Is Multi-Carrier Modulation Needed for 100Gbps over 1 λ in the Data Center?

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OUTLINE

- **Assumptions and Motivations**
- **Is any advanced modulation needed?**
- **Is it PAM-M vs. DMT-N?**
  - Overview and comparison
- **A theoretical look at capacity and modulation choice**
- **What is Signal, Noise, and Distortion?**
- **Some practical observations with distortion(s) and time-varying noises**
- **Conclusions, History, and Future directions**

ASSUMPTIONS WITH MOTIVATIONS

- **Low (lowest?) cost and power electro-optical parts**
  - So only Direct Detection (DD) of optical Intensity
  - I.e., since not considering long haul, then not considering ‘coherent,’ where the optical field phase (aka carrier) can be controlled (modulated) at the TX, and ‘tracked’ (detected) at the RX
- **Low (lowest?) power electrical solutions**
  - Electronics power is first order proportional to ‘Baud Rate,’ so we can’t afford the power of Transmitting and Receiving frequencies that deliver little or no information
    - So we limit ourselves to Band-Width limited systems where SNR(f) >> 0dB for all frequencies used
    - E.g., no ‘integer oversampling’ (a.k.a. fractionally spaced equalizers, etc.)
  - But will consider DSP to mitigate certain electro-optics issues
    - Limited trade of electrical power vs. optical costs

IS ADVANCED MODULATION NEEDED?

- **NRZ is a very simple and effective system, but IFFI the desired data rate can be achieved**
- **Copper NRZ SERDES can work with 25dB (or more) Insertion loss (attenuation) at the Nyquist frequency**
  - But where SNR(f) is still ‘high’ at these frequencies
- **Can an optical system ‘modulated’ at 100GSamples/sec still achieve ‘high enough’ SNR(f) at f=50GHz?**
  - And with increased frequencies to support overhead for transcoding and low latency FEC, etc.
  - IF not, THEN we consider advanced modulation, which trades lower ‘Bandwidth’ for higher SNR requirements

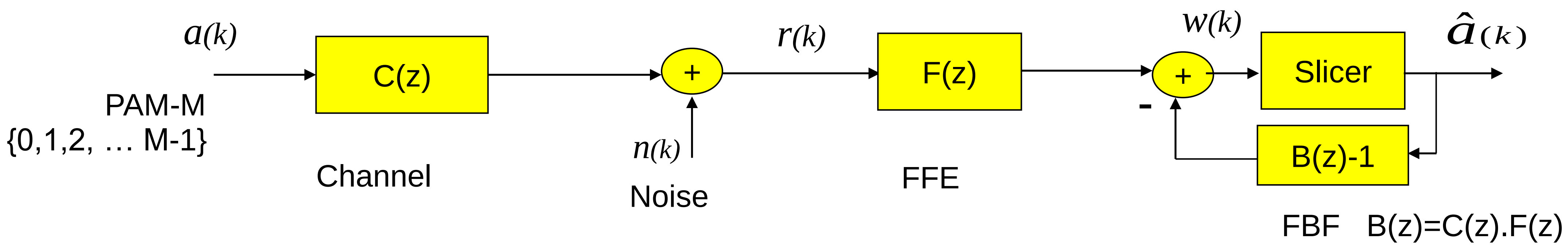
IS IT ONLY PAM-M VS. DMT-N ?

- **The communication theory literature deals with this choice as ‘Single Carrier’ vs. Multi-Carrier**
  - Pulse Amplitude Modulation (PAM) and Quadrature Amplitude Modulation (QAM) are the most common examples of ‘Single Carrier’
  - Discrete Multi Tone (DMT) and Orthogonal Frequency Division Multiplexing (OFDM) are the most common example of ‘Multi-Carrier’
- **Both are very general categories that leave a host of details open**
  - Kind of like saying, “We will send data with Photons.”   This still leaves many important variants to specify!
- **And there are a near infinite number of such variants**
  - Technically, PAM-M is a trivial subset of DMT using N=1 frequency bins
  - So fully optimized DMT can NOT be inferior to PAM-M (else it would optimize to be PAM-M)

PULSE AMPLITUDE MODULATION (PAM-M)

