A New Approach to Peak-to-Average-Power Reduction for Hybrid FM+IBOC Transmission

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Presentation Objectives

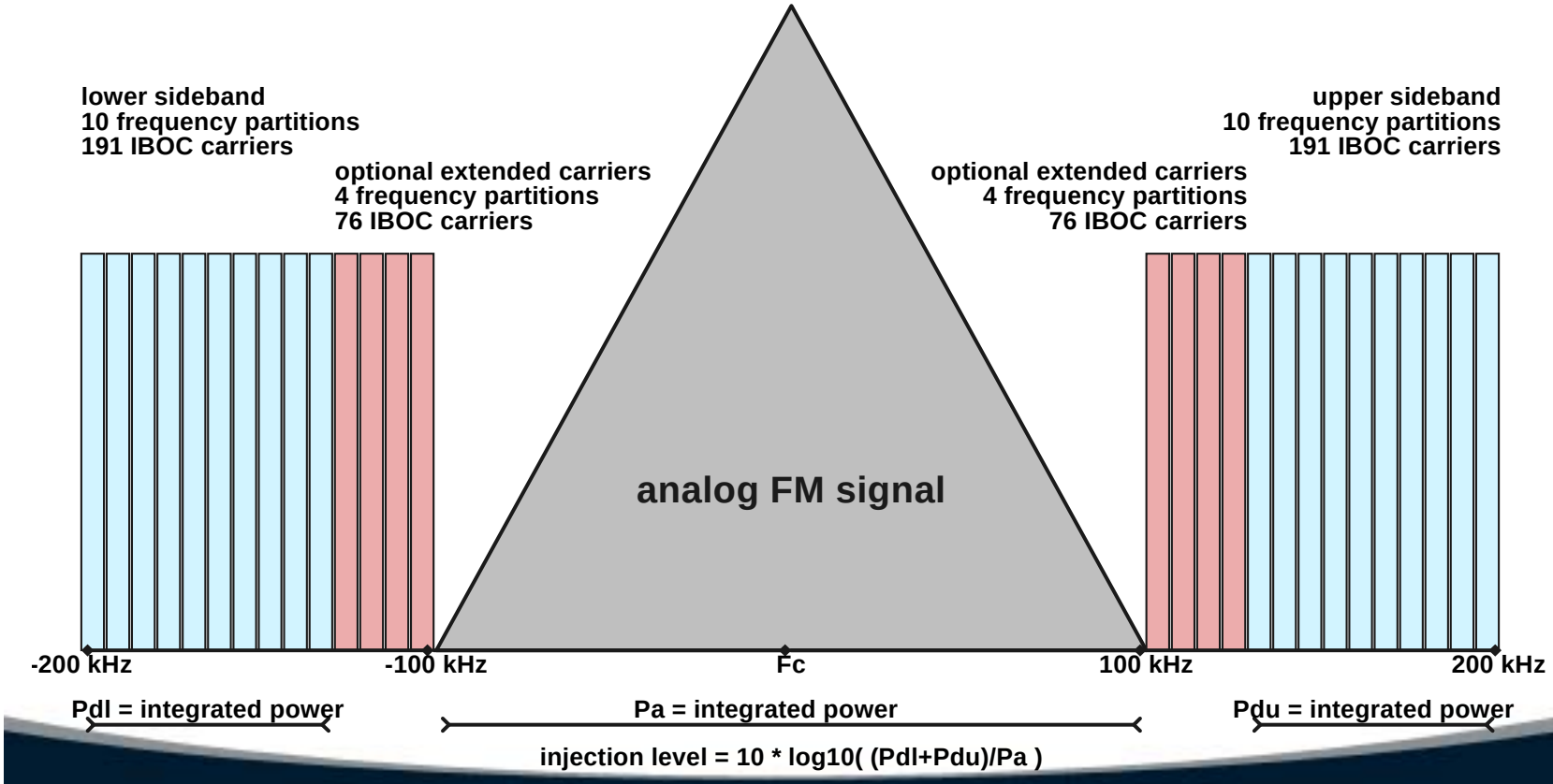
This presentation has the objectives of …

- **conveying research results on peak-to-average-power ratio (PAPR) reduction.**
- **explaining the standard peak-to-average-power reduction technique**
- **providing information on the challenges of 10 dB IBOC carrier increases for low level combined transmitters.**
- **Introducing a new PAPR reduction technique that can help broadcasters adopt higher IBOC power levels and improve HD Radio™ coverage.**

The presentation is not intended to establish Nautel transmitter power specifications. All results are to be treated as preliminary.

IBOC Signal Characteristics

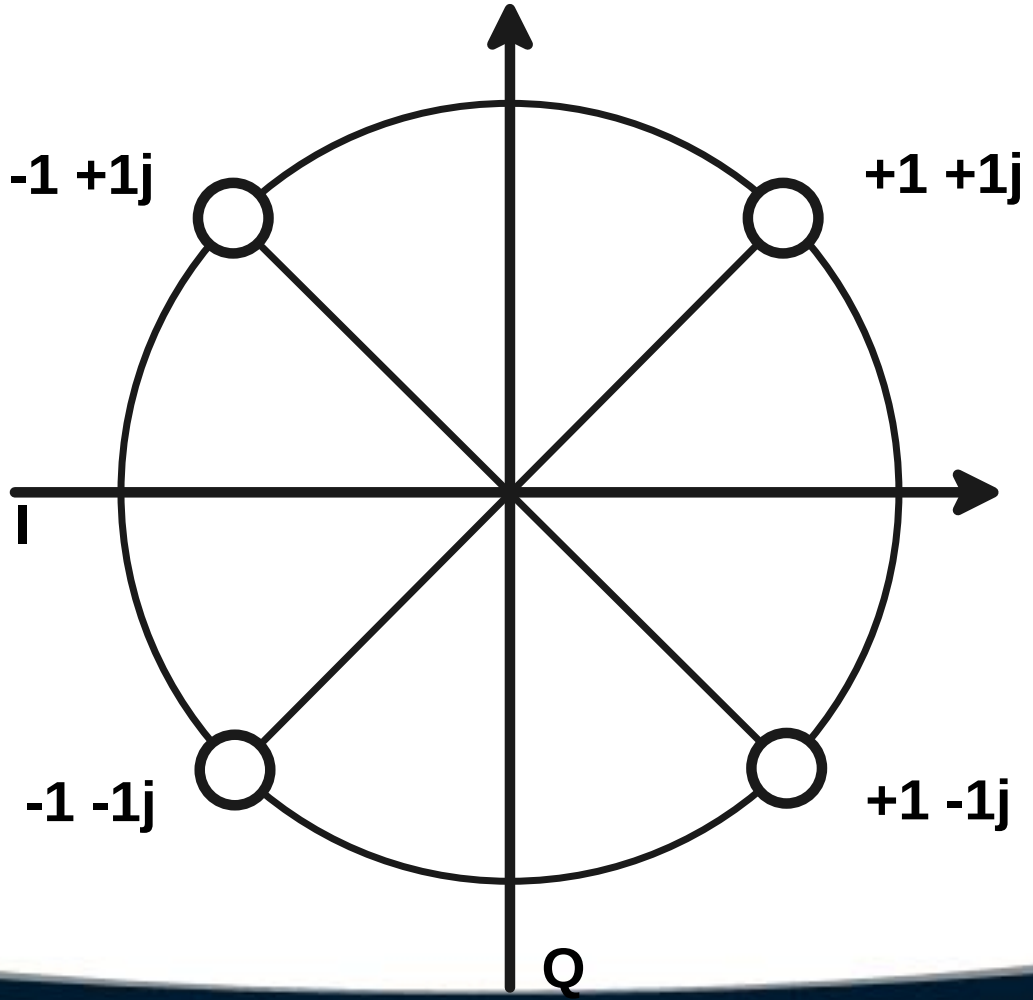
- the In-Band-On-Channel (IBOC) Signal is based on orthogonal frequency division multiplexing (OFDM)
- large number of individual data and reference carriers (FM: 1 carrier)
  - combats frequency selective fading
- current injection levels are at -20 dBc (1% of analog)
- new proposed injection levels at -10 dBc (10% of analog)



IBOC Signal Characteristics

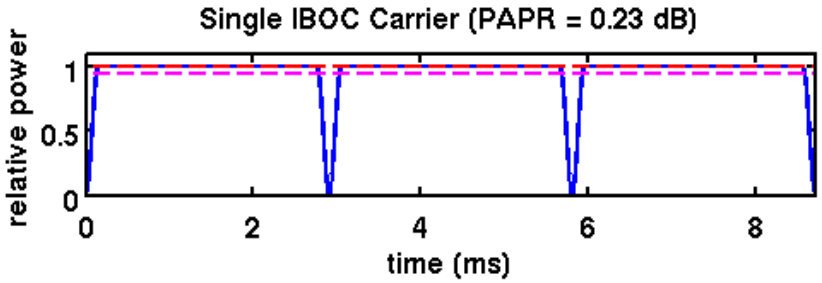
"Ideal" IBOC Signal Modulation:

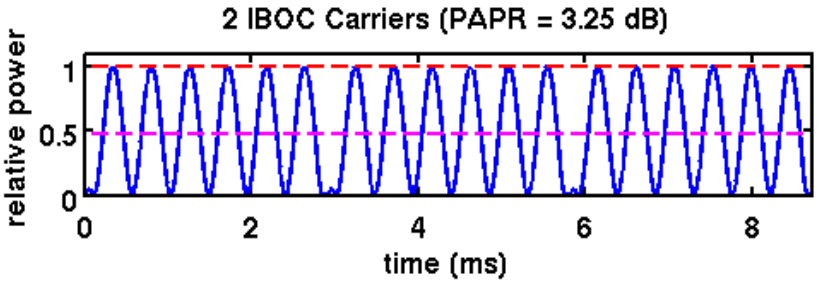
- **Quadrature Phase Shift Keying (QPSK) on each data carrier**
- **Binary Phase Shift Keying (BPSK) on reference carriers**

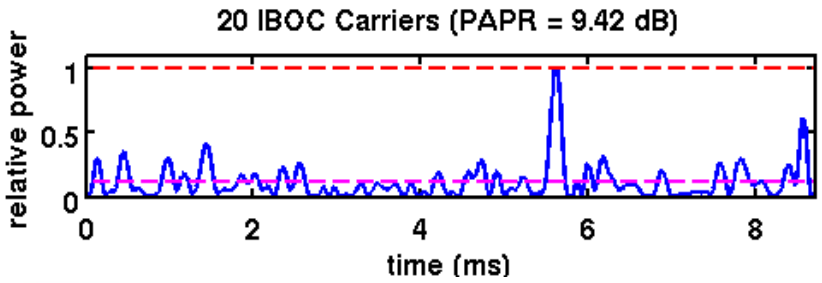


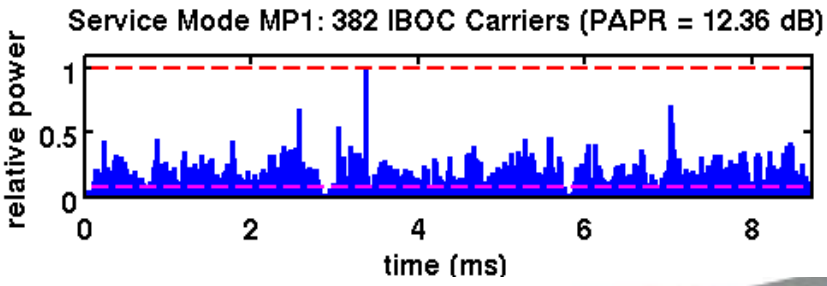
IBOC Signal Characteristics

- single carrier: constant power except for pulse shaping function
- additional carriers add constructively / destructively
  - Peak-to-Average-Power Ratio (PAPR) = peak power / average power
  - maximum possible PAPR = 10 log10 (N)
- "random" amplitude modulation based on carrier modulation
- peaks become shorter – often form multiple successive peaks
- focus on power envelope prior to channel modulation
  - constant 3 dB difference compared to channel modulation (actual RF signal)

