Waveform Design Choices for Wideband HF

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Presentation Overview

- Motivation
- Waveforms Design Objectives
- Waveform Choices
- Summary

Motivation

- There is a need for higher data rates on HF links
- Current 3 KHz allocations can provide a maximum of 9600 bps
  - Wider bandwidth HF systems can provide much higher data rates
  - Wider bandwidth HF systems can provide same data rates as 3 KHz with lower SNR requirements
    - 9600 bps in 3 KHz utilizes 64-QAM
    - 9600 bps in 6 kHz utilizes 8-PSK
      - 9600 bps would work more often on HF links using 6 KHz than 3 KHz

Waveforms Design Objectives

- Design a family of waveforms which support the following:
  - Multipath
    - Up to 6 msec.
  - Doppler Spread
    - Up to 8 Hz for lower data rate waveforms
    - Up to 2 Hz for higher data rate waveforms
  - Bandwidths
    - 3 KHz, 6 KHz, 12 KHz, 24 KHz
      - For better utilization of channel allocations include
        - 9 KHz, 15 KHz, 18 KHz, 21 KHz
  - Max Data Rate (24 KHz)
    - Close to 76800 bps (i.e. 8x9600)

- Waveform Choices
  - Single-Carrier equalized waveform
    - Single-carrier (Single-Sideband)
    - Multiple-carriers (Multiple-Sidebands)
  - Multi-tone Waveform
    - Orthogonal Frequency Division Multiplexing (OFDM)

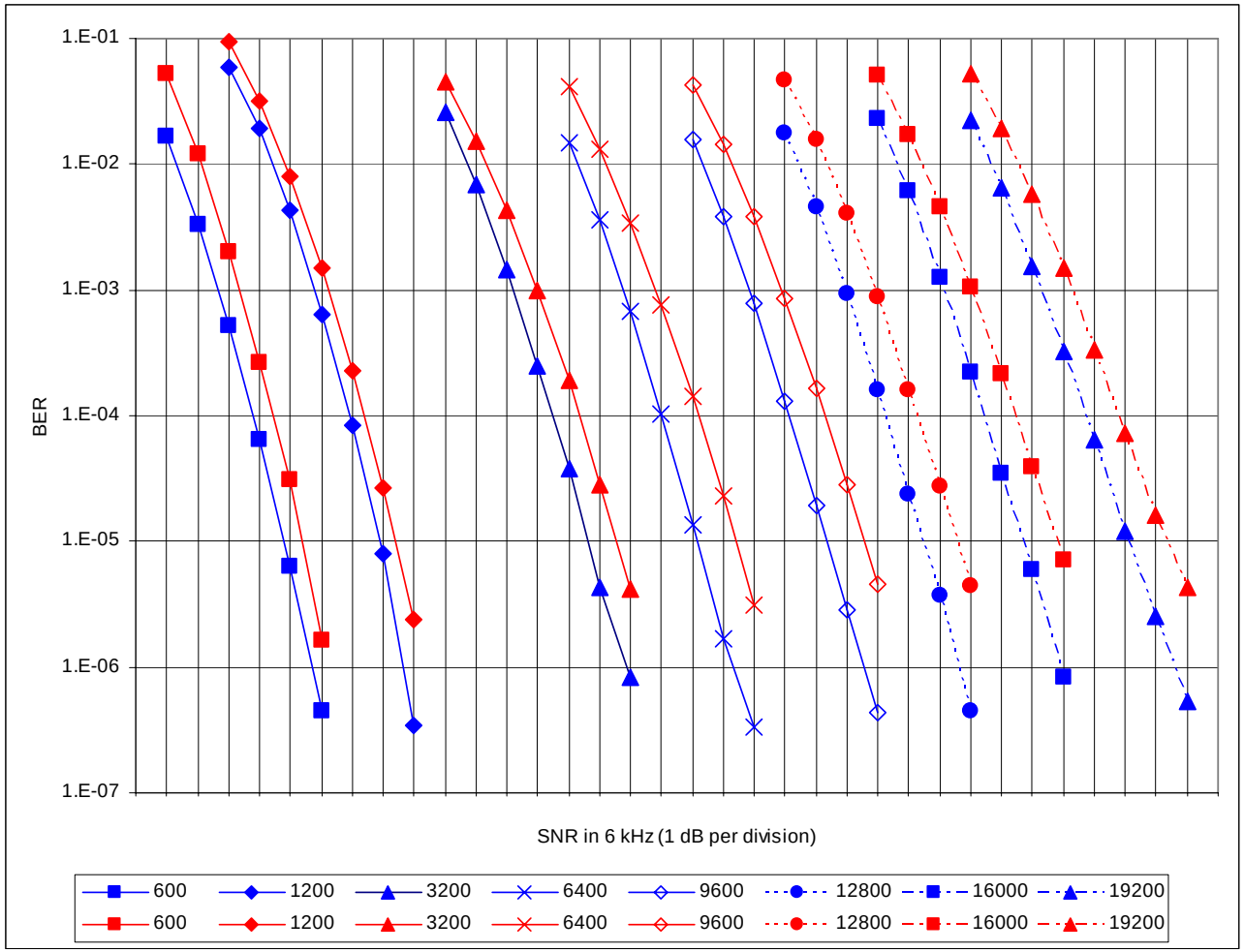
- Single Carrier Single-Sideband Equalized Waveform
  - Advantages
    - Much lower Peak Power to Average Power Ratio (PPAPR) than OFDM
    - Channel estimation process provides a processing gain
      - In 3 KHz, 16 symbols used to compute each tap of channel estimate (i.e. 12 dB gain)
        - Channel estimates are much higher quality than actual SNR of demodulated data
    - Flexibility to select multipath and Doppler spread capability
      - Many sequences to choose from for channel estimate
        - Heimiller sequences (9, 16, 25, 36, 49, 64, 81, 100, 121)
        - Mini-probe length is at least (2*sequence_length) - 1
      - Sequence insertion rate determines Doppler spread capability
        - 128 Data Symbols followed by 32 Mini-probe Symbols can handle twice the Doppler spread of 256 Data Symbols followed by 32 Mini-probe symbols