- **A type of ‘Base-Band’ modulation (== Single Carrier at DC)**
- **Without loss of generality performance fundamentally identical to QAM**
  - Difference is band-pass vs. baseband channels, ignored herewith
- **Generally with uniformly spaced amplitude levels**
  - Without loss of generality, think of PAM-M as the set {0,1,2, …, M-1}
  - And NRZ == PAM-2, on {0,1}
  - Typical for base-band implementations, DC and very low frequencies are normally finessed with various well known techniques
  - PAM generalizes to non-uniform levels, which have been suggested for very high RIN dominated channels [bhoja_01_0112_NG100GOPTX]
- **Transmitters can be ultra-simple**
  - Only the small number of M levels, so no high resolution multi-bit DACs are required

PAM WITH DECISION FEEDBACK EQUALIZER (DFE)



- **Optimal DFE both 'whitens' the noise at *w(k)* and transforms the signal to minimum phase**
- **The performance of an MMSE optimized DFE achieves the Salz *SNR_dB = mean{10*log10[1+SNR(f)]}* over the Nyquist**
- **The ZFE-DFE solution achieves the geometric mean of the SNR(f), which for high SNR converges to the Salz SNR**
- **In many SERDES applications, the FeedForward Equalizer (FFE) function is performed solely by, or in conjunction with, an analog Continuous Time Filter (CTF)**
- **'Very Good' channels allow ultra-simple inverting equalizer RX, F(z)=1/C(z), so no FBF (no DFE) required**

DFE FOR POOR CHANNELS

- **For poor channels that show 'poor' SNR(f), the DFE architecture has certain limitations**
  - E.g., in AWGN channels with high Inter-Symbol Interference (ISI), the SNR(f) can become poor for a large swatch of high frequencies,
  - E.g., for certain channels with high frequency selectivity, such as many sharp nulls from transmission line stubs (xDSL and PowerLine modems) and from radio multi-path cancellation,
  - And then the Feed Back Filter coefficients (and power in general) would become large, leading to the phenomenon of Error Propagation
- **There are many well known techniques that 'practically solve' error propagation, for all but the most 'spikey' SNR(f) channels**
  - Tomlinson Harashima Precoders (THP) move the feedback to the transmitter
  - Partial Response Precoders, as used in 100GBASE-KP4, are efficient THPs for small M
  - Soft and/or erasure decision architectures
  - Maximum Likelihood Sequence Detector (MLSD). 100GBASE-KP4 supports practical implementations by using 'state pinning' (non-information) symbols