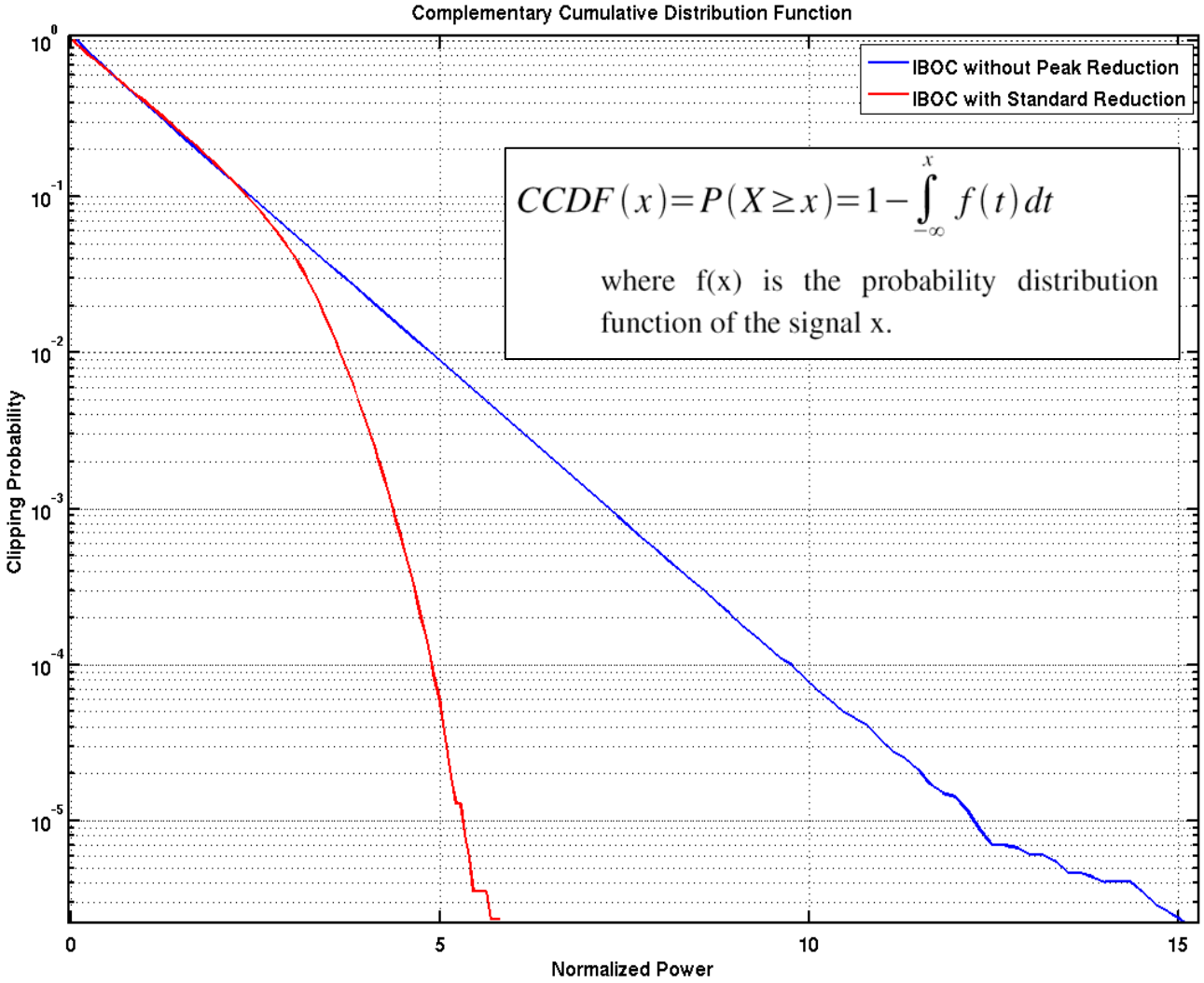






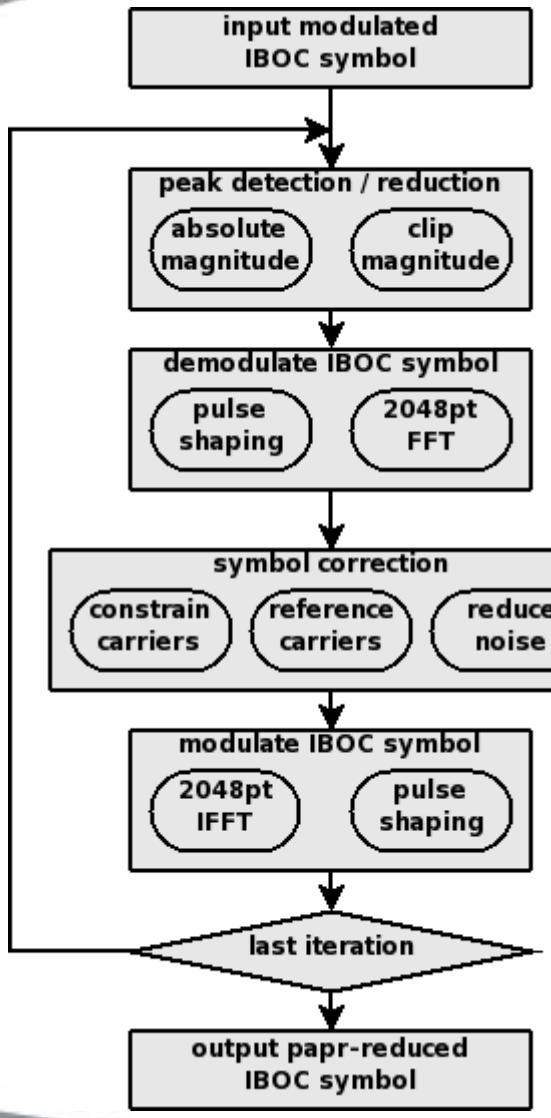


IBOC Signal Characteristics



- CCDF indicates clipping probability at threshold X
- 10^{-6} clips once per second
  - requires 15x (<12 dB) peak power capability
- standard IBOC modulators provide PAPR reduction algorithm
  - reduces required peak power capability to 6x (<8 dB)
- the signal can be further reduced to 3.6x (5.5 dB) through transmitter compression
  - limited by spectral emission mask

Standard PAPR Reduction



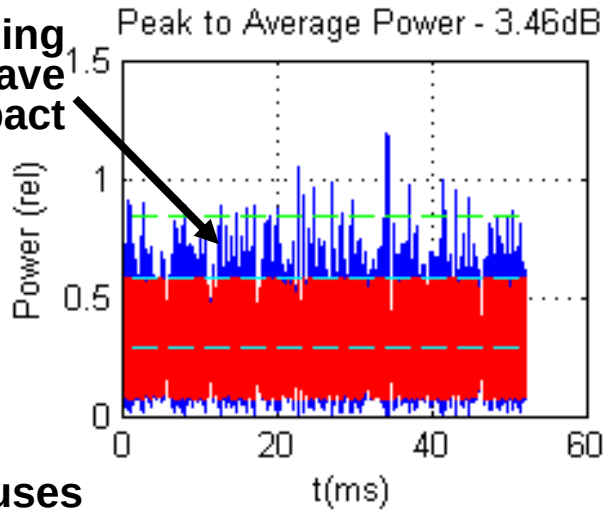
Algorithm Operation

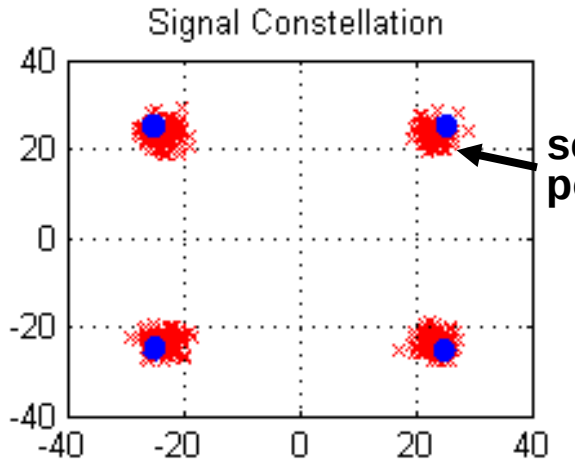
- works on IBOC signal only
- signal clipping
  - magnitude is clipped at a threshold
  - phase angle is maintained
- resultant symbol is demodulated
  - removes pulse shaping function
  - performs 2048 point FFT
- effects of clipping are corrected
  - all carriers constrained around QPSK points
  - reference carrier phase angle is corrected
  - noise in non-carrier bins is suppressed
- resultant symbol is re-modulated
  - performs 2048 point IFFT
  - re-applies pulse shaping function
- iterative algorithm
  - diminishing returns with each iteration
  - computationally expensive