- Single-Carrier Single-Sideband Equalized Waveform
  - Disadvantages
    - Computational complexity of equalizer increases very quickly as bandwidth is increased (for same multipath capability)
  - One approach to reduce computational complexity
    - Use multiple carriers instead of 1 carrier
      - 8 carriers (each 3 Khz wide) instead of 1 carrier (24 KHz wide)
        - Equalizer complexity is only 8x complexity of 3 KHz waveform

- Single-Carrier Single-Sideband Equalized Waveform
  - 24 KHz
    - Symbol Rate 19200 (i.e. 8x2400)
    - In order to handle 6 msec. of multipath
      - Channel estimate at least 116 symbols
        - Heimiller sequence of length 121 (mini-probe >= 241 symbols)
      - Equalization process significantly more complex (64 times more complex than 3 KHz)
    - Benefits
      - PPAPR similar to US MIL-STD-110B single-carrier waveforms
        - Approximately 4.5-5.5 dB for 64-QAM
      - Excellent equalizer performance in multipath channels
      - Performance of waveforms similar to performance of 110B Appendix C waveforms (for same constellation size and code rate)
        - 9600 bps requires 21 dB SNR in 3 KHz (AWGN, 64-QAM, rate 3/4 code)
        - 38400 bps requires 21 dB SNR in 12 KHz (AWGN, 64-QAM, rate 3/4 code)

- Single Carrier (SC) Waveform - Multiple-Sideband Equalized Waveform
  - Advantage
    - Lower computational complexity than single-carrier equalized waveform approach
  - Disadvantage
    - PPAPR increases as the number of carriers increases
      - 2 carriers approximately 2-3 dB worse PPAPR
      - 4 carriers approximately 5-6 dB worse PPAPR
      - 8 carriers approximately 8-9 dB worse PPAPR
      - Based on PPAPR, no more than 2 carriers would be practical for use on HF due to high PPAPR penalty
    - Bit Error Rate (BER) performance about 1 dB worse than single-carrier approach (see next page)
      - SNR is signal-to-noise ratio in a specified bandwidth