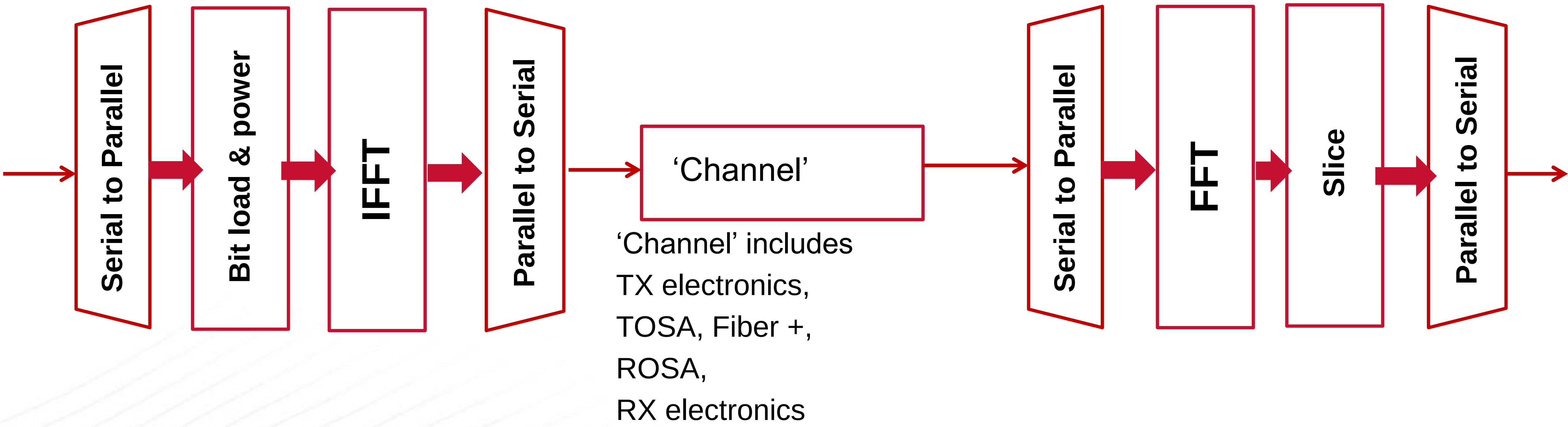
HISTORY OF SERDES IS DFE

- **For high Inter-Symbol Interference (ISI) channels the simplest receivers (especially for PAM-2) have been Decision Feedback Equalizers (DFE)**
  - A large number of relatively low-cost degrees of freedom in the Feed-Back Filter (FBF) (to closely match the dips and bumps of the ISI channel)
- **For M>2 and very high speeds, the cost and complexity of the FBF increases very fast**
  - The ‘look-ahead’ loop unwinding complexity grows with M^L, where L is the FBF length
- **For M>2 and high ISI, the error propagation from DFEs can become significant**
  - Techniques to mitigate / fix error propagation exist and are used, but can be a nuisance
    - Note that in 802.3bj 100GBASE-KP4 (PAM-4 for the backplane), the specification includes an integer non-linear TX precoder of 1/(1+D) Modulo(4), and it includes ‘state pinning symbols’ to ease the implementation of a 4-state MLSD (Viterbi Algorithm detector)

DISCRETE MULTI TONE (DMT)

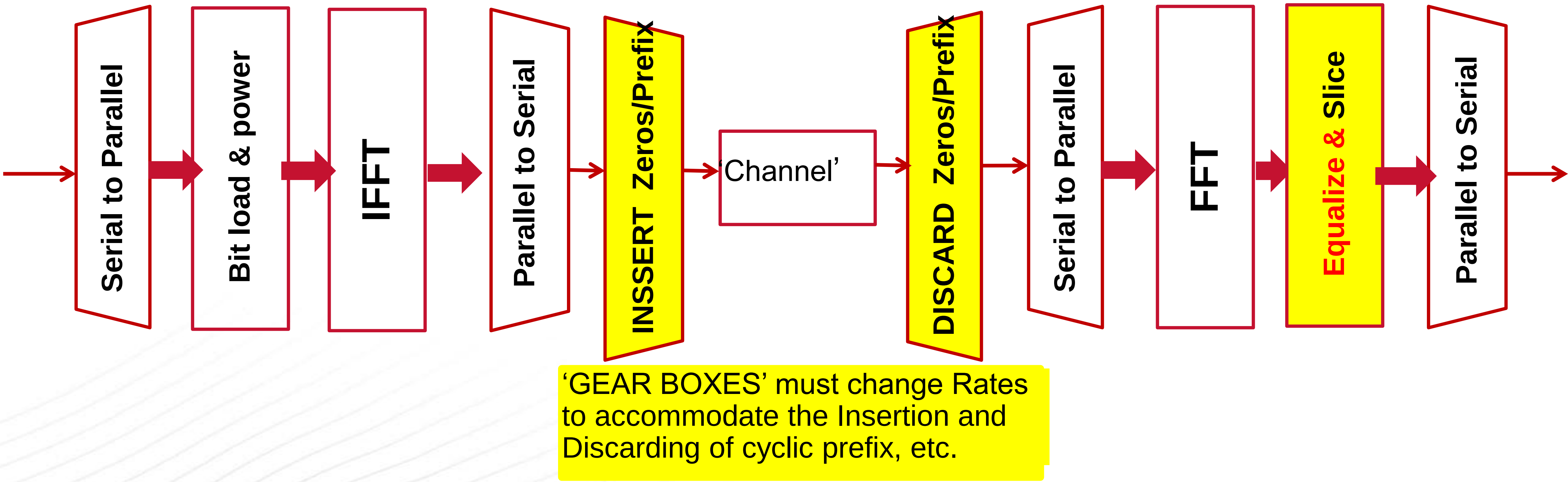
- **DMT performs IFFTs on blocks of data to be transmitted, and performs FFTs on blocks of received data**
- **Because the 'blocks of data' are essentially rectangular windows in time, then the DMT isn't exactly 'multi-carrier'**
  - Frequency 'bins' are not pure tones, but are SINC(f) shape in frequency, so they overlap significantly in frequency
  - But the 'bins' are orthogonal when synchronized to the block, so they don't interfere with each other in a synchronized receiver
    - But the connection to Fourier (and FCC) 'frequency' is maintained
- **DMT maps simple 'integer / digital user data' into real (continuous, like analog) values to be transmitted**
  - So high resolution (multi-bit, approaching 'continuous') DAC and TX are required

