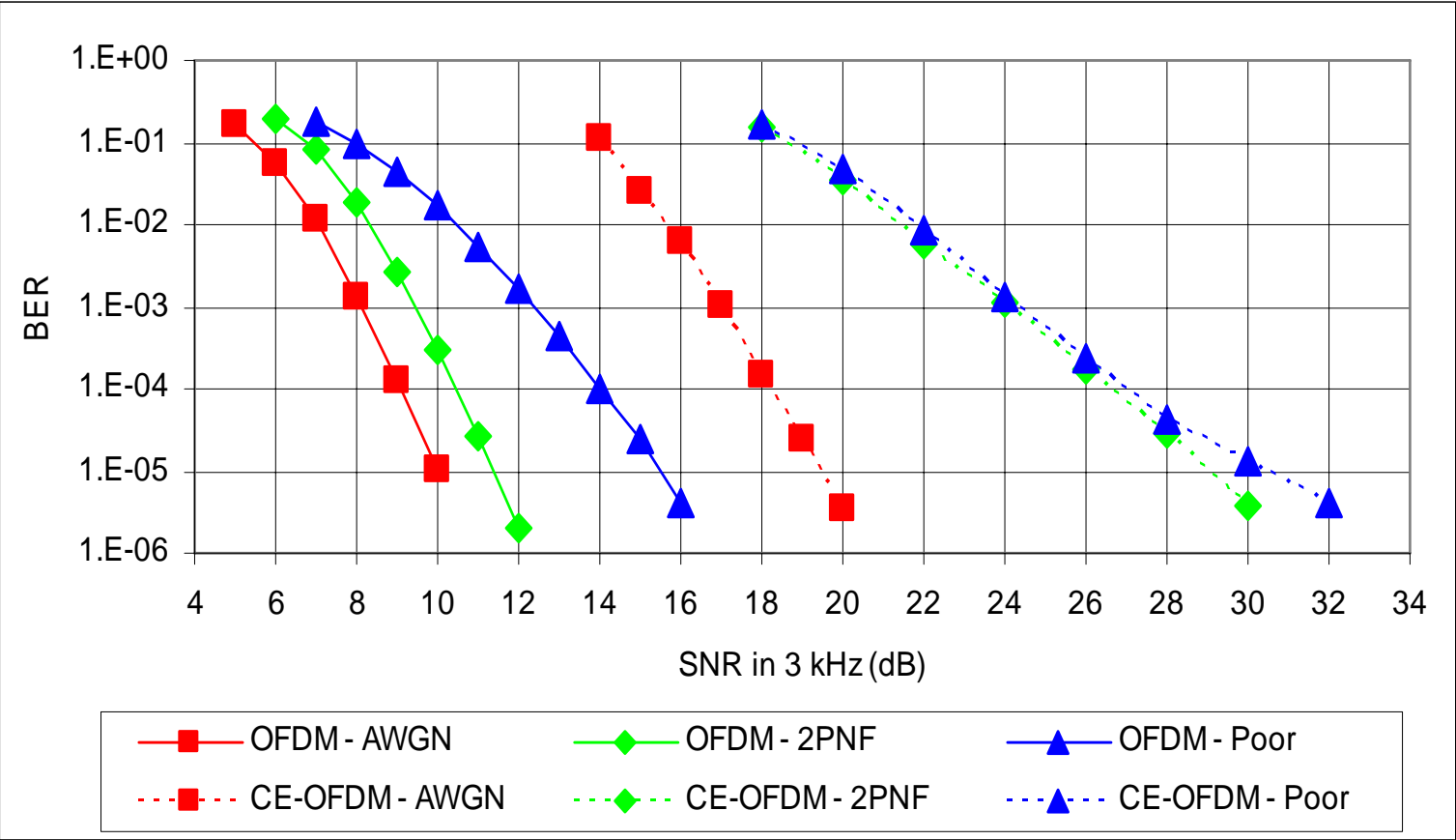
Rate 1/2 4-PSK OFDM and 4-PAM CE-OFDM Waveforms (2133 bps)



Rate 1/2 8-PSK OFDM and 8-PAM CE-OFDM Waveforms (3200 bps)



Rate 1/2 16-QAM OFDM and 16-PAM CE-OFDM Waveforms (4267 bps)