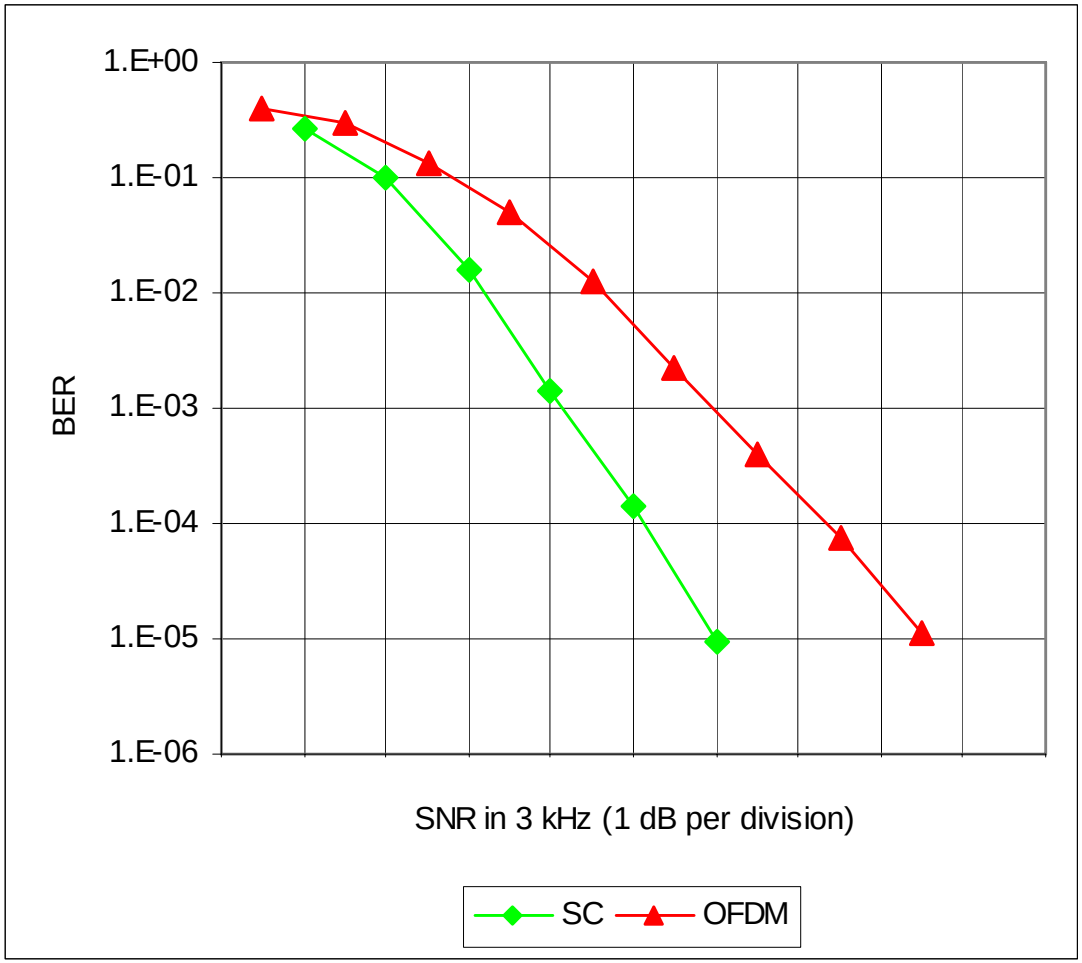
Performance of SC 1-Sideband (Blue) and SC 2-Sideband (Red) 6 KHz Waveforms for 2 Path (Equal Power) 2 Ms 1 Hz Channel (ITU Mid-Latitude Disturbed Channel)



Waveform Choices

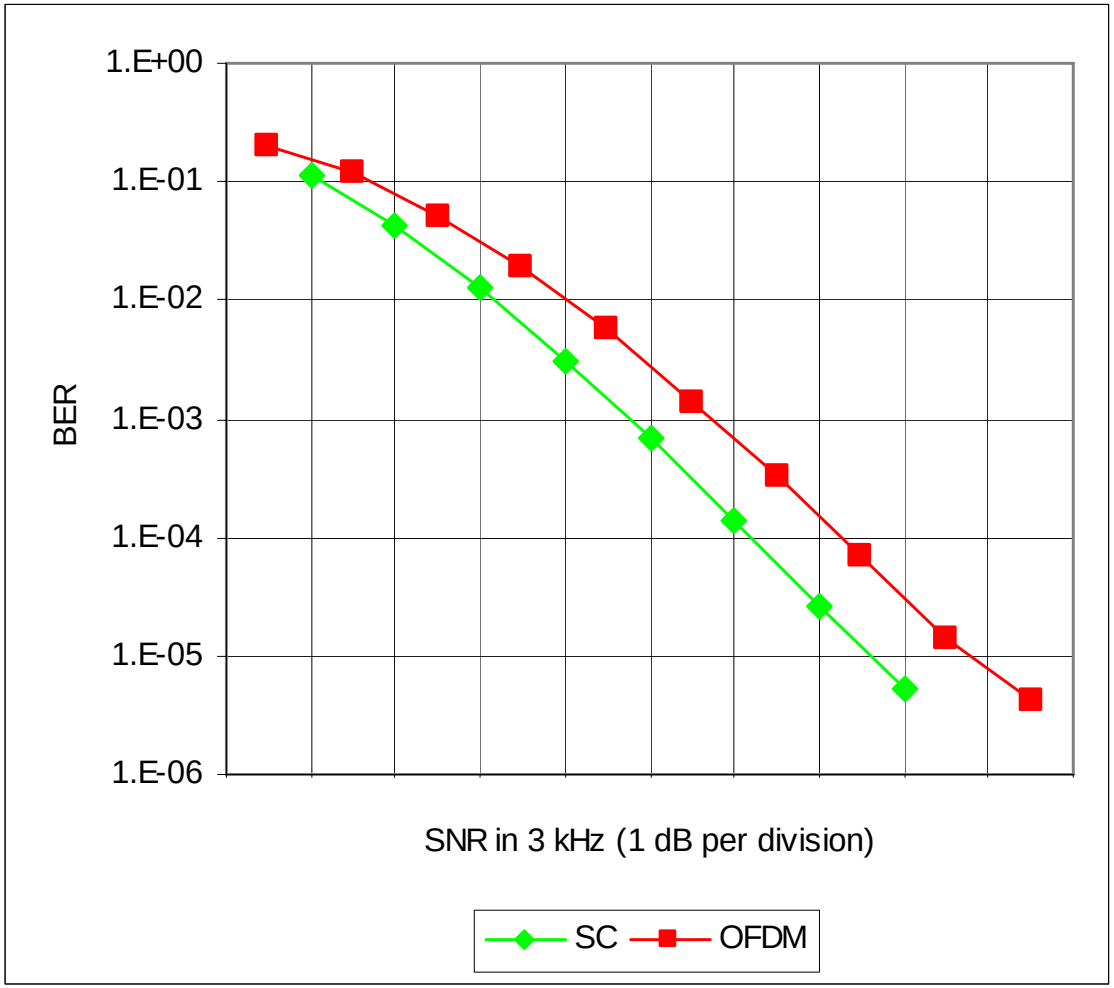
- Multi-tone Waveform - OFDM
  - Advantages
    - Guard time removes the need for a complex equalizer
  - Disadvantages
    - Loss of information (i.e. faded tones) due to frequency selective fading
    - Sensitive to ripple in passband of analog/digital filters
    - High PPAPR
    - Higher data rates require coherent processing (i.e. 16-QAM, 32-QAM, 64-QAM)
      - Larger Power Amplifier back-off required to support 32-QAM, 64-QAM SNR
        - Less average power transmitted
      - Pilot tones must be inserted in frequency domain to estimate channel
      - Every FFT bin carrying data in frequency domain requires a channel estimate
      - No processing gain for pilot tones
        - Channel estimate SNR same as demodulated data
      - Pilot tone insertion rate determined by multipath capability
        - Interpolation over time and frequency can reduce the required number of pilot tones
    - On multipath fading channels, no OFDM waveform (using perfect channel state information) has outperformed single-carrier equalized waveforms using mini-probe for channel estimate