Standard PAPR Reduction

Comparison of Ideal and Clipped Hybrid IBOC Signal

lower clipping levels have greater impact

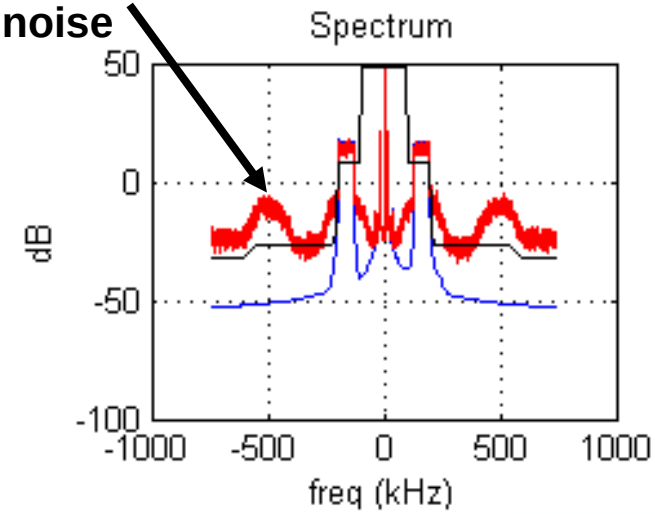


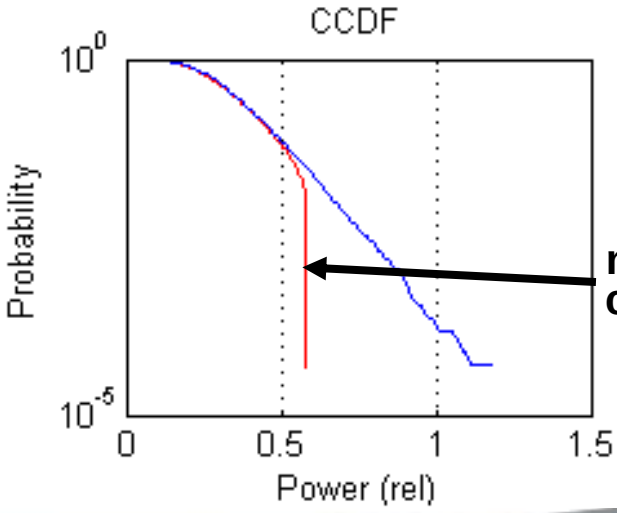


scattering and slight power reduction

clipping causes wideband noise

adds $\delta(t)$



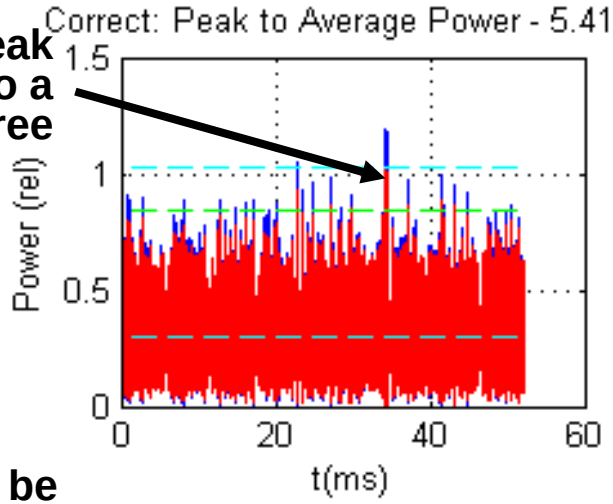


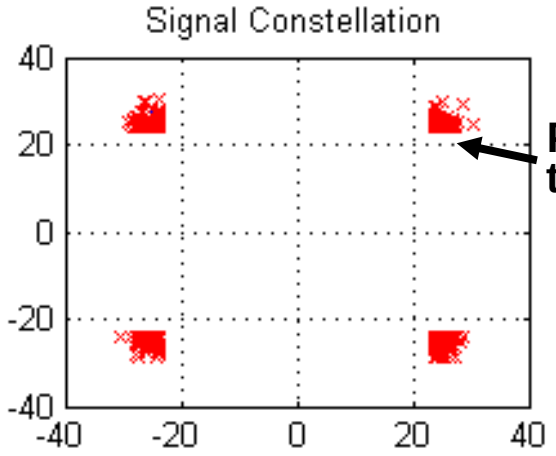
no power above clipping threshold

Standard PAPR Reduction

correcting the effects of a clipped signal

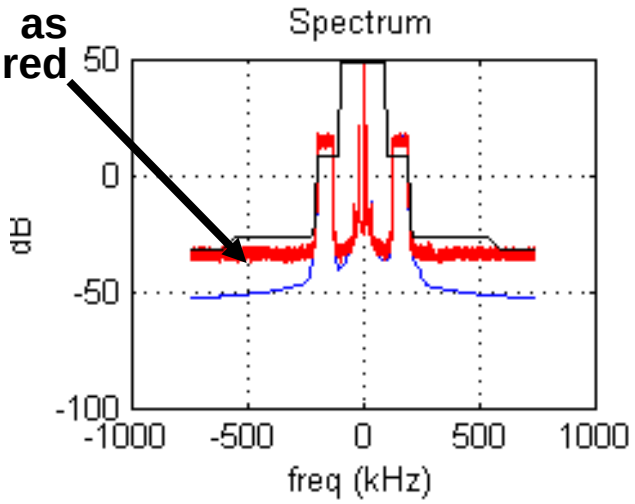
same peak return to a lesser degree

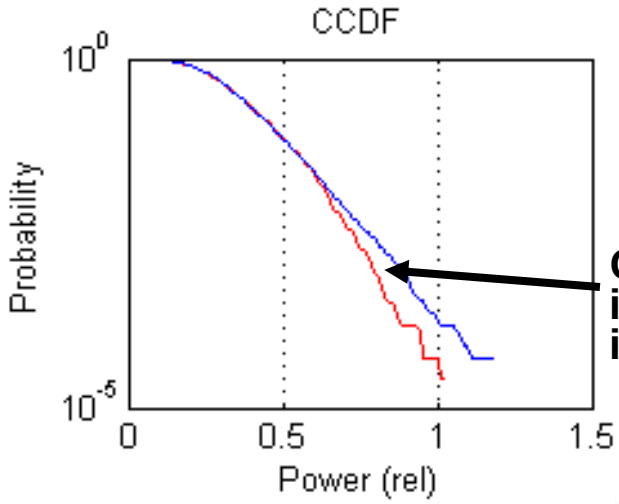




Points pushed back toward QPSK point

noise can be shaped as desired



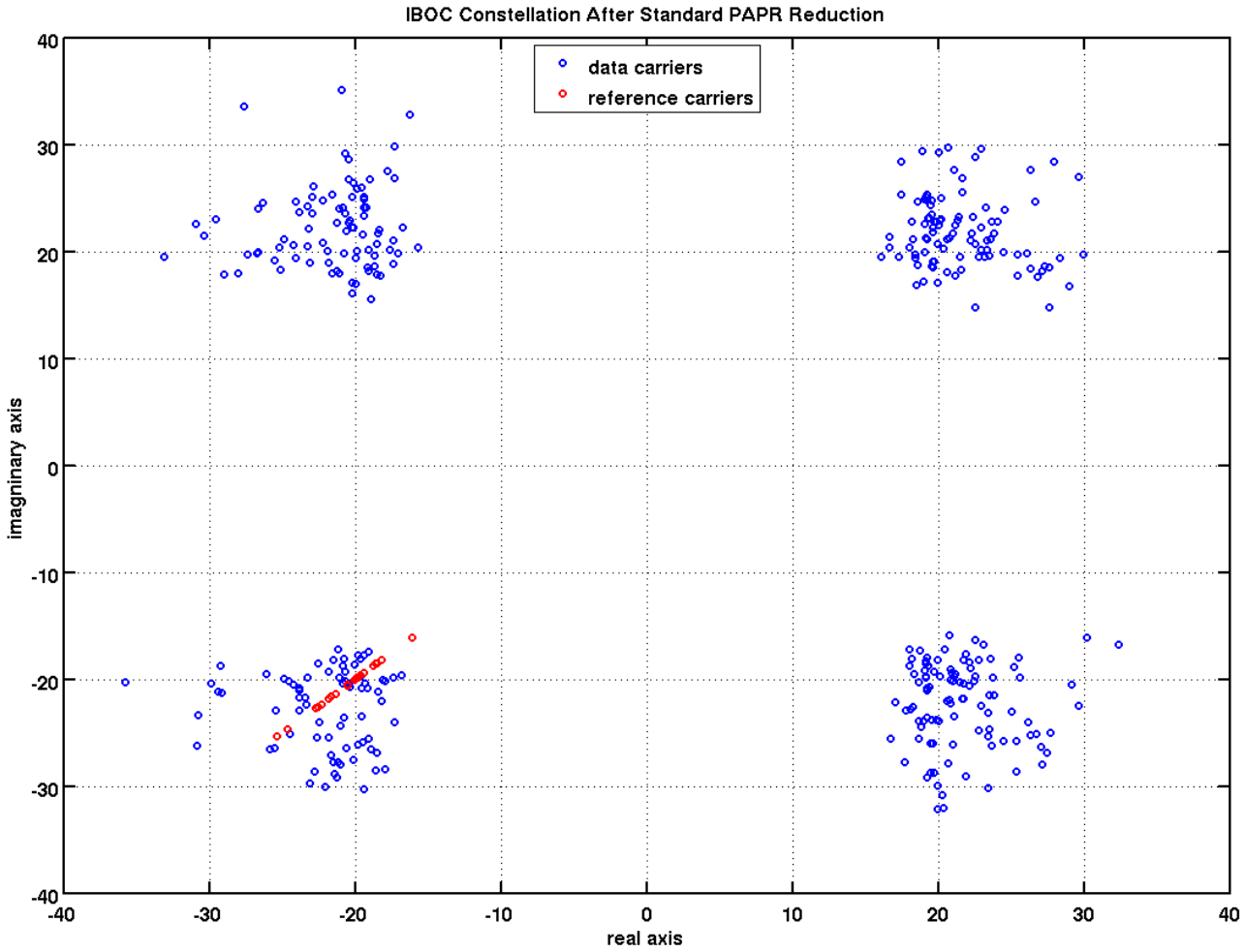


Only slight improvement in CCDF

Standard PAPR Reduction

IBOC Signal captured from Exgine IBOC modulator:

- **final result depends on degree of signal clipping and amount of signal correction**



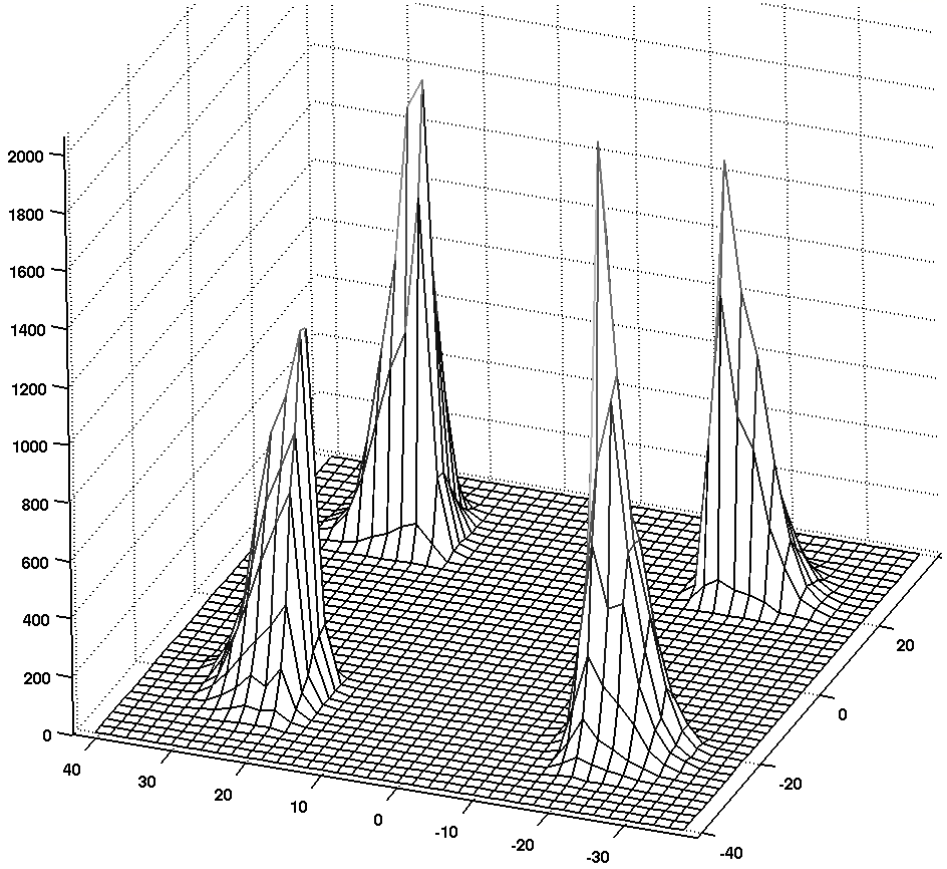
Standard PAPR Reduction

The spread in the constellation is not very significant (see constellation histogram)

Compared to the ideal IBOC constellation, the PAPR reduced version exhibits a reduction in noise performance in average white Gaussian noise (AWGN) as shown here:

Carrier Bit Error Rate	Reduction in Noise Performance (Reduced/Ideal)
$5x10^{-2}$	0.29 dB (1.07)
10^{-2}	0.49 dB (1.12)
10^{-3}	0.57 dB (1.14)
10^{-4}	0.72 dB (1.18)
10^{-5}	0.83 dB (1.21)

On-air tests have shown a small but tangible improvement in coverage area when turning PAPR reduction off.