DISCRETE MULTI -TONE (DMT-N)



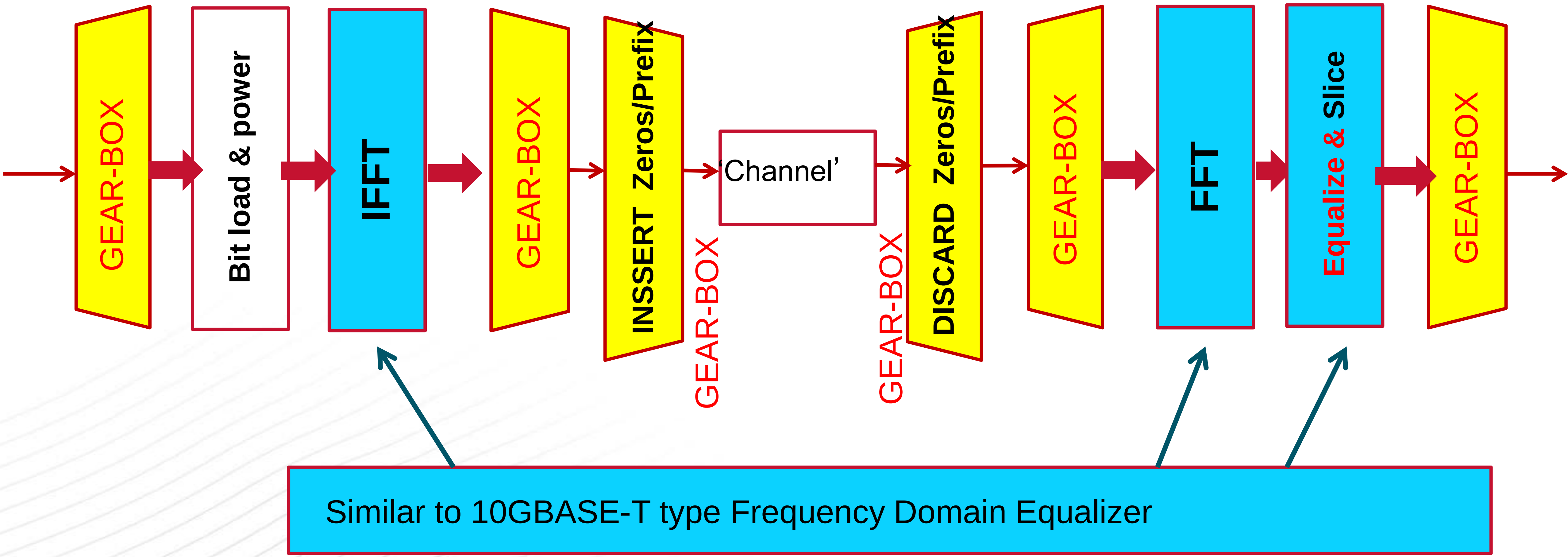
- **If the complete 'channel' response is the 'unit pulse' (no ISI), then the IFFT * FFT block operation is the identity matrix, so 'lossless' (ignoring any noises)**
- **Without loss of generality we can consider each 'frequency bin' (each bit loading) as either QAM or PAM. System performance is nearly identical and either serves our illustrations**
  - We follow the literature with the order IFFT ➔ FFT, so think of frequency domain data bins (input and output) and time domain values in the channel

DMT WITH CYCLIC PREFIX, ETC FOR ISI CHANNEL



- **Typical applications have 'some ISI' of length L in the channel**
- **Typical 'lowest complexity' fix is to prepend L Bauds of 'cyclic prefix' (non-information carrying) to each block of N Baud samples**
  - Which converts the FFT based 'cyclic convolution' into an effective linear convolution
  - Each of N frequency bins are 'equalized' with complex multiplies