Performance of 2-PSK for 2 Equal Power (2 msec) Non-Fading Path Channel



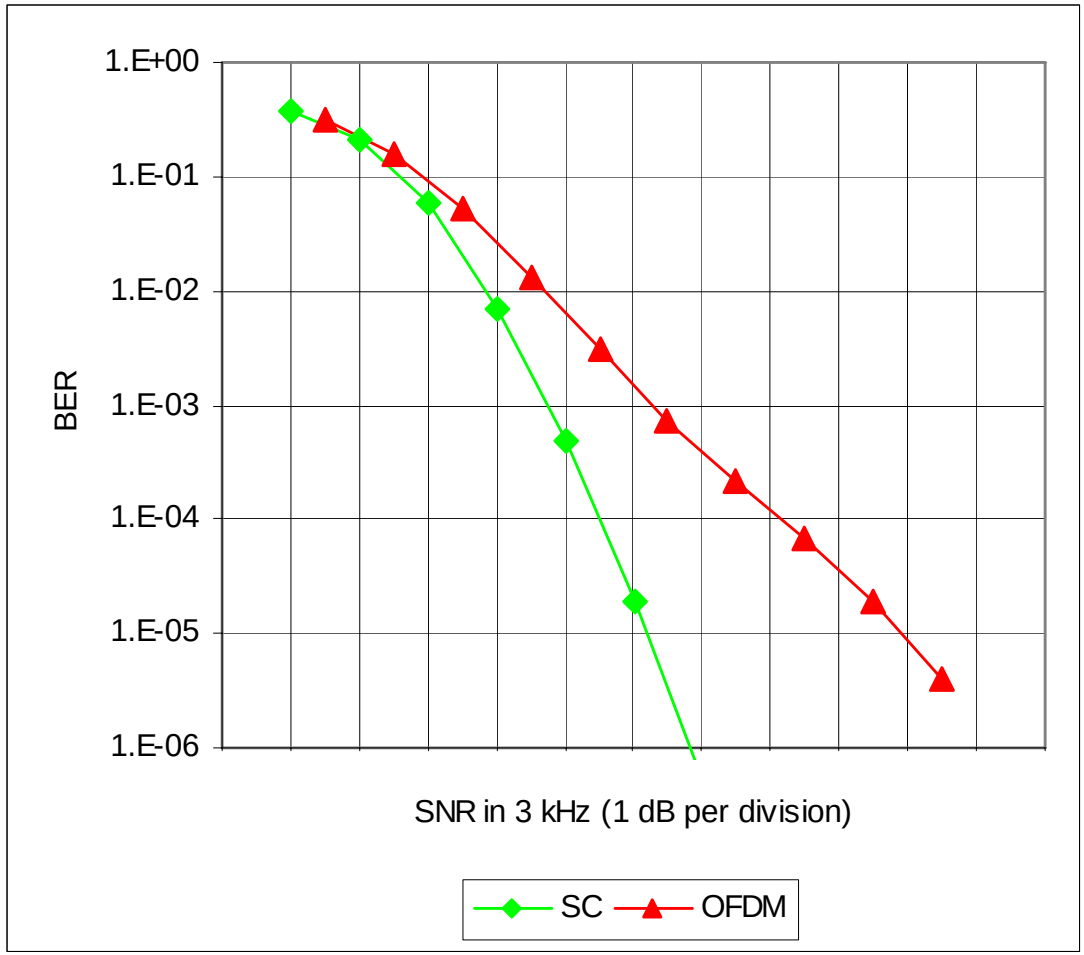
OFDM demodulation process utilizing perfect channel state information