3D IBOC constellation histogram

Standard PAPR Reduction

- iBiquity has developed and fielded an effective method of peak-to-average-power reduction
- virtually all IBOC implementations today use this standard PAPR reduction technique
- standard PAPR reduction enabled realistic IBOC implementations
- standard PAPR algorithm parameters have been chosen adequately with little impact on the signal's noise performance

However …

With 10 dB carrier increases, IBOC design input is changed and IBOC design decisions must be reviewed.

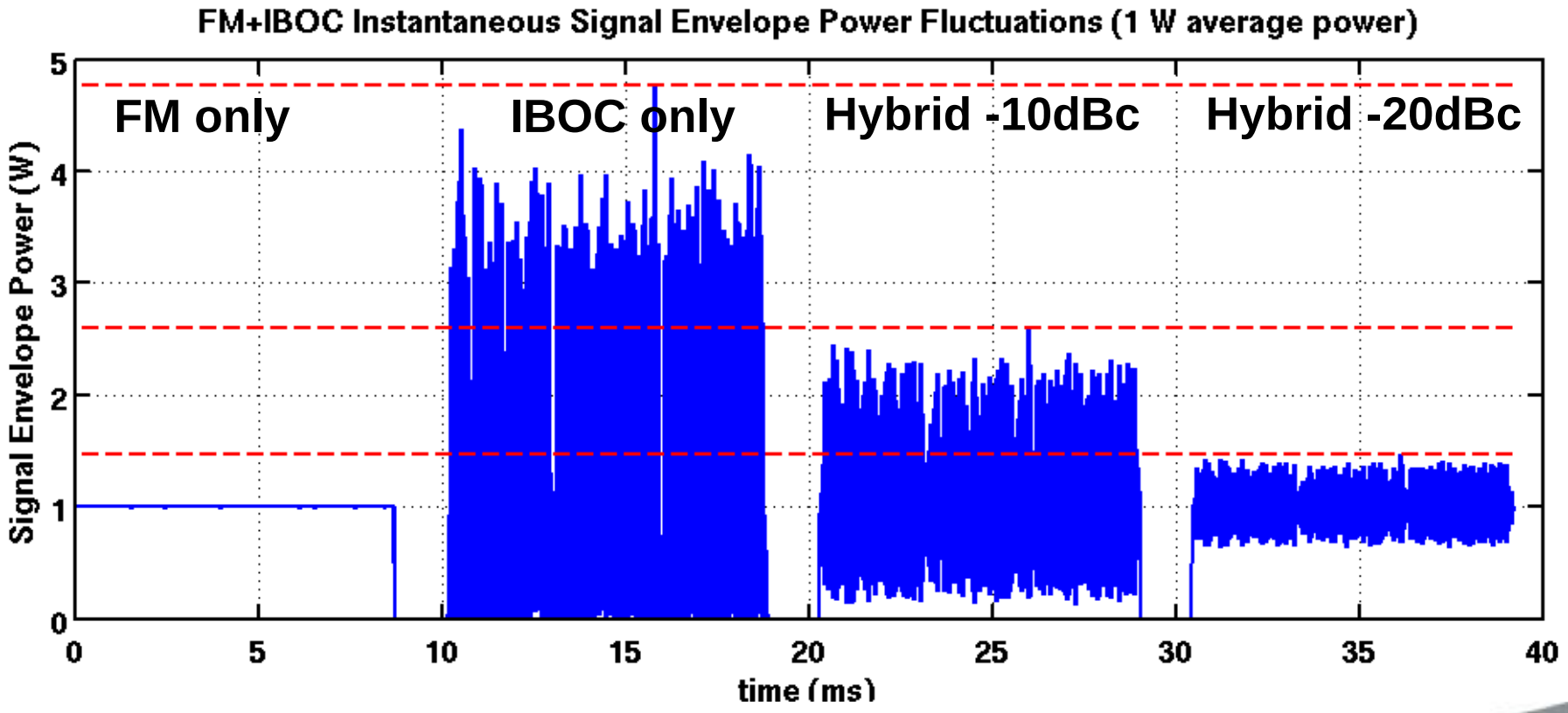
10 dB Carrier Increases

High Level Combined: IBOC transmitters require more power

Low Level Combined: Significant change in signal characteristics

Both: Spectral emission mask remains unchanged

=> no more transmitter compression



10 dB Carrier Increases

A 10 kW FM transmitter requires a peak power capability of

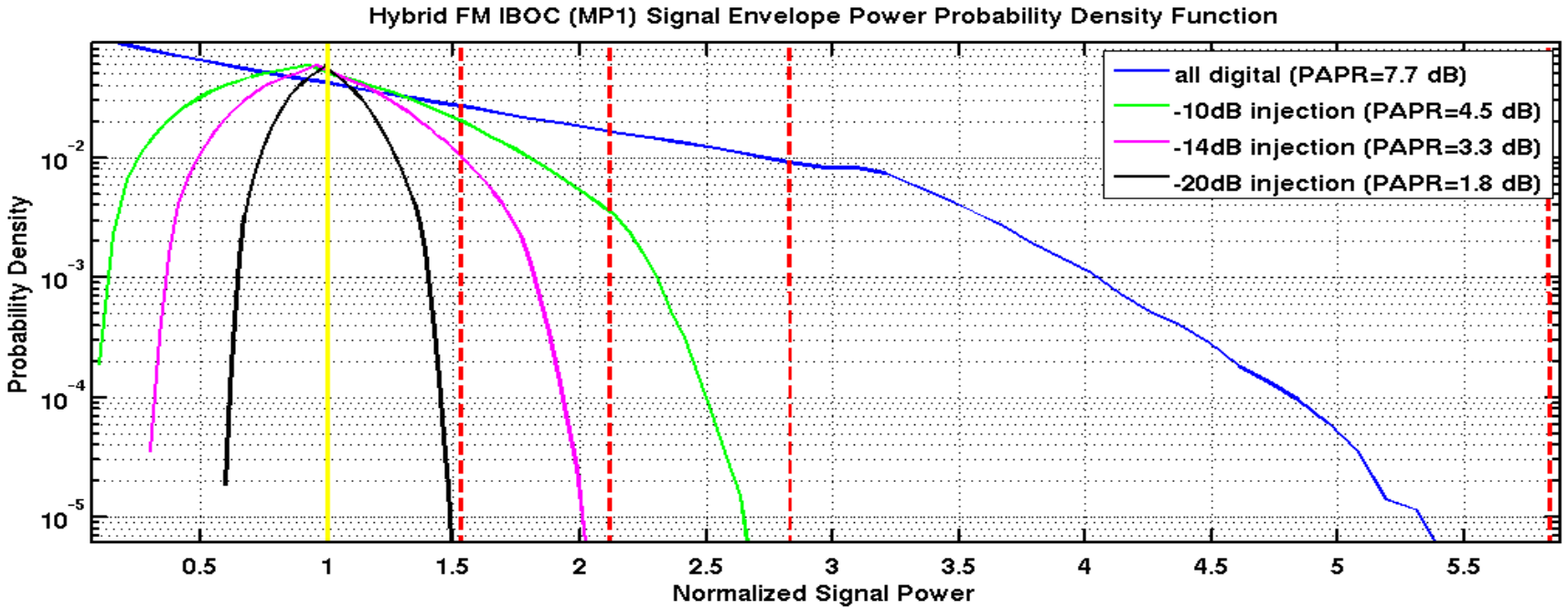
15.3 kW at -20 dBc injection levels (compression possible)

22.2 kW at -14 dBc injection levels (some compression)

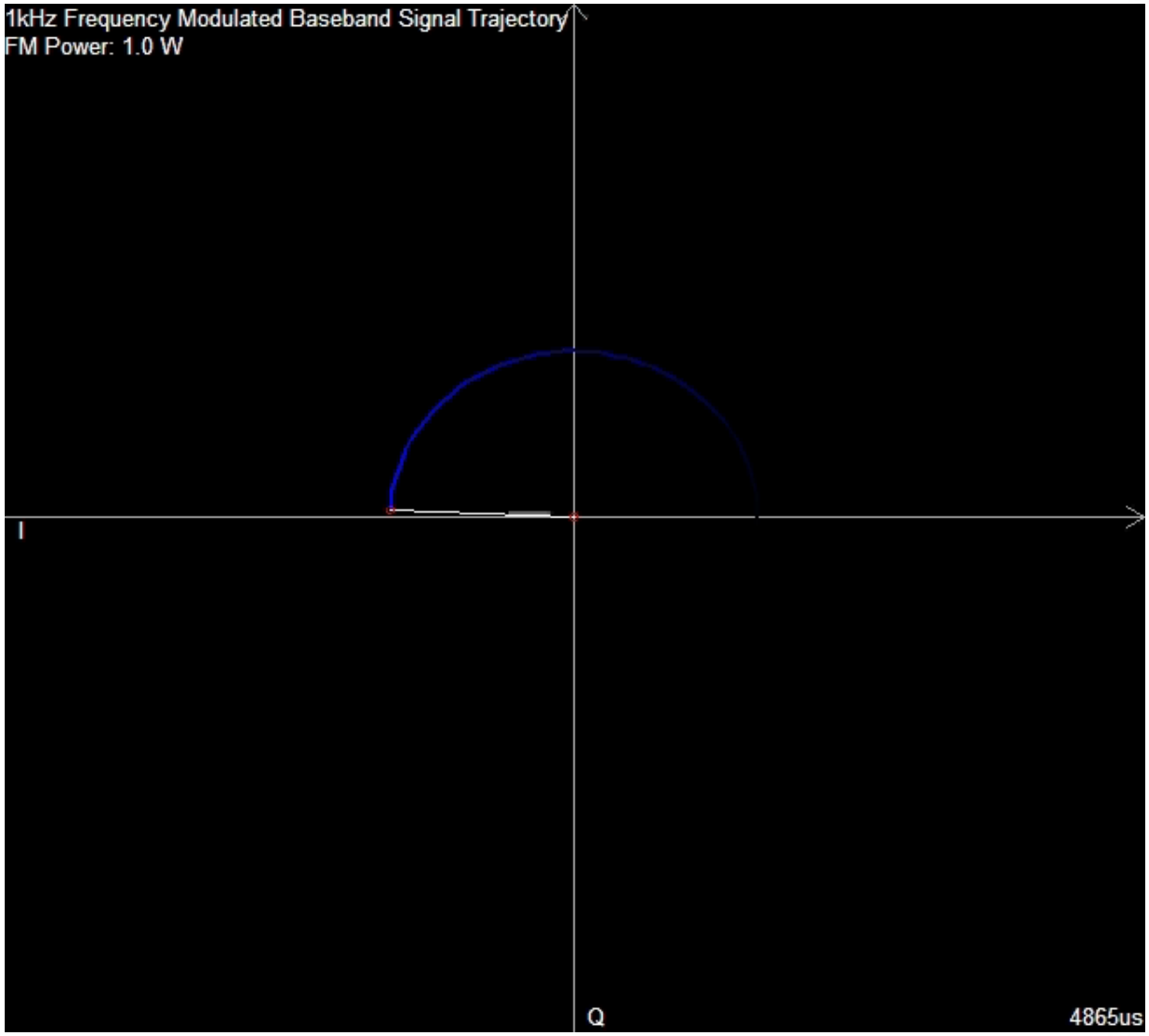
31.0 kW at -10 dBc injection levels (no compression)