DMT, DESCRIBED IN 802.3 TERMINOLOGY

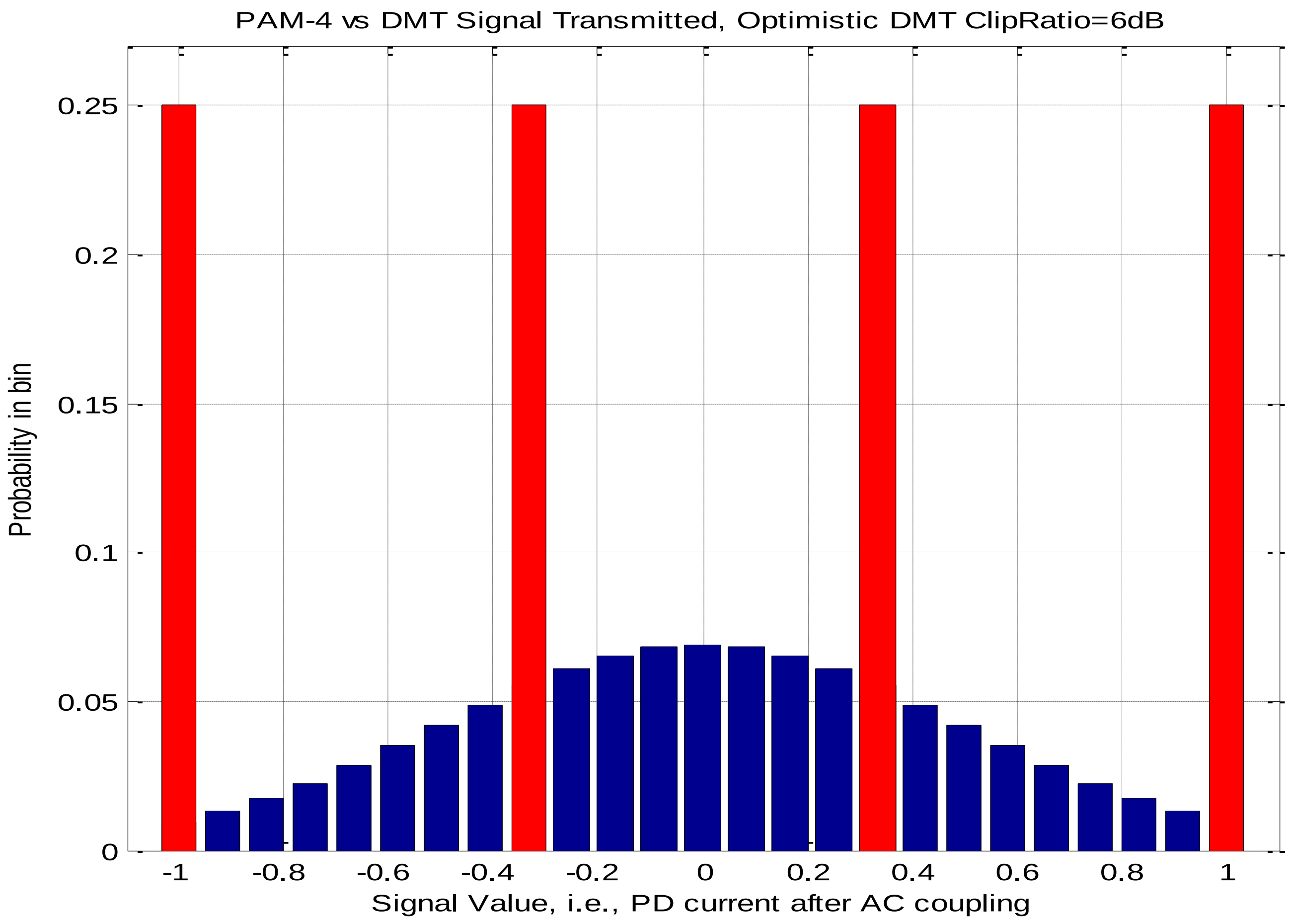


- **The DMT achieves channel equalization with a Frequency Domain approach, very similar to that used in 10GBASE-T implementations**
- **Except the DMT proposals runs at over 70 times higher speed (throughput)**

DMT DESIGN TRADEOFFS

- **Typically the ‘DC bin’ and the ‘Nyquist bin’ are zeroed (no information) because of practical difficulties**
- **Typically one or more bins are dedicated to ‘pilot tones’ to accomplish Clock Data Recovery (CDR)**
- **Typically many non-information Bauds are inserted per block of N Bauds for ‘cyclic prefix’ or similar**
- **All three of these above push towards large ‘N’, the number of Baud samples in the FFT engines, but …**
- **Large N increase the computational burden per information bit**
- **Large N increases the number of ‘constants’ which must be learned and saved. E.g., expect ~1,000 Bytes .**
- **Large N increases the Peak to Average Ratio (PAR) of the transmitted and received signals**
  - Typical implementations use designed clipping at the TX to avoid further loss of average signal variance (a.k.a. power in communications)