Performance of 2-PSK for 2 Path (Equal Power) 2 Ms 1 Hz Channel



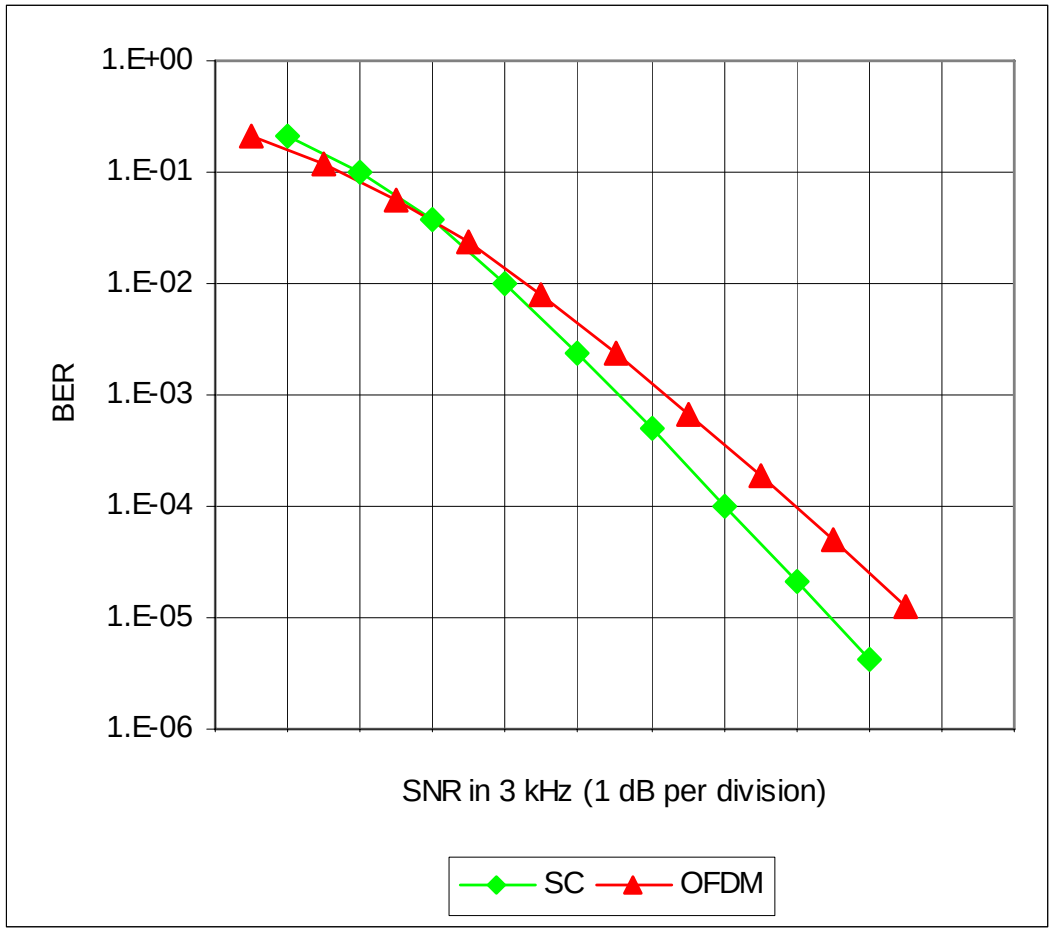
OFDM demodulation process utilizing perfect channel state information