High Level combined: 10dB (injection losses) + 7.7dB (signal) transmitter overhead

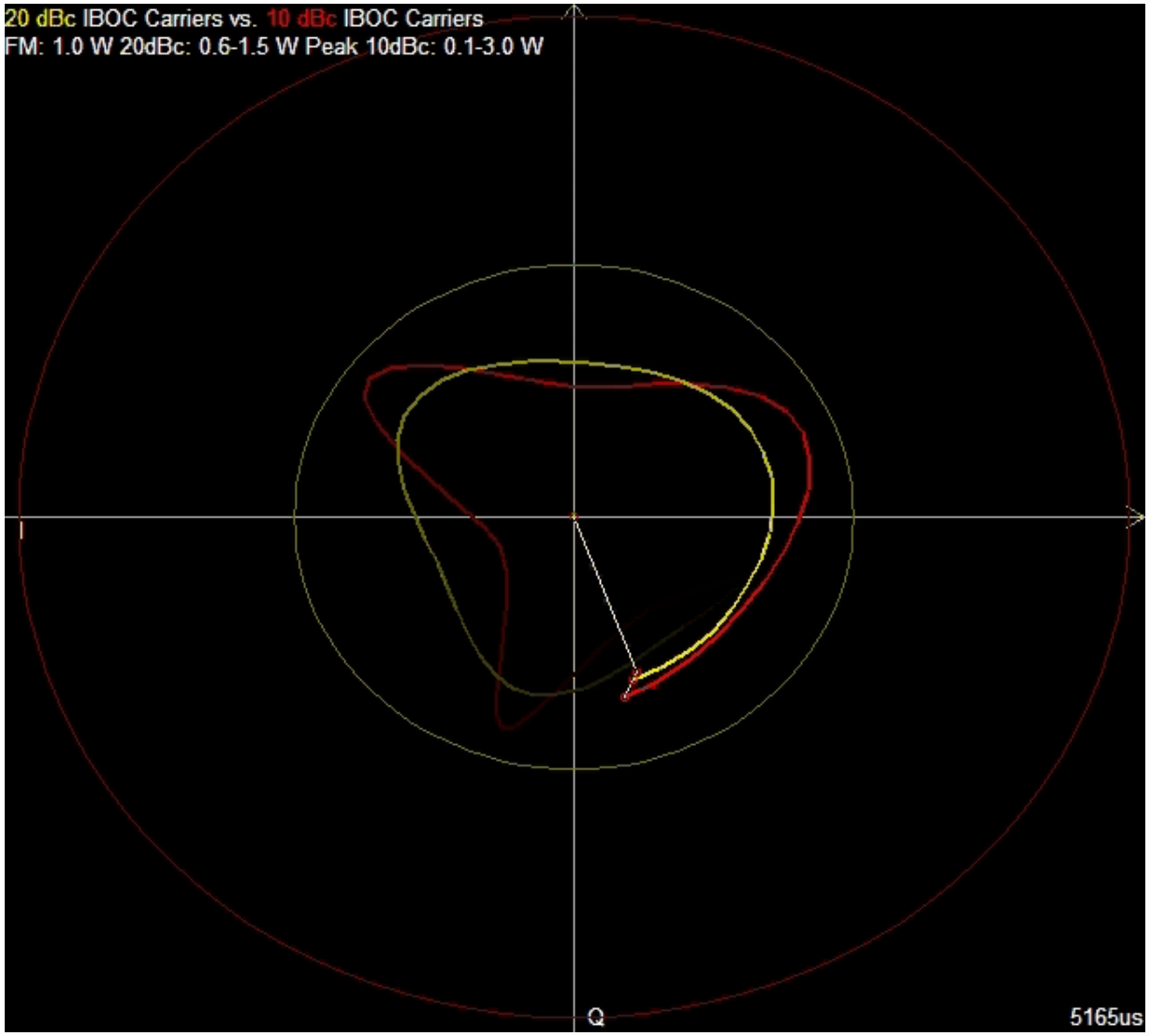
10.0 kW FM power plus ~58 kW IBOC power at -10dBc



10 dB Carrier Increases

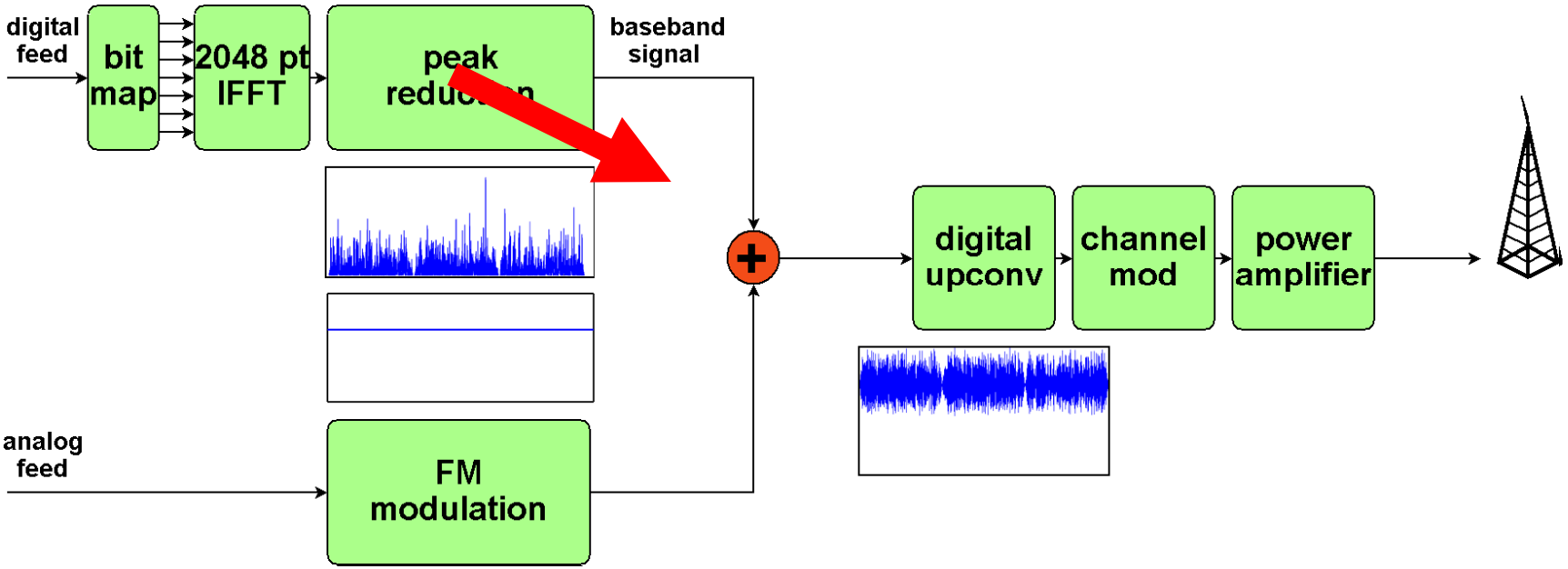


10 dB Carrier Increases



Proposed PAPR Reduction

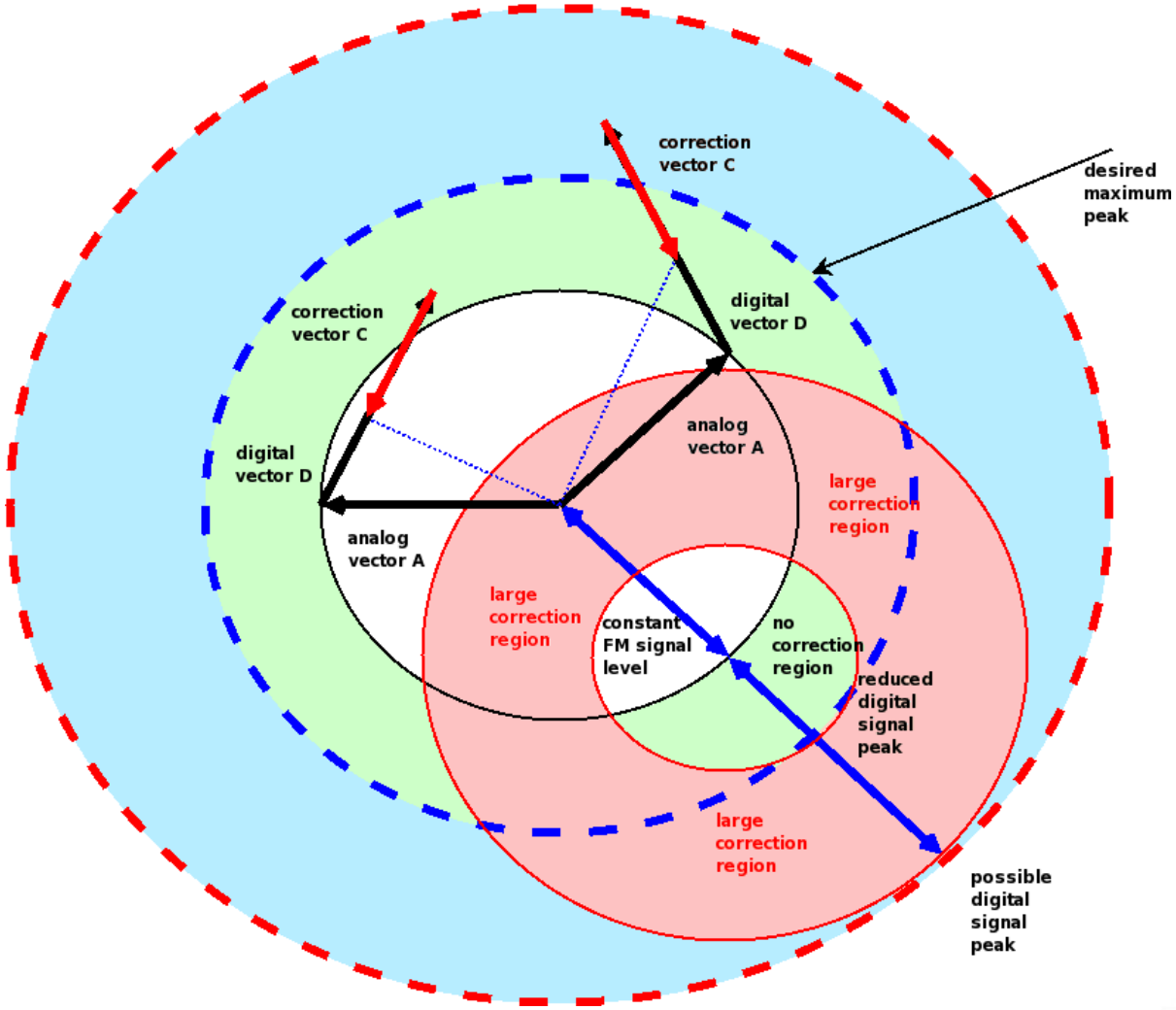
Standard PAPR reduction only considers the IBOC signal …



… what if we considered both the analog and digital signals together?