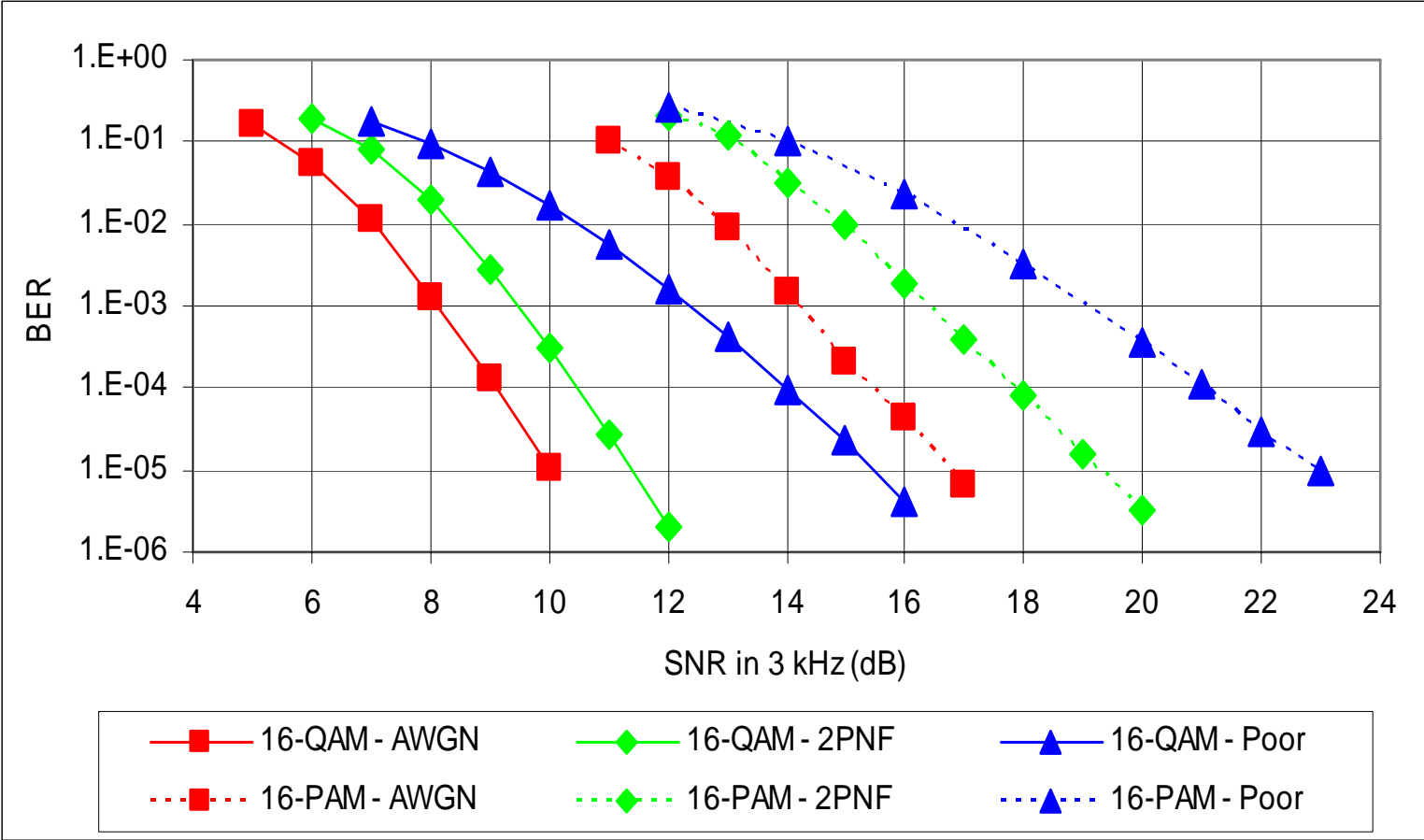


Performance



	OFDM	OFDM	CE-OFDM	Delta	Channel
	SNR (dB)	SNR + APBO (db)	SNR (dB)	(dB)	
2-PSK (OFDM) 2-PAM (CE-OFDM)	0.5	6.5	5.8	-0.7	AWGN
	2.3	8.3	9.0	0.7	2PNF
	4.6	10.6	11.0	0.4	Poor
4-PSK (OFDM) 4-PAM (CE-OFDM)	4.0	10.0	10.5	0.5	AWGN
	5.5	11.5	15.5	4.0	2PNF
	9.0	15.0	16.5	1.5	Poor
8-PSK (OFDM) 8-PAM (CE-OFDM)	8.0	14.0	15.5	1.5	AWGN
	9.5	15.5	23.0	7.5	2PNF
	12.8	18.8	23.0	4.2	Poor
16-QAM (OFDM) 16-PAM (CE-OFDM)	10.0	16.0	19.5	3.5	AWGN
	11.5	17.5	29.0	11.5	2PNF
	15.5	21.5	30.0	8.5	Poor

Rate 1/2 16-QAM and 16-PAM OFDM Waveform



- CE-OFDM's constraint of purely real modulations requires much higher SNR per added bit than complex modulations (i.e. 16-PAM instead of 16-QAM)
- The use of a linear frequency domain equalizer provides poor performance on multipath fading channels
- Unless new demodulation techniques can be developed to improve the performance of CE-OFDM, its constant envelope property comes at too high an SNR price to make it a practical high data rate solution for HF
- Note that CE-OFDM's demodulation process is significantly more computationally complex than OFDM
- Even if PA efficiency is used instead of APBO (i.e. additional 1.1 dB penalty for OFDM waveform), CE-OFDM will not outperform OFDM above 4-ary modulations