Performance of 4-PSK for 2 Equal Power (2 msec) Non-Fading Path Channel



OFDM demodulation process utilizing perfect channel state information

Performance of 4-PSK OFDM and SC Waveform for a 2 Path 2 Ms 1 Hz Channel



OFDM demodulation process utilizing perfect channel state information

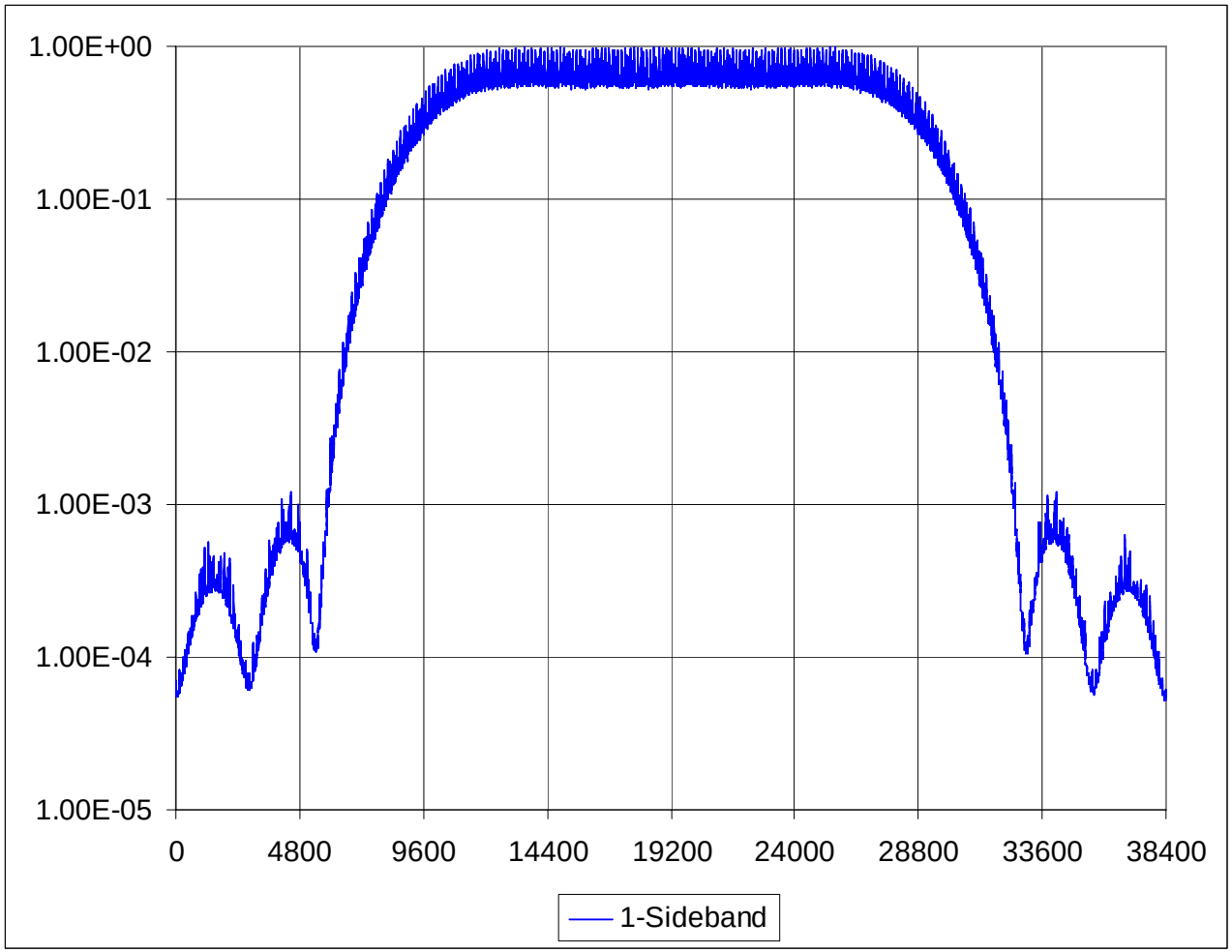
Comparison of Average Transmit Power (ATP), Measured Average Power Back-Off (MAPBO) into Power Amplifier and Receive SNR (RX SNR) for Single-Carrier and Multi-Tone US MIL-STD-110B 3 KHz Waveforms

	SC_2400	39T_2400	SC_9600
ATP	10 Watts	6 Watts	8 Watts
MAPBO	3 dB	5.3 dB	4 dB
RX SNR	30 dB	21 dB	30 dB

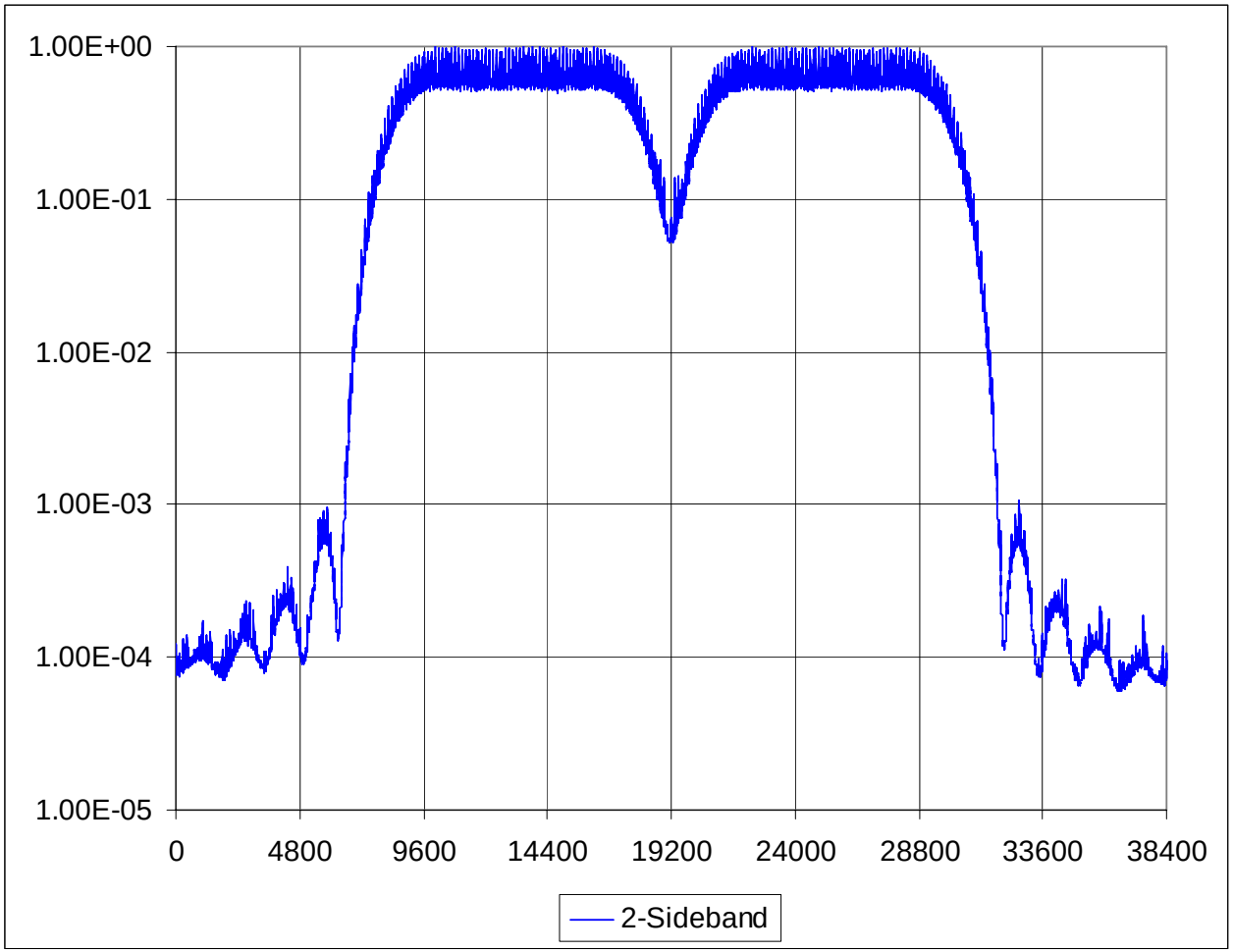
Note that OFDM waveform (39T_2400) was soft-clipped in order to increase ATP