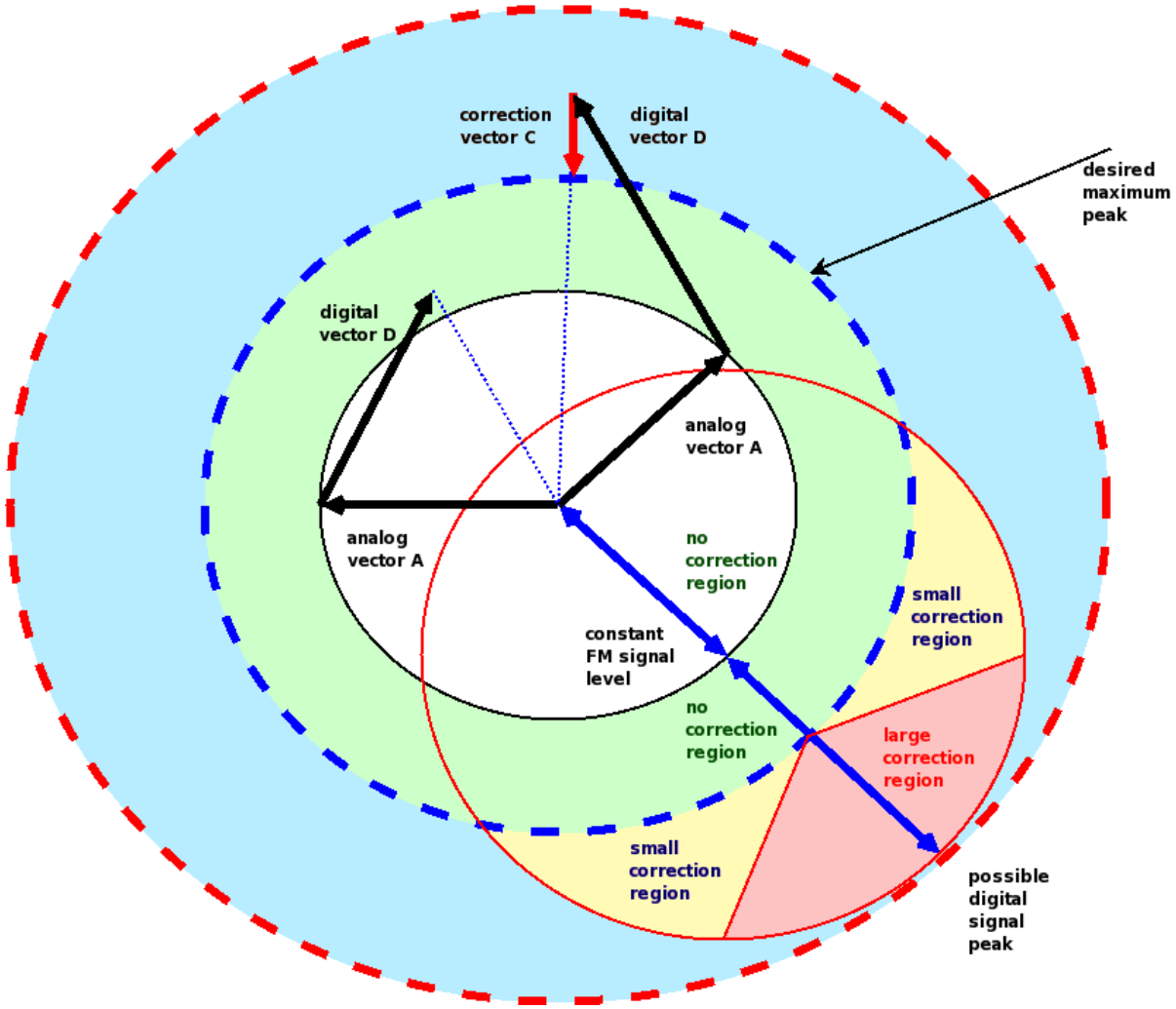
Proposed PAPR Reduction

Standard PAPR reduction applied to hybrid FM+IBOC signal

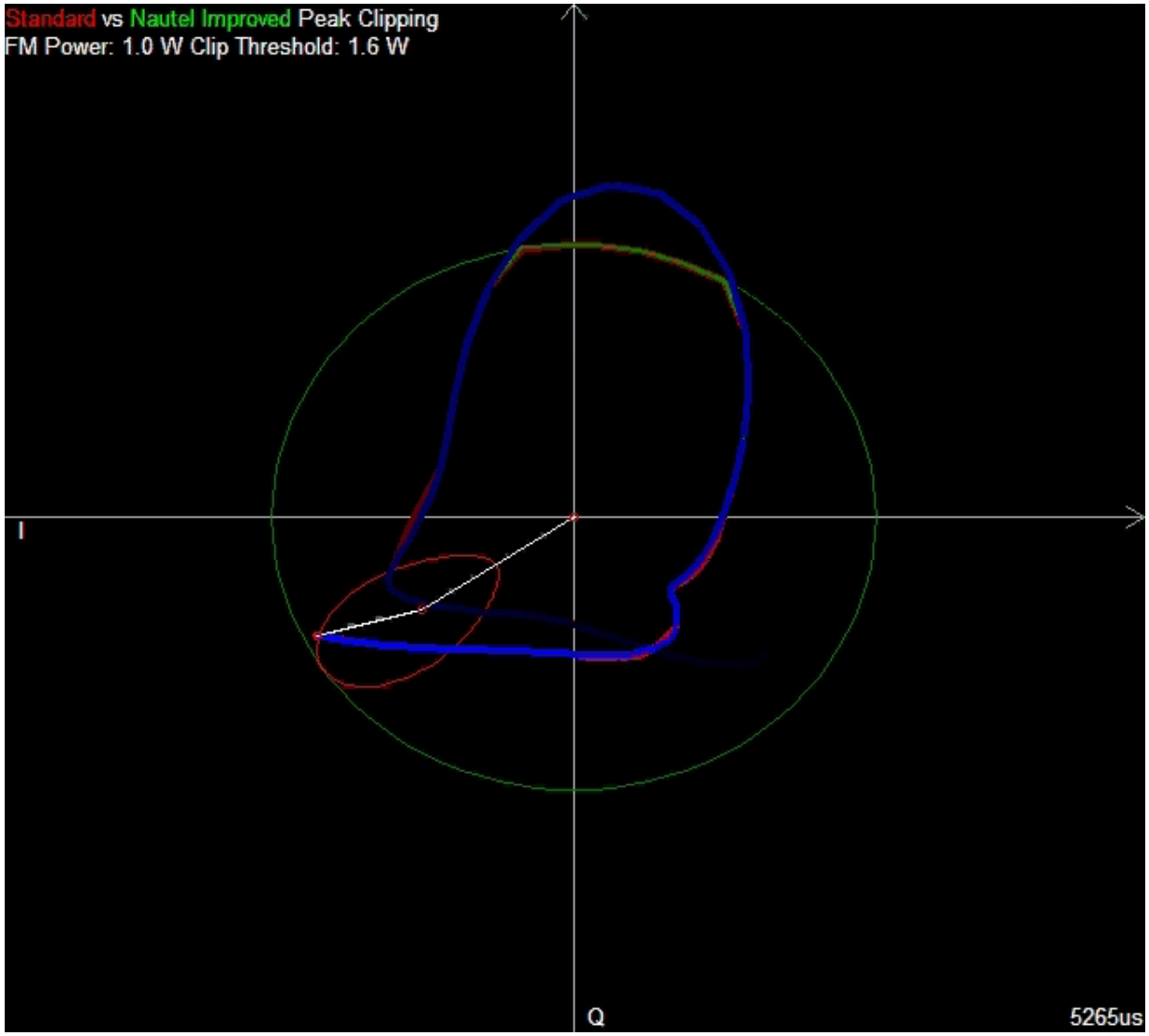


Proposed PAPR Reduction

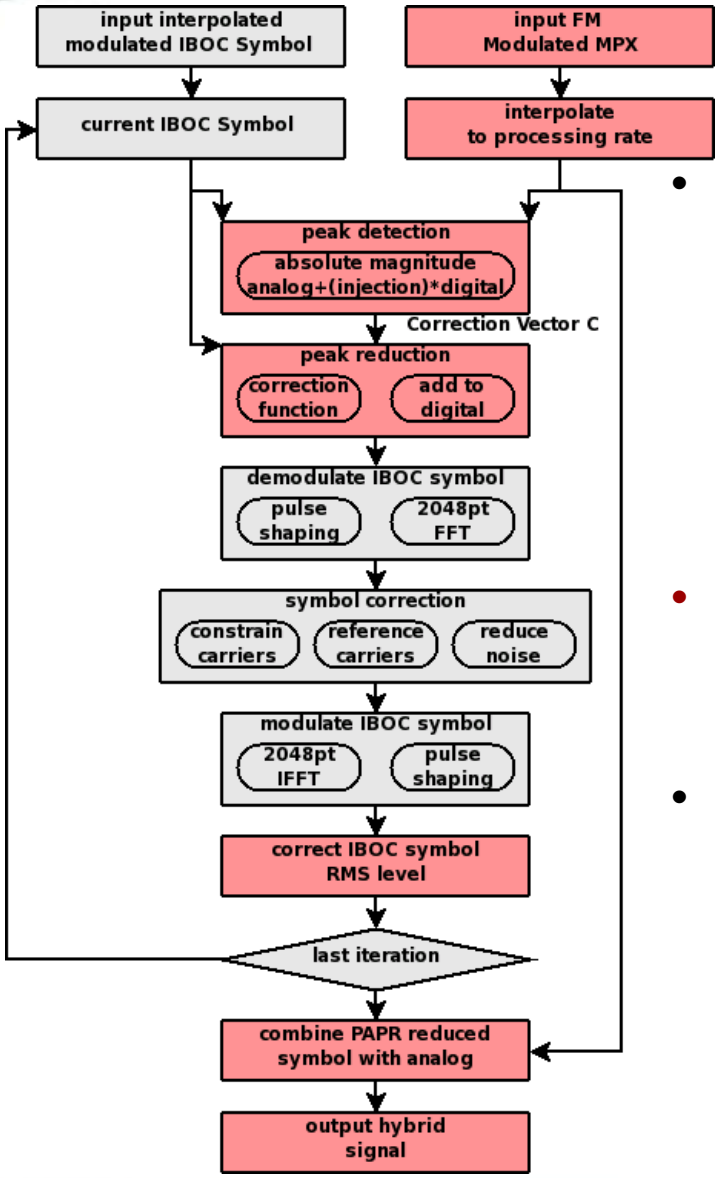
Proposed PAPR reduction applied to hybrid FM+IBOC signal



Proposed PAPR Reduction

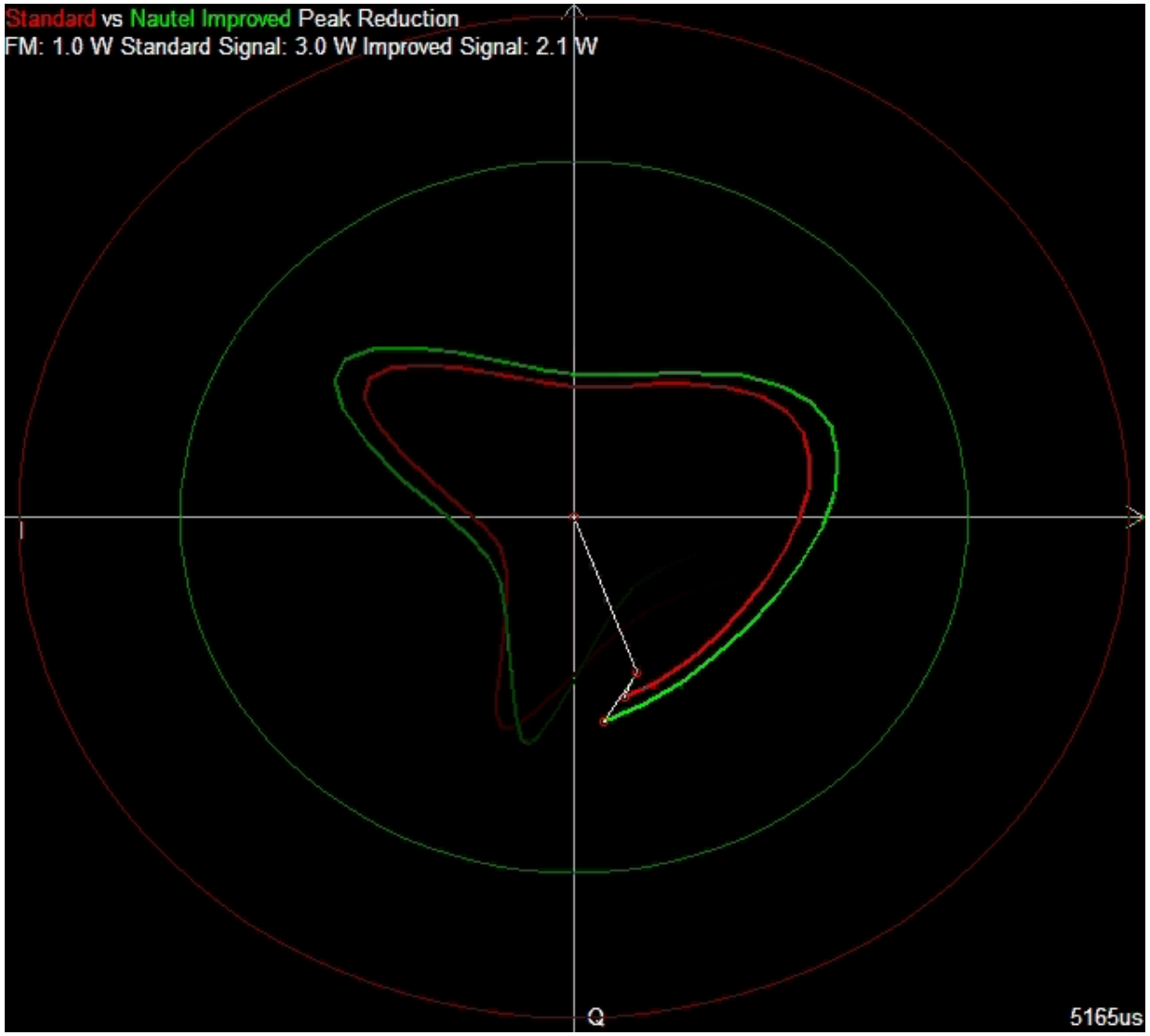


Proposed PAPR Reduction



- follows standard PAPR reduction, except for
  - inputting FM signal
  - improved peak detection
  - over-sampling both signals (detects peaks reliably)
  - improved symbol correction
- FM signal is never modified
  - only an input to the process
  - added to IBOC at the end
- differs from IBOC radio broadcast systems architecture
  - requires new exciter technology

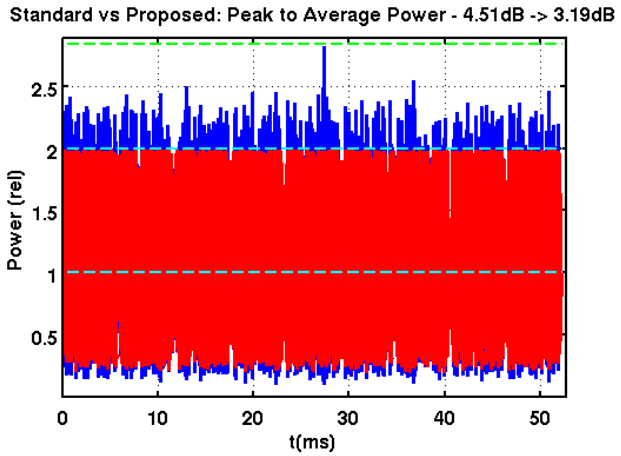
Proposed PAPR Reduction

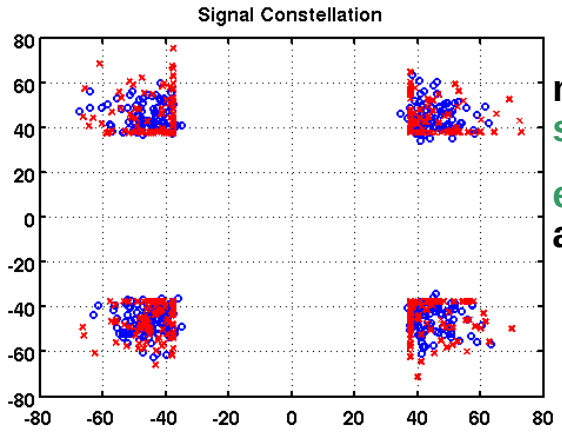


Simulation Results

Basic PAPR Reduction Mode

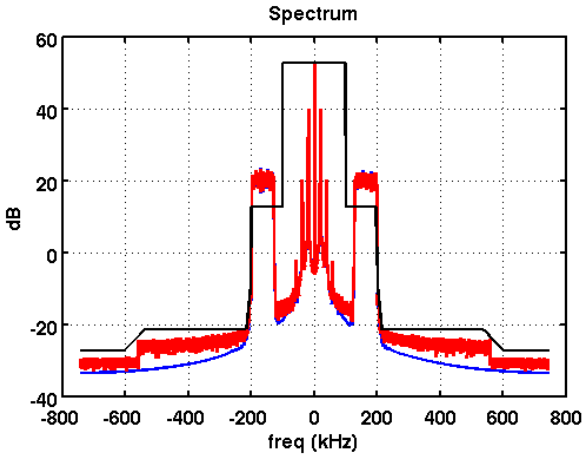
targeted at new installations

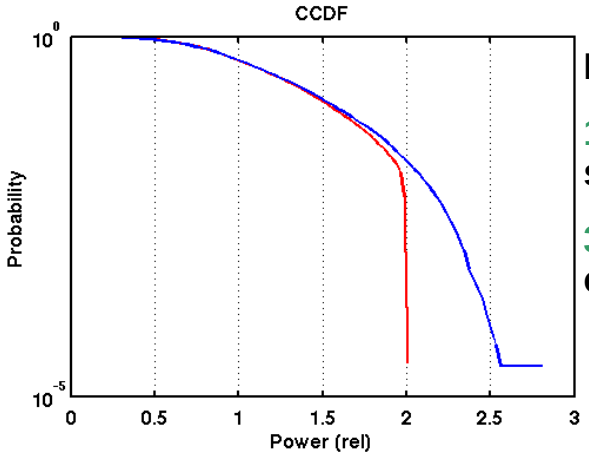




maintains comparable signal constellation

extended carriers used as data carriers





For -10dBc carriers:

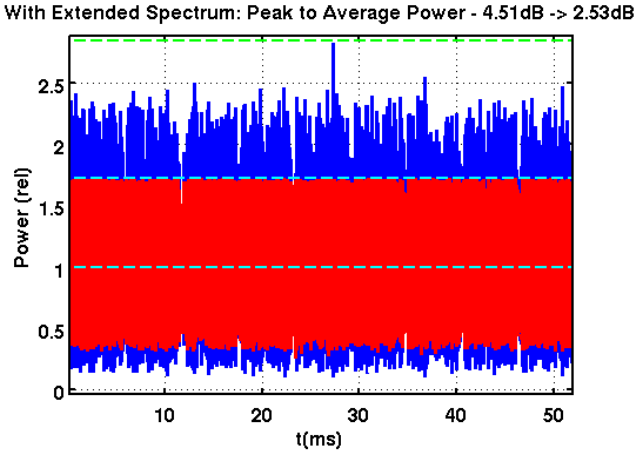
1.3 dB improvement over standard PAPR reduction

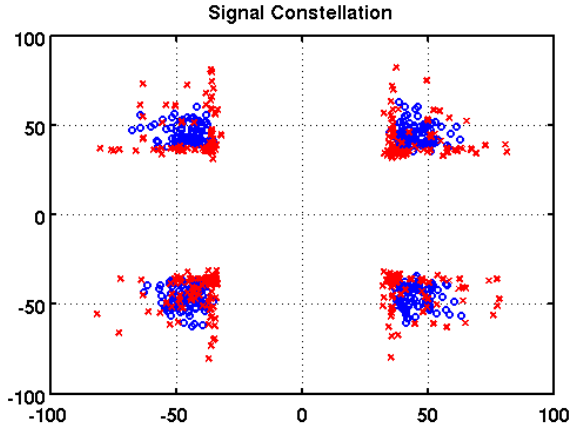
34% increased transmitter output power

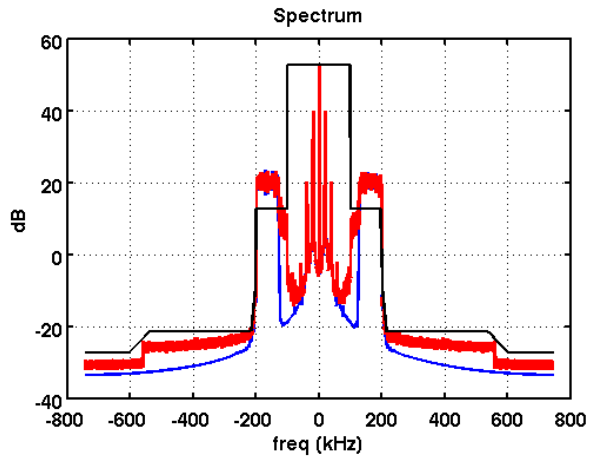
Simulation Results

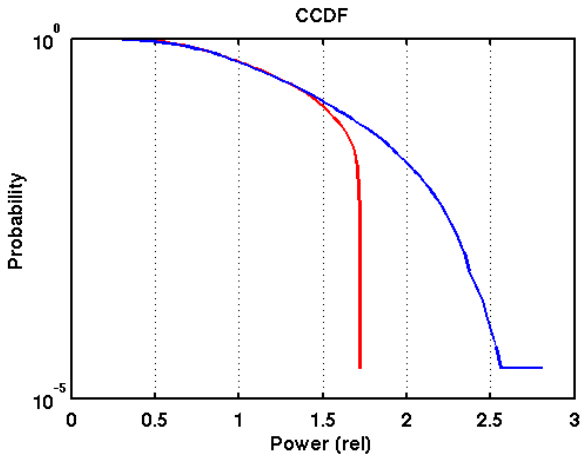
Aggressive PAPR Reduction Mode

targeted at existing peak power limited installations









allows small degradation in signal constellation

around 1.65 dB drop in noise performance

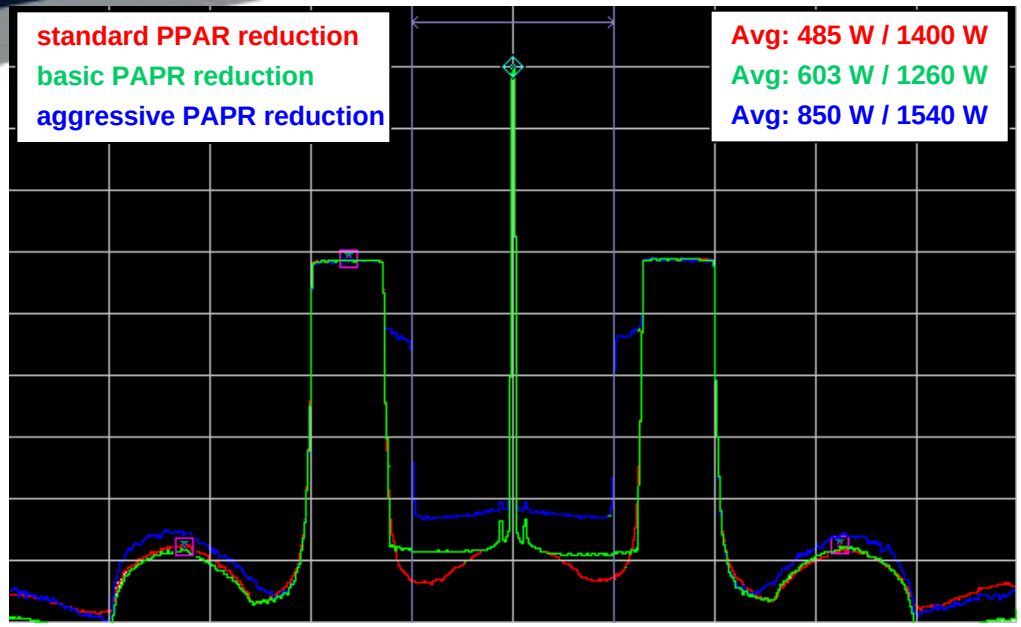
extended carriers used as "correction" carriers

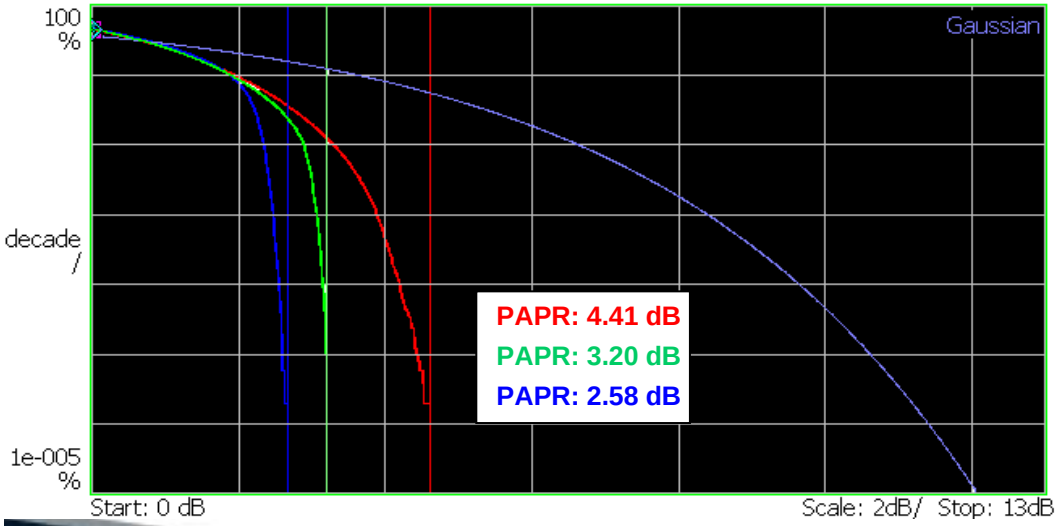
For -10dBc carriers:

2 dB improvement over standard PAPR reduction

58% increased transmitter output power

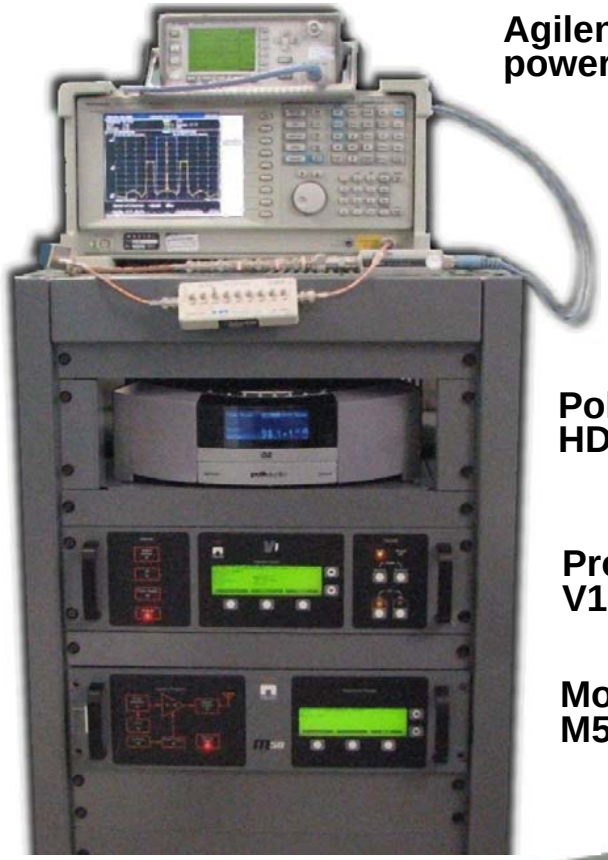
Hardware Results at -10dBc





Test setup with Nautel V1 transmitter:

- **15s receivable IBOC offline vector**
- **includes HD-1/HD-2/HD-3**



Agilent RMS power meter

Tektronics Real-time Spectrum Analyzer

PolkAudio HD receiver

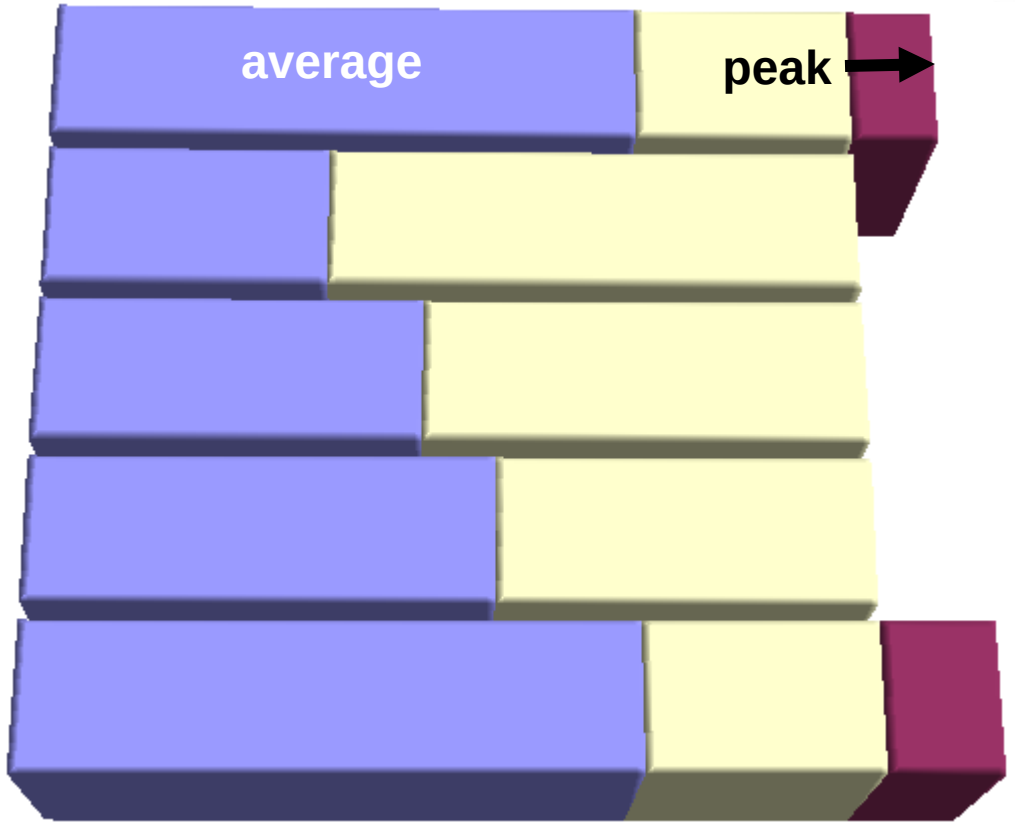
Production V1 transmitter

Modified M50 exciter

Measured Power Improvements

Signal Types:

- **Standard IBOC at -20 dBc**
  Average: 1000 W Peak: 1550 W
  Approx. efficiency: 55%
- **Standard IBOC at -10 dBc**
  Average: 485 W Peak: 1400 W
  Approx. efficiency: 40%
- **Basic Reduction at -10 dBc**
  Average: 636 W Peak: 1370 W
  Approx. efficiency: 45%
- **Aggressive Reduction at -10 dBc**
  Average: 771 W Peak: 1400 W
  Approx. efficiency: 50%
- **Aggressive Reduction at -14 dBc**
  Average: 1000 W Peak: 1590 W
  Approx. efficiency: 55%



Compared to Standard PAPR Reduction

- **Basic PAPR Reduction yields 32% TPO increase**
  (no trade-offs to standard PAPR reduction)
- **Aggressive PAPR Reduction yields 59% TPO increase**
  (uses extended carrier space and lower noise performance)

Milestones and Future Work

Accomplished Milestones

• developed extensive PAPR simulation suite	completed
• real-time IBOC demodulation for test vectors	completed
• setup offline vector test system	completed
• verified simulation results against hardware	completed
• checked signal reception using standard HD radios	completed
• on-air signal tests on experimental station	completed

Future Work

• research advanced concepts (higher service modes, …)	in progress
• specify transmitter performance	in progress
• develop real-time online proof-of-concept system	short term
• perform bit error tests with on-line system	short term
• perform coverage tests with proposed signal	long term
• perform on-air field trials	long term

Conclusion

- results of this research are too powerful to ignore
  - PAPR reduction should be in the hands of broadcast equipment manufacturers
  - justifies redefining the radio systems broadcast architecture
  - requires new exciter technology
- the basic PAPR reduction mode is close to becoming reality
  - spectrum is identical to existing IBOC signal
  - no trade-offs for the broadcaster
- the aggressive PAPR reduction mode to be considered academic to-date
  - targeted at existing or peak power limited installations
  - optimal signal level dependent on available overhead
- as a broadcast community we must develop better acceptance tests for IBOC
  - broadcasters should insist on noise performance tests
  - not every Watt of IBOC power is created equal
- research is on-going exploring advanced topics
  - further gains may be attainable in the future
  - partner with Nautel to create robust HD Radio solutions for tomorrow