DMT TX 'SIGNAL VARIANCE' AND CLIPPING



- **DMT example with severe clipping ratio = 6dB**
- **Over 1% of transmitted samples clipped**
- **The 'Signal Variance' (which is communication theory TX power) is still 3.5 dB lower than that of PAM-4**
- **Note laser has same peak-peak power range and equal average power**

THEORY OF COMMUNICATION ; CAPACITY

- **Consider Linear Time Invariant (LTI) channels with Additive White Gaussian Noise (AWGN)**
  - This is the main theoretical development in the literature
  - For additive colored Gaussian noise, it's easy to 'whiten' and apply the theory
- **The Shannon-Hartley Capacity of such channels (for asymptotic zero probability of error) for Band Width limited channels is**

$$C_{SH} = \int_0^{BW} log_2 \left(1 + \frac{S(f)}{N(f)}\right) df$$

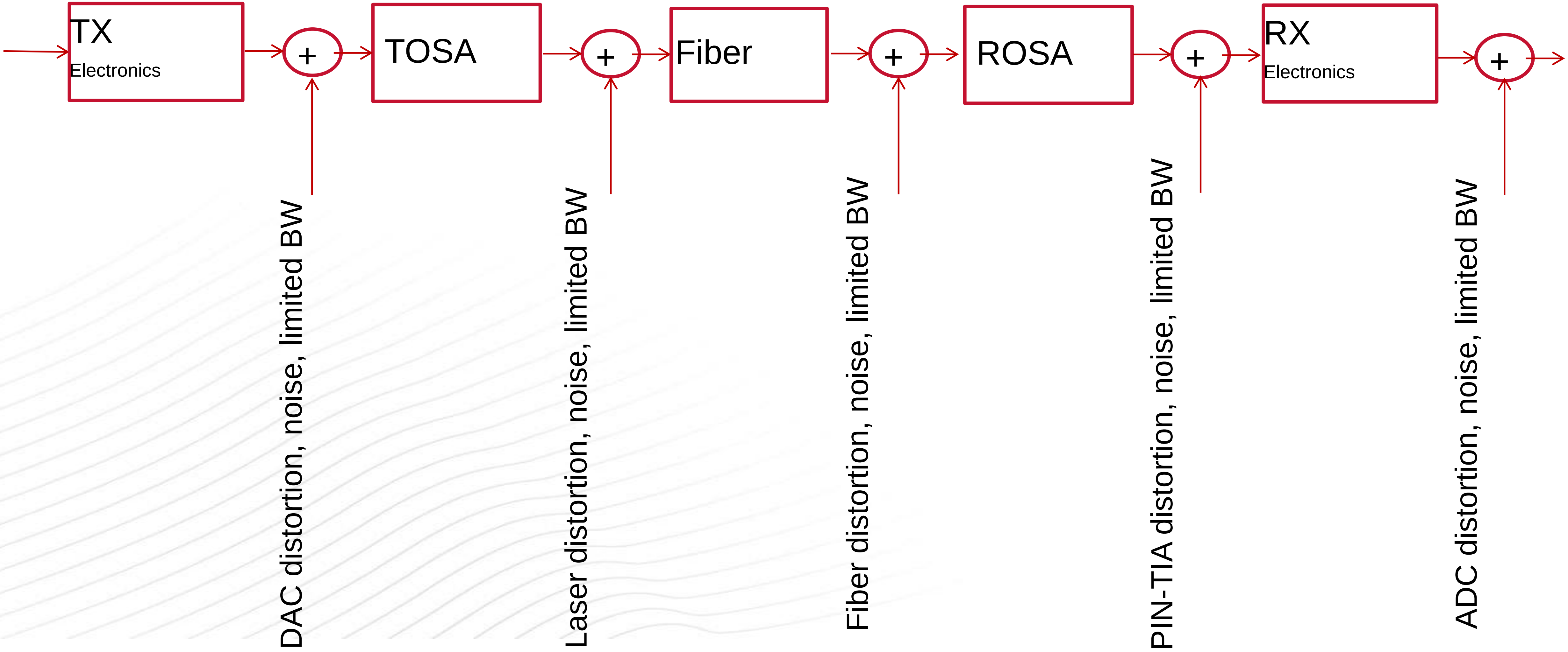
- **Surprisingly, the Capacity is just a scaled version of the DFE's Salz SNR,** C_{SH} **= *(Fs/6.02)(bit/dB) * Salz_SNR_dB***
- **Note that NRZ with Bandwidth == B Hz (single sided positive frequency only measure), can only achieve only 2*B bits/sec/Hz**
- **Conclusion is that IF you have higher SNR, then you can try to send more information.**

MAXIMIZING CAPACITY

- **First proof of maximizing capacity was with the 'water filling' algorithm, which apportions a given finite *average* TX power**
  - Which is akin to multi-carrier
  - Which for some time was thought to be a requirement to approach capacity
- **But further development of PAM-DFE showed 'surprising' results**
  - [Cioffi, Dudevoir,Eyuboglu, Forney, IEEE Tr. Communication Thy., Oct. 95] showed that an unbiased MMSE-DFE is a canonical (lossless) receiver
    "Finally, at the optimized symbol rate, there is no distinguishable performance difference between a flat transmit spectrum and an optimized spectrum on a wide range of channels with ISI."
    "There are also differences in implementation and system issues between single-tone and multitone systems, such as how filtering is implemented, how the system is adapted, delay, sensitivity to other types of distortion, and so forth. … Since, as we have seen, there will be essentially no difference in maximum achievable SNR performance between these two classes of systems, particularly when used with powerful codes, the choice between them will come down to other factors, such as these."
    "Simulation results suggest an even stronger result: on typical ISI channels, a non-optimized flat transmit spectrum yields near-optimal MMSE-DFE performance down to rather low SNR, …"

THE ‘CHANNEL’ IS MORE COMPLEX THAN JUST ‘RX SENSITIVITY’

- **Distortions and some noises are ‘Data Dependent’ (not additive)**



WHAT IS SIGNAL, NOISE, AND DISTORTION?

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- **Everyone thinks they know, but different applications and individuals use the terms differently, so DEFINE here;**
- **Noise = the non-repeatable portion of observed waveforms (experiments) when we believe all the known experimental conditions are identical (e.g., the same data pattern)**
  - Probably need to include temperature, pressure, humidity, ‘voltage’, etc., as ‘controls
  - Define (Signal + Distortion) as the result of averaging out the Noise
  - Note that the Noise can also be broken into ‘stationary’ and ‘time varying’
- **Signal = the portion of the (Signal + Distortion) above that is ‘fit’ by a Linear Time Invariant (LTI) model**
  - Say of length L Baud samples
  - The effect of the LTI systems is Inter Symbol Interference (ISI) here
  - Sometimes called the ‘Linear part of the Signal’
- **Distortion = the portion of the (Signal + Distortion) that is NOT fit by the LTI model above**
  - Sometimes called the ‘Non- Linear part of the Signal’

HOW DOES DISTORTION IMPACT PERFORMANCE?

- **Typical first order analysis is to treat distortion as a noise, and to hope (pretend) its 'like' AWGN**
  - White meaning adjacent samples are independent (not correlated), etc.
  - Can be an OK approximation for some systems with certain 'wideband' type distortions and when distortion is much less than noise
  - Performance then goes with *{Signal / (Noise + Distortion) }*
- **Real performance can be closely approximated by applying the Union Bound, considering the Baud by Baud 'loss of distance' due to each pattern dependent sample of distortion**
  - Performance of each 'sample_k' goes as *{ (Signal_k - Distortion_k)/ Noise }*
  - Each 'distortion sample_k' is stealing away 'distance', noted here as losing signal
  - And if noise is pattern dependent, like RIN, then Noise statistics are also a function of the sample 'k'

PERFORMANCE OF DMT IN DISTORTION?

- **DMT performance in distortion and pattern dependent noise has one significant difference from (typical vanilla) PAM systems**
- **The signal, distortion and noises are all passed through the block FFT before being 'sliced' to PAM (or equivalently QAM)**
  - The big FFT transformation effects an 'averaging'
  - E.g., an 'impulsive distortion', like rare clipping, is transformed (spread) more or less equally across all 'bins'
- **DMT performance in distortion and pattern dependent noise will tend to *{Signal / (Noise + Average_Distortion)}***
  - Even when the distortion is larger than the noise
  - This can be a significant advantage when the distortion or time varying noise has significant Peak/ Average ratio
  - E.g., consider when peak distortion is around $d_{min}/2$, so on a 'decision boundary'. The FFT block averaging' removes a near certain error at the expense of slightly increased BER for all in the block of N Baud samples.

PERFORMANCE OF PAM-DFE IN DISTORTION?

- **In large and wide range distortion, Vanilla PAM performs like the previously mentioned *{(Signal_k – Distortion_k) / Noise }***
- **But much better detectors are available if they can ‘match’ (model) the distortion**
- **The simplest such is the non-linear DFE, which cancels the trailing distortion terms and optimally sets the decision thresholds**
  - See [Winters, Kasturia, Jounal of Lightwave Tech., July 1992]
  - Advantages over ‘spreading’ the distortion like DMT exist, and the performance can go as high as *{ Signal / Noise },* as if the distortion didn’t exist
- **More complex methods, including MLSE, can in some cases use the distortion power itself to enhance the decision distance**
  - Performance can go as high as *{(Signal_k + Distortion_k) / Noise }*
  - The goal is not necessarily to minimize distortion
- **It’s relatively easy to ‘match/model’ TX distortions at the decision device, because the RX is already ‘estimating the TX’**
  - Its impractical to do this general modeling / matching with DMT, as the FFT has ‘smeared’ this information.

CONCLUSIONS

- **DMT offers no theoretical ‘spectral efficiency’ advantages over PAM-DFE on any reasonable channels we’ll consider**
  - We don’t (shouldn’t) have a large number of spectral / SNR(f) nulls
  - We don’t want to operate over significant bands where SNR(f) is low
  - A flat TX power spectrum is sufficient for optimal single carrier
  - Theory aside, many works show DMT and PAM ‘close competitors’ on LTI AWGN channels
- **Our peak constrained transmitters are a significant disadvantage for DMT vs. PAM**
  - The DMT average signal variance will be 3-6dB lower! This is what limits DMT
  - The severe DMT clipping needs to be evaluated w.r.t. our 1e-17 BER goal
- **A qualitative high level look at the impacts of distortion and time varying noise on these systems showed**
  - DMT ‘averages’ (spreads / smears) the distortions and noises, which is a large advantage in conditions with large and wide ranging distortions and noises
  - But PAM-DFE systems can perform better than this ‘average’ if the distortions and noises can be modeled at the detector
- **The implementation power / cost of DMT vs. PAM is significantly higher, so it makes sense to search beyond ‘Vanilla PAM-DFE’**

HISTORY OF PAM VS. DMT, WITH SPECULATIONS

- **PAM advocates have generally been assuming 'quite good' channels**
  - Relatively high BW
  - Often using MZM, with little or no distortion
  - With fairly good RIN, such that there is little spread of SNR across different 'levels'
  - All the channels supported with simple 'inverting equalizer' + slicer for the RX (no DFE or advanced detector, etc)
- **DMT advocates have been working on some 'quite difficult' channels**
  - Quite low BW. E.g., using 10Gbps components to achieve 100Gbps
  - Using DML, apparently with considerable distortions
  - Net SNR(f) graphs shown with surprising difficulties
    - Some show a very large number of 'notches' with a comb like structure. We speculate that these are due to time-interleaving errors in the DAC and/or the ADC
    - Some (all) show SNR(f) going to 0dB. We speculate these are again due to DAC and/or ADC , or are from a RIN peaking effect, or are simply from severe ISI, or?

FUTURE WORK

- **Start working on the same channels!**
- **Develop standardized methods to describe (and share) channel models that include the distortion(s) and time-varying noise(s)**
- **The best development paths are based on available a priori information**
- **Do we have any simple models of distortion?**
  - For DML DFB
  - For DML VCSEL
  - For MZM (segmented or not)
  - For EAM
- **Do we have RIN models generalized to high frequency with ‘RIN peaking’?**
- **Any other channel impairments?**
- **PAM advocates to demonstrate advanced RX for poor channels modeled above**
- **How poor of channels does it make sense to support?**
  - The goal is a cost and power effective product, not just technical possibility
  - See 10GBASE-T history

Thank you