RF-5800H Radio Used for all measurements

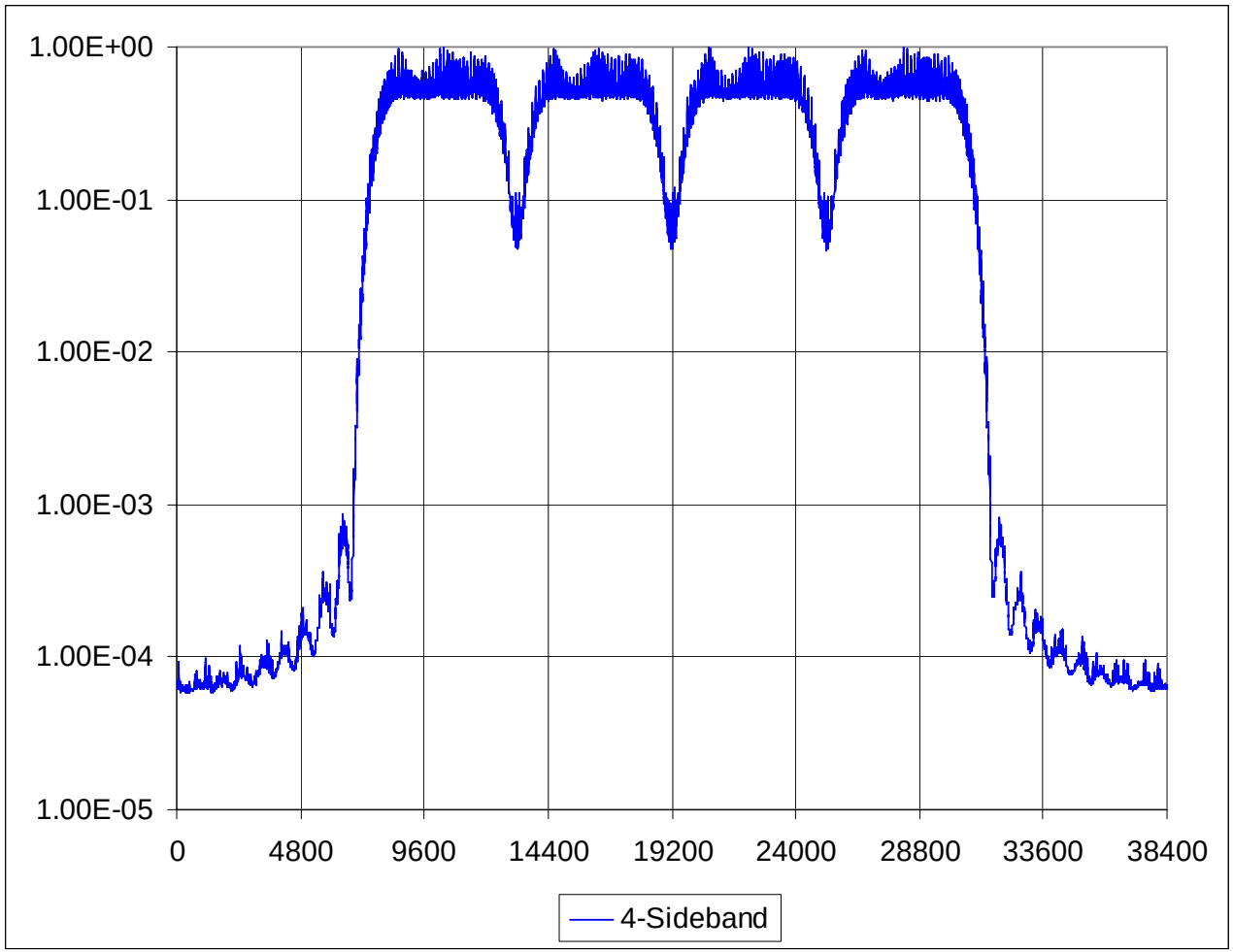
Frequency Spectrum of SC 24 KHz Waveform on a 19.2 KHz Carrier



