Soft-Decision-Data Reshuffle to Mitigate Pulsed Radio Frequency Interference Impact on Low-Density-Parity-Check Code Performance

Jianjun (David) Ni

Abstract

This presentation briefly discusses a research effort on mitigation techniques of pulsed radio frequency interference (RFI) on a Low-Density-Parity-Check (LDPC) code. This problem is of considerable interest in the context of providing reliable communications to the space vehicle which might suffer severe degradation due to pulsed RFI sources such as large radars. The LDPC code is one of modern forward-error-correction (FEC) codes which have the decoding performance to approach the Shannon Limit. The LDPC code studied here is the AR4JA (2048, 1024) code recommended by the Consultative Committee for Space Data Systems (CCSDS) and it has been chosen for some spacecraft design. Even though this code is designed as a powerful FEC code in the additive white Gaussian noise channel, simulation data and test results show that the performance of this LDPC decoder is severely degraded when exposed to the pulsed RFI specified in the spacecraft's transponder specifications. An analysis work (through modeling and simulation) has been conducted to evaluate the impact of the pulsed RFI and a few implemental techniques have been investigated to mitigate the pulsed RFI impact by reshuffling the soft-decision-data available at the input of the LDPC decoder. The simulation results show that the LDPC decoding performance of codeword error rate (CWER) under pulsed RFI can be improved up to four orders of magnitude through a simple soft-decision-data reshuffle scheme. This study reveals that an error floor of LDPC decoding performance appears around CWER=1E-4 when the proposed technique is applied to mitigate the pulsed RFI impact. The mechanism causing this error floor remains unknown, further investigation is necessary.

Avionic Systems Analysis

Soft-Decision-Data Reshuffle to Mitigate Pulsed Radio Frequency Interference Impact on Low-Density-Parity-Check Code Performance

Jianjun (David) Ni

Jianjun.Ni@escg.jacobs.com / david.ni-1@nasa.gov

281-461-5447 / 281-483-1467

Avionic Systems Analysis Section (ASAS)

ERC/ESCG@JSC/NASA

Outline

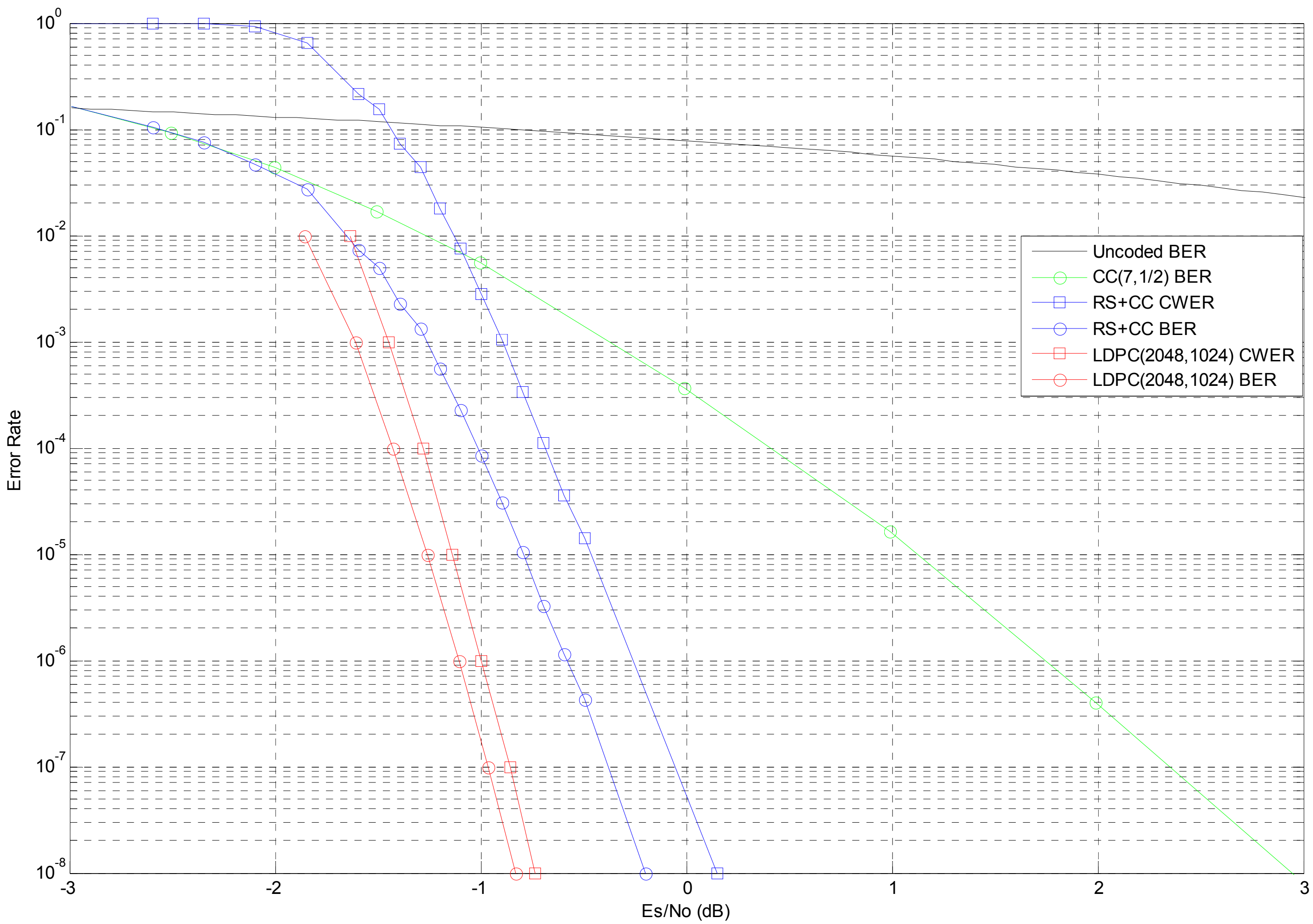
- Purpose
- LDPC Decoding Performance
- Pulsed RFI Specifications
- Simulation Results with Pulsed RFI
- Pulsed RFI Modeling
- With Theoretical ‘SNR’ Estimator
- Histogram of Soft-Decision-Data
- Reshuffle Schemes to Mitigate Pulsed RFI
- Summary
- References

Purpose

- **To evaluate the effects of the pulsed Radio Frequency Interference (RFI) on Low-Density-Parity-Check (LDPC) decoding performance. This problem is of considerable interest in the context of providing reliable communications to the space vehicle which might suffer severe degradation due to pulsed RFI sources such as large ground based radars [1-3].**

- **In this study, we explore the implemental techniques (soft-decision-data reshuffle) to mitigate pulsed RFI impact on LDPC code AR4JA (2048, 1024) decoding performance.**

LDPC Decoding Performance



Pulsed RFI Specifications

- **NASA legacy systems such as ISS ACS Transponder, 4th Gen Transponder and Integrated Receiver [4-6] have similar requirement regarding pulsed RFI specifications as follows:**

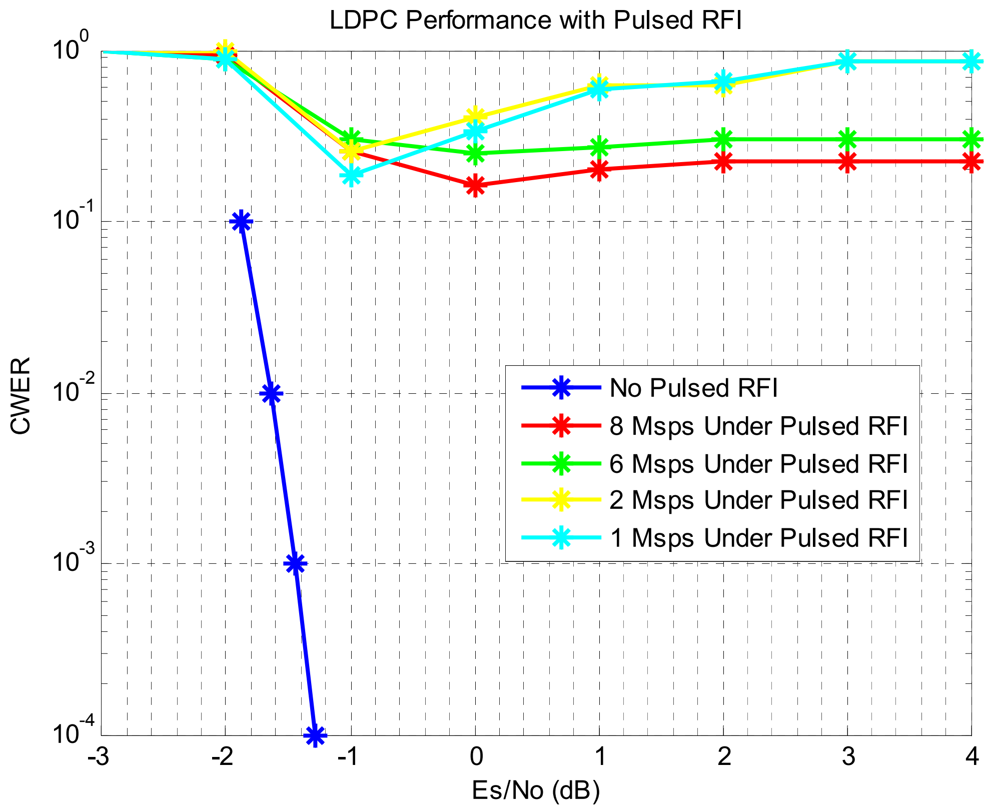
  The transponder shall perform with less than 3-dB degradation in acquisition, tracking, and command thresholds when an in-band pulsed Radio Frequency Interference (RFI) signal with the following characteristics is present:

  - Level: +10 dBm
  - Frequency: Fr +/- 10 MHz
  - Pulse Width: 10 microseconds.
  - Repetition Rate: 3333 pps
  - Duty Cycle: 3%

- **Today, some spacecraft-in-design adopts the above pulsed RFI specifications. Hence, the above parameters of pulsed RFI are used in this study.**

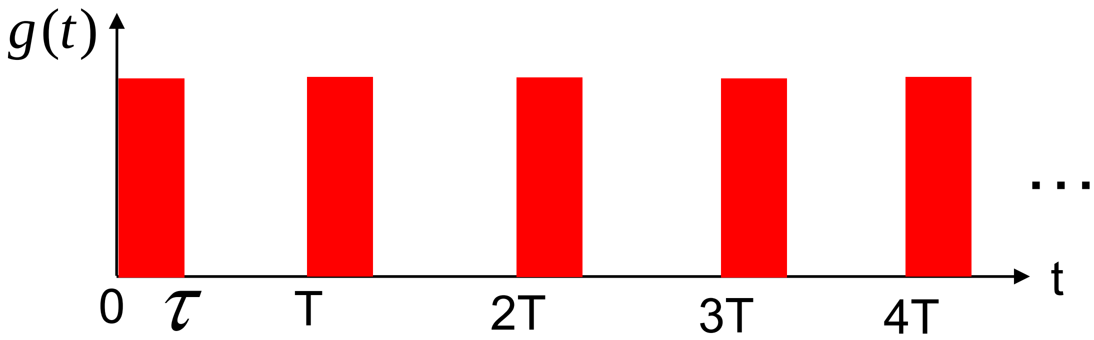
Simulation Results

- Previous analysis work [7] shows that the LDPC decoder is severely impaired when exposed to pulsed RFI. The Codeword Error Rate (CWER) is degraded to greater than 20% when the pulsed RFI power is 10 dB stronger than the desired signal power.
- Some available test results approximately match with the simulation results



Pulsed RFI Modeling

- **Pulsed RFI Signal Model [2] (single source)**

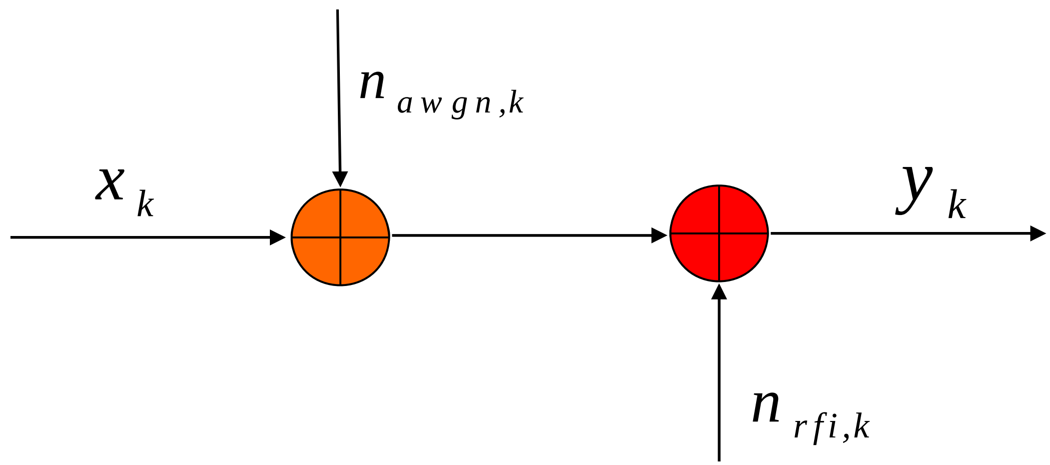


$$I(t) = \sqrt{2P}\, g(t) \sin(\omega t + \theta)$$

where P, ω and θ are the peak power, center frequency and phase of RFI signal respectively; The pulse train function $g(t)$ is assumed to be periodic gating function with pulse repetition rate rate 1/T and duty cycle τ/T.

Pulsed RFI Modeling

- **RFI Channel Model**



$$y_k = x_k + n_{awgn,k} + g(t) * n_{rfi,k},$$

$$where\ n_{awgn,k} \sim \mathrm{N}(0, \sigma_1^2)$$

$$n_{rfi,k} \sim \mathrm{N}(0, \sigma_2^2).$$

Simulation Approach

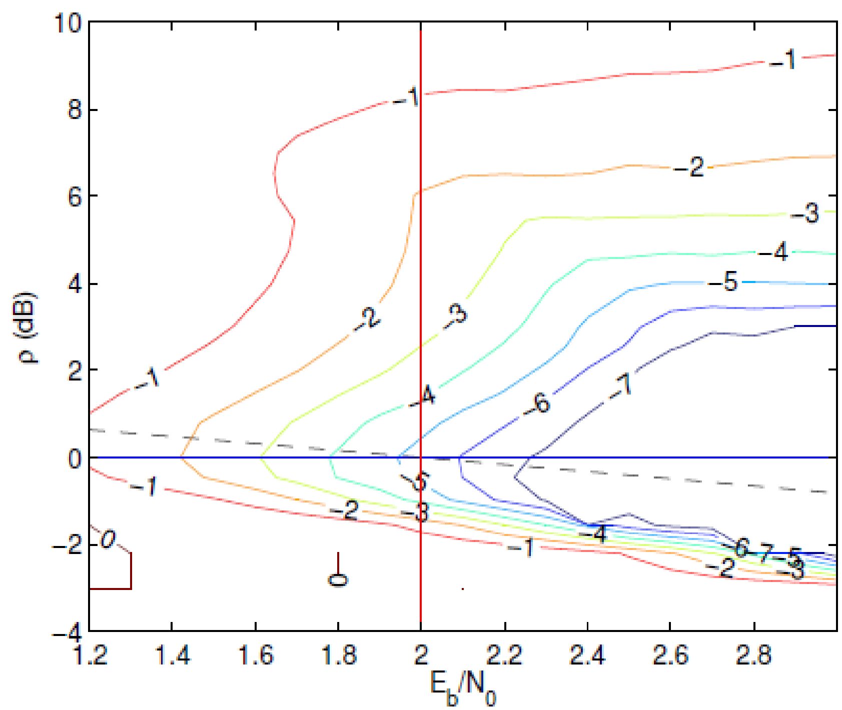
- Assumption: perfect frame synchronization, and accurate 'SNR' estimation when no pulsed RFI. (For detailed facts and assumptions on pulsed RFI modeling, see [8])
  - Pulsed RFI parameters: Pulse Width = 10us, Pulse Period = 300 us, Pulse Repetition Rate = 3333 pps, Power ~100 dB RFI/Signal .

Symbol Rate (Msps)	Pulse Width (symbol)	Pulse Period (symbol)	Data Frame (symbol)	Number of effected symbols in one frame (~symbol)	LCM (Data Frame, Pulse Period) (symbol)	Number of Frames to repeat
8	80	2400	2112	70	52800	25
6	60	1800	2112	70	158400	75
2	20	600	2112	70	52800	25
1	10	300	2112	70	52800	25
0.2	2	60	2112	70	10560	5
0.1	1	30	2112	70	10560	5

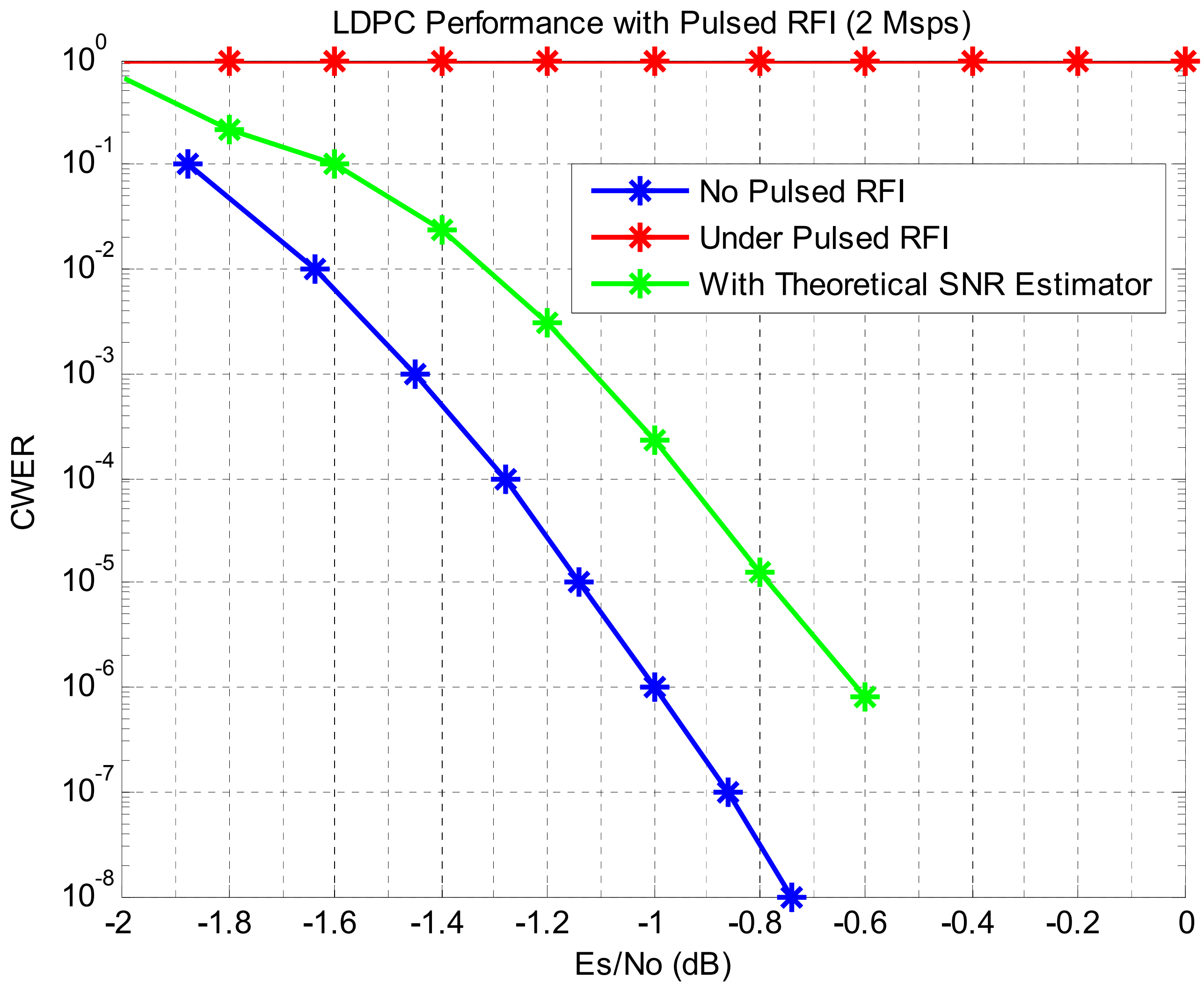
Why 'SNR' Estimation is so Critical?

- Decoders for the modern LDPC codes are based on probabilistic inference.
- The input to the decoder is not just the noisy received symbols; instead, the log Likelihood ratio (LLR) as the probability information is request as decoder input. In fact, LLR is the scaled symbols with a scaling factor called "combining ratio" (sometimes casually referred to as 'SNR').
- Study shows [9] that error in 'SNR' estimation results in degradation of decoding performance.
- A theoretical 'SNR' estimator responds immediately to the SNR variations and scales the corrupted symbols appropriately (symbol-wise 'SNR' estimator).

$$
\begin{aligned}
\lambda &= \log \frac{P(y|c=0)}{P(y|c=1)} \\
&= \log \frac{e^{-(y-A)^2/2\sigma^2}}{e^{-(y+A)^2/2\sigma^2}} \\
&= \frac{2A}{\sigma^2} y.
\end{aligned}
$$

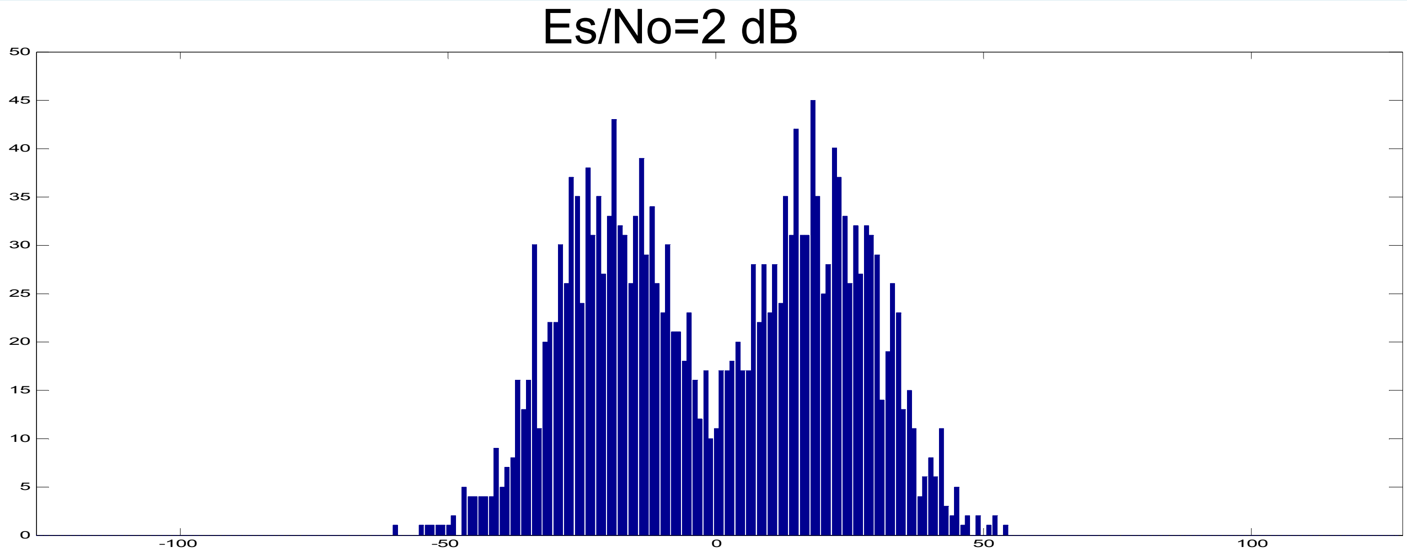


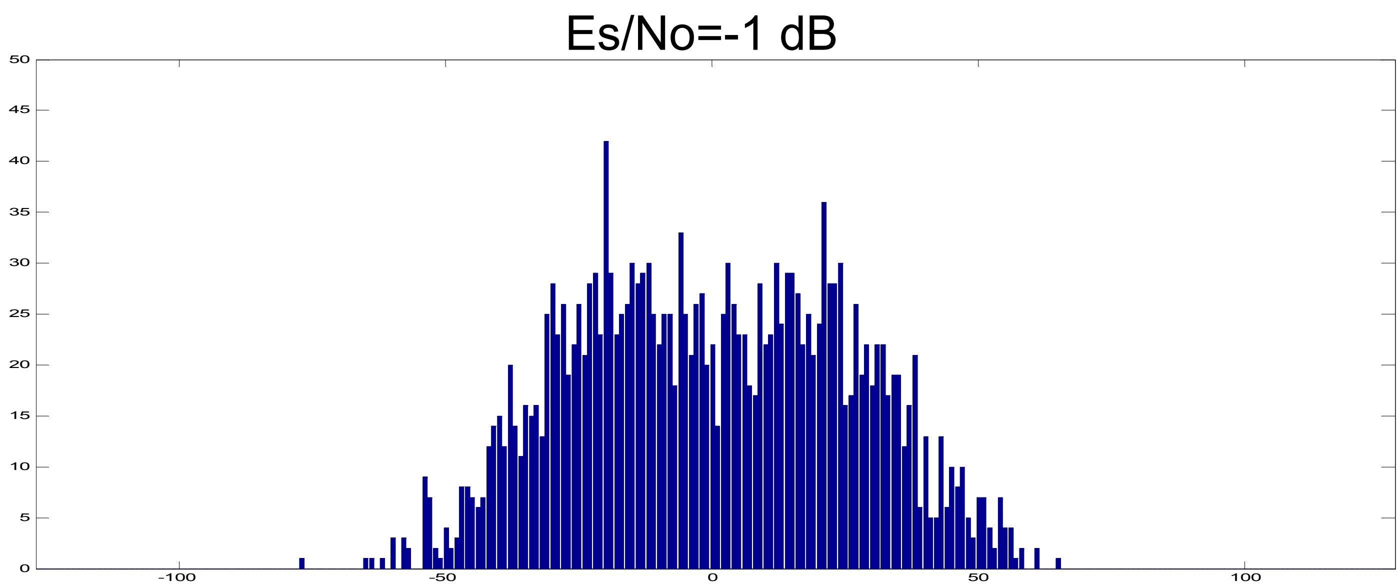
LDPC Performance with Theoretical 'SNR' Estimator



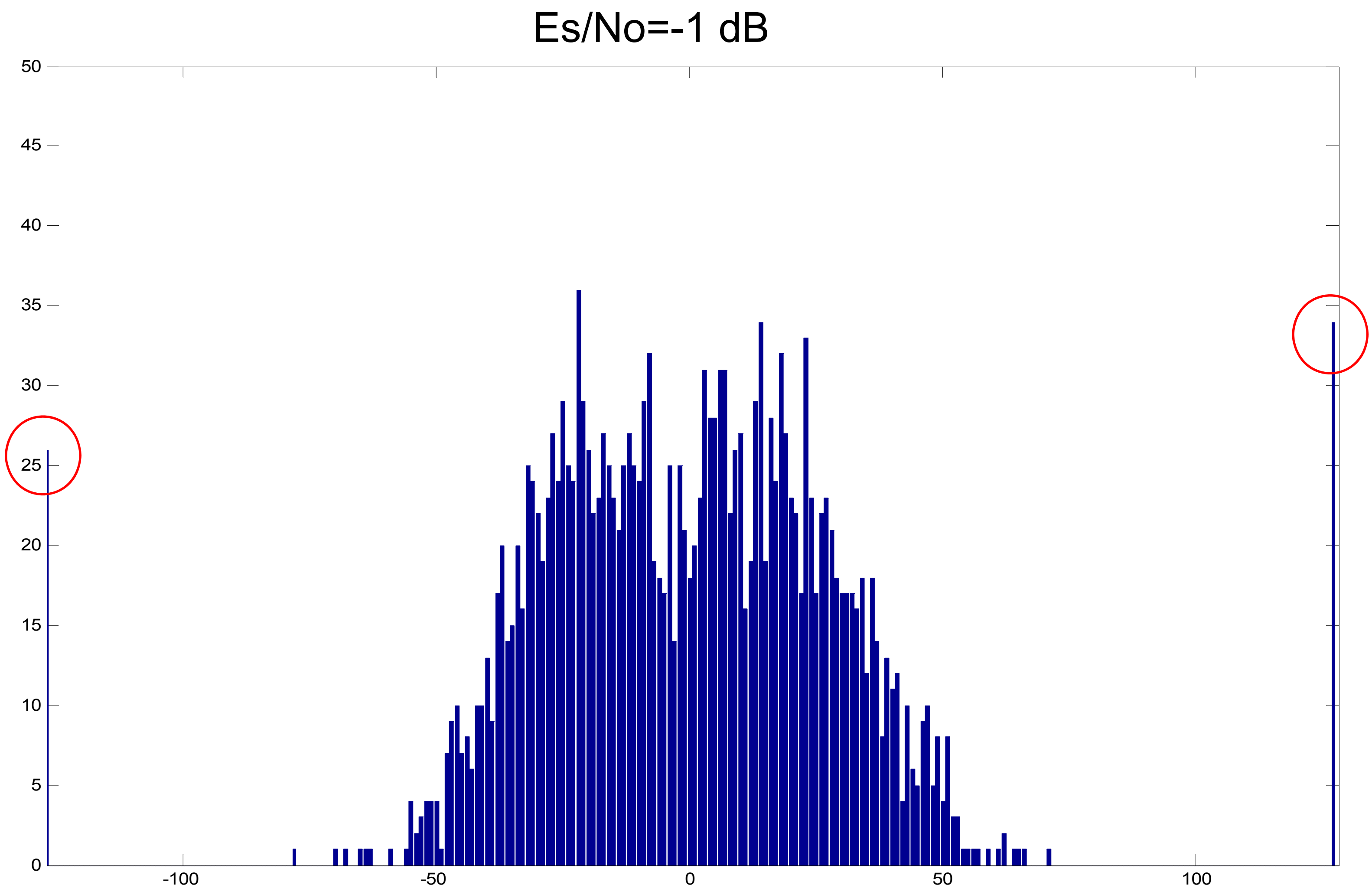
Histogram of Soft-Decision-Data without Pulsed RFI

Avionic Systems Analysis

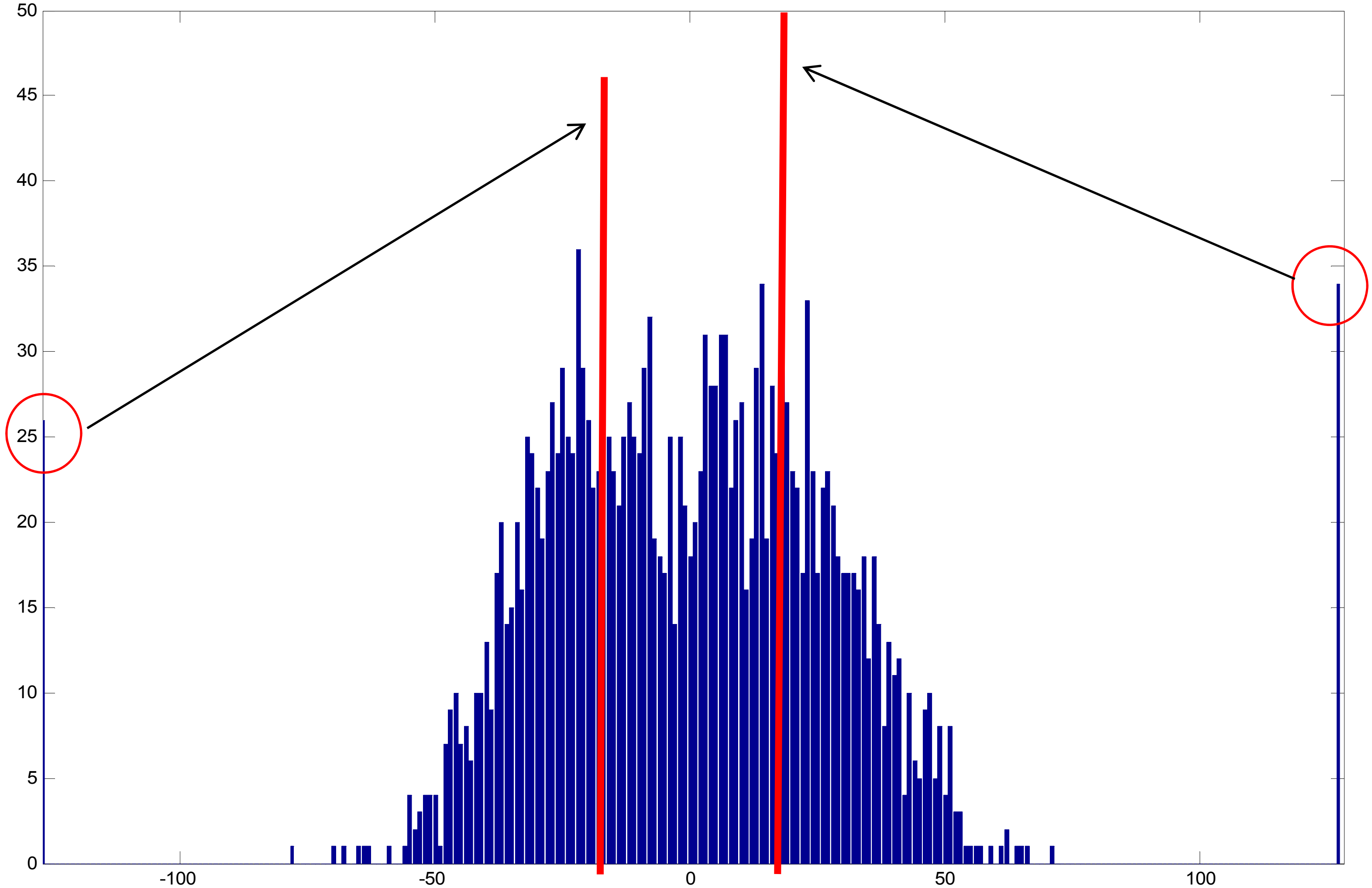




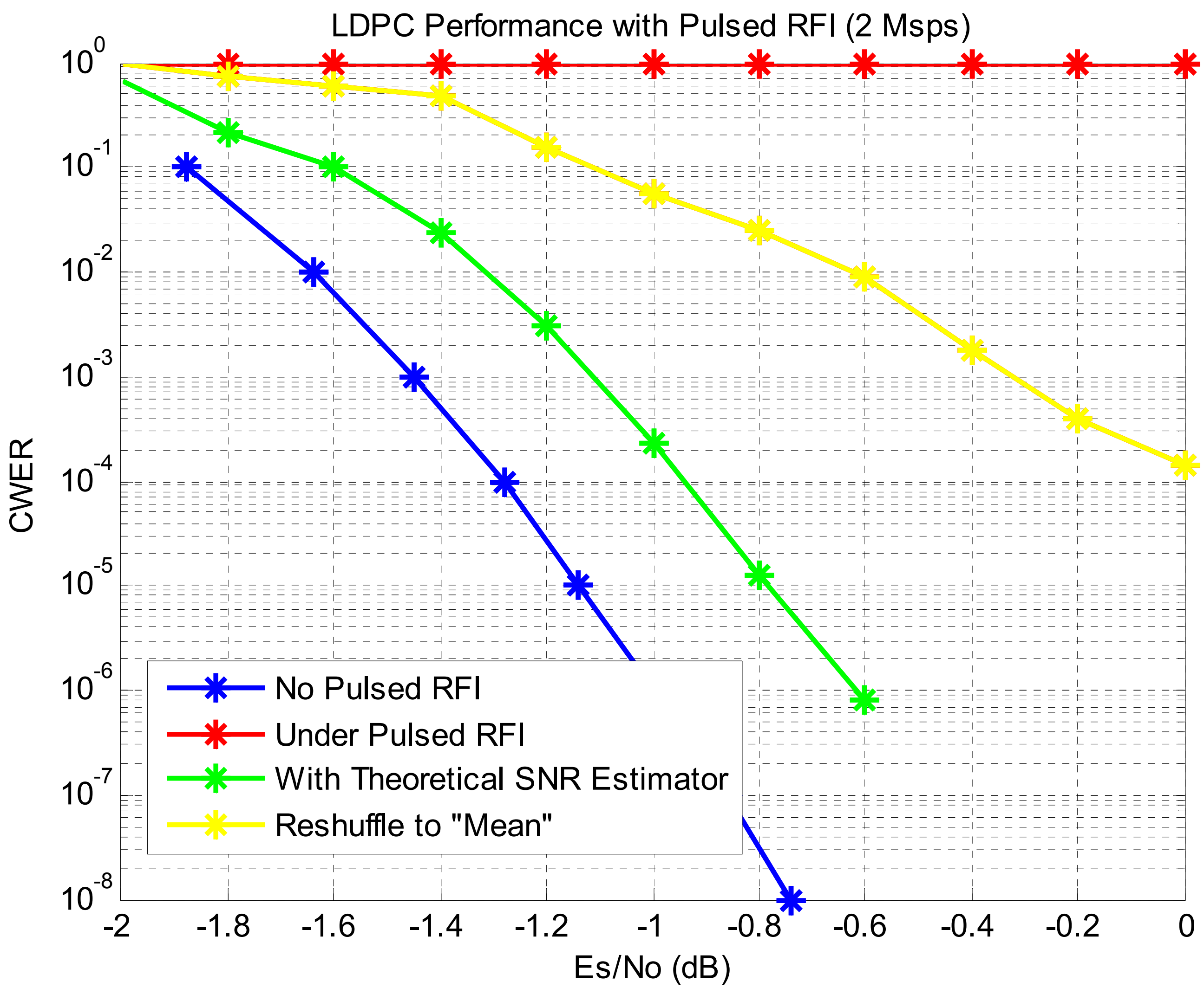
Histogram of Soft-Decision-Data under Pulsed RFI



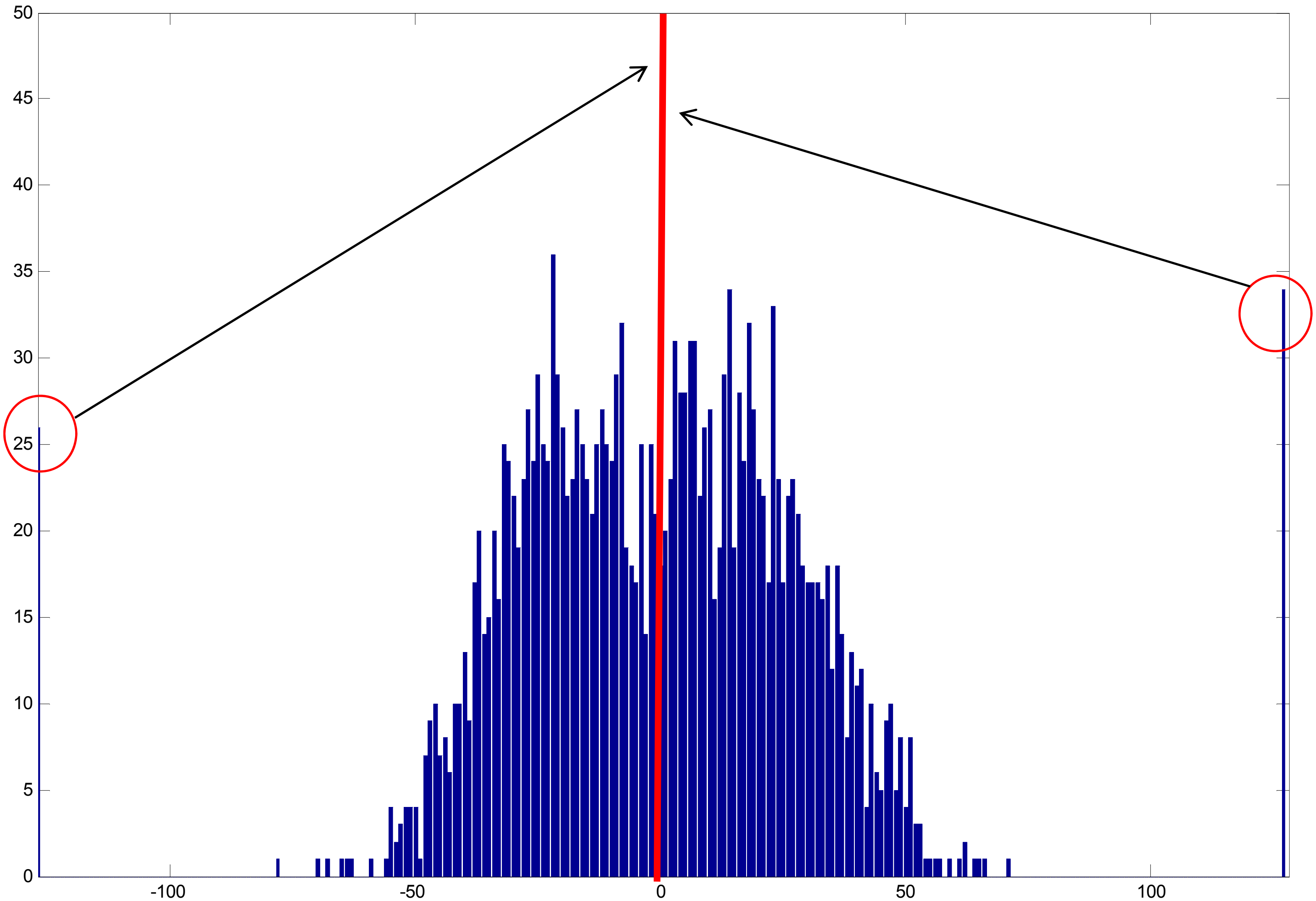
Reshuffle to "Mean"



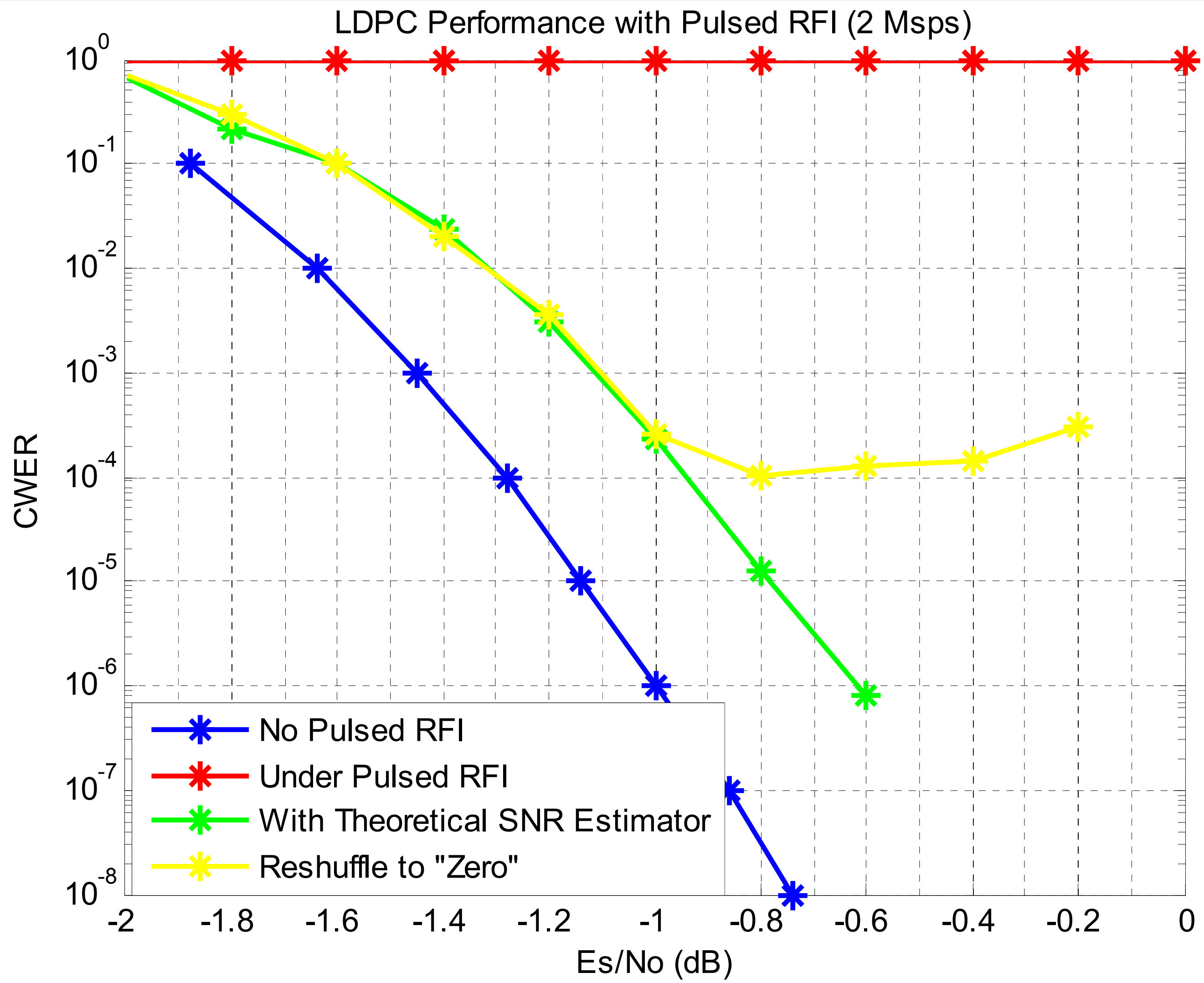
Reshuffle to "Mean"



Reshuffle to “Zero”



Reshuffle to “Zero”



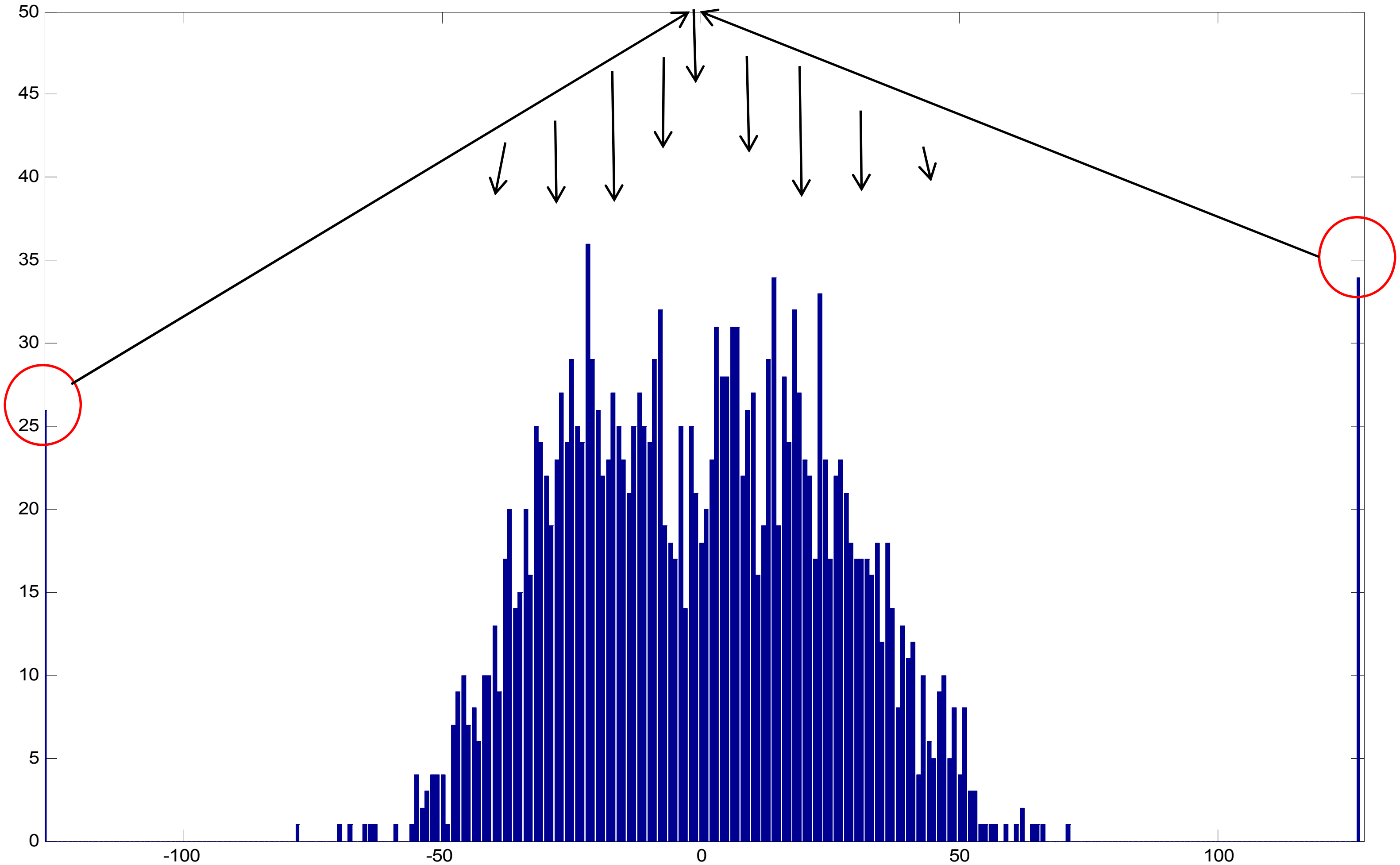
Discussion on Reshuffle to “Zero”

Avionic Systems Analysis