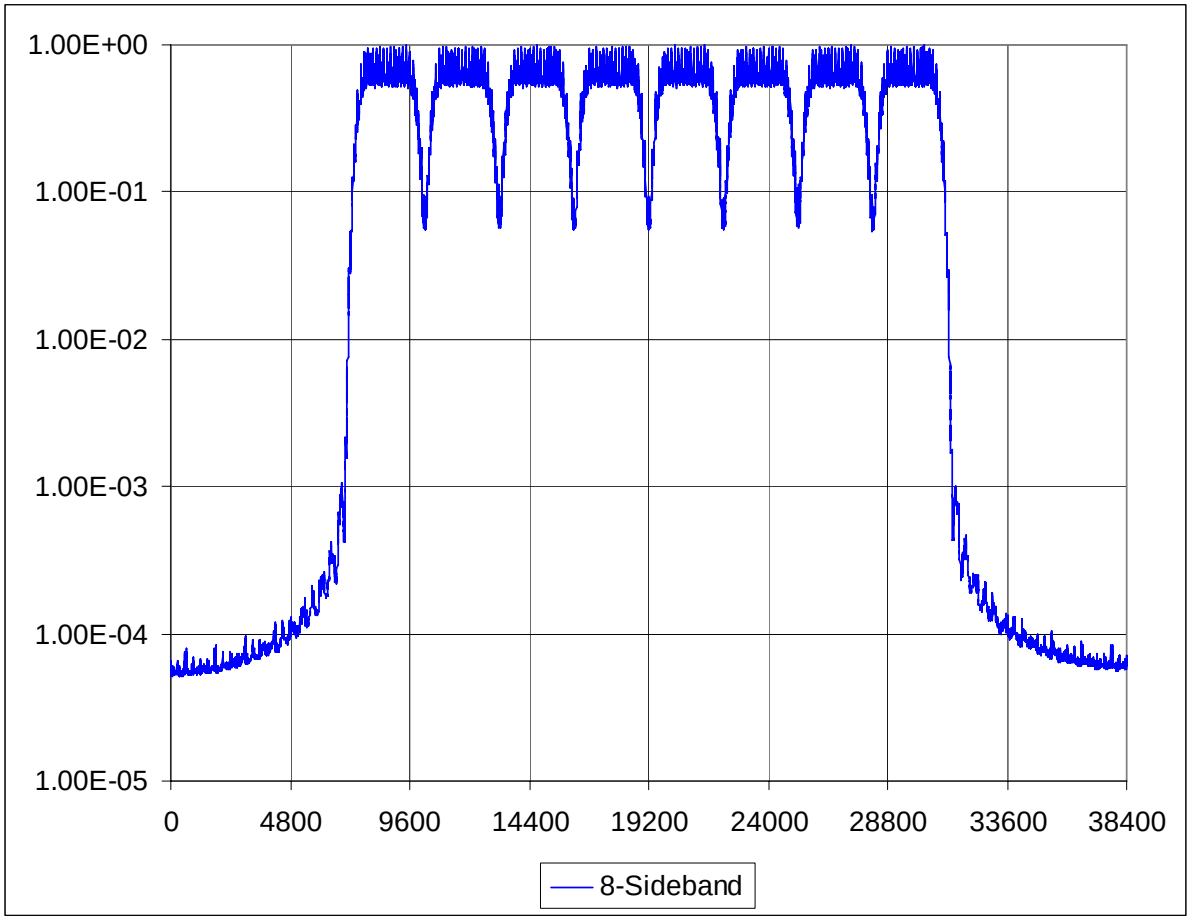
Frequency Spectrum of SC 2-Sideband 24 KHz Waveform on a 19.2 KHz Carrier



Frequency Spectrum of SC 4-Sideband 24 KHz Waveform on a 19.2 KHz Carrier



Frequency Spectrum of SC 8-Sideband 24 KHz Waveform on a 19.2 KHz Carrier



Summary

- Based on all the advantages offered by Single-Carrier Single-Sideband waveforms, this approach seems to offer the most promising waveform design for wider bandwidth HF waveforms (up to 24 KHz)
- Although the equalizer complexity will be very high for 24 KHz waveforms, future radio designs incorporating the latest DSP and FPGA technologies should help to achieve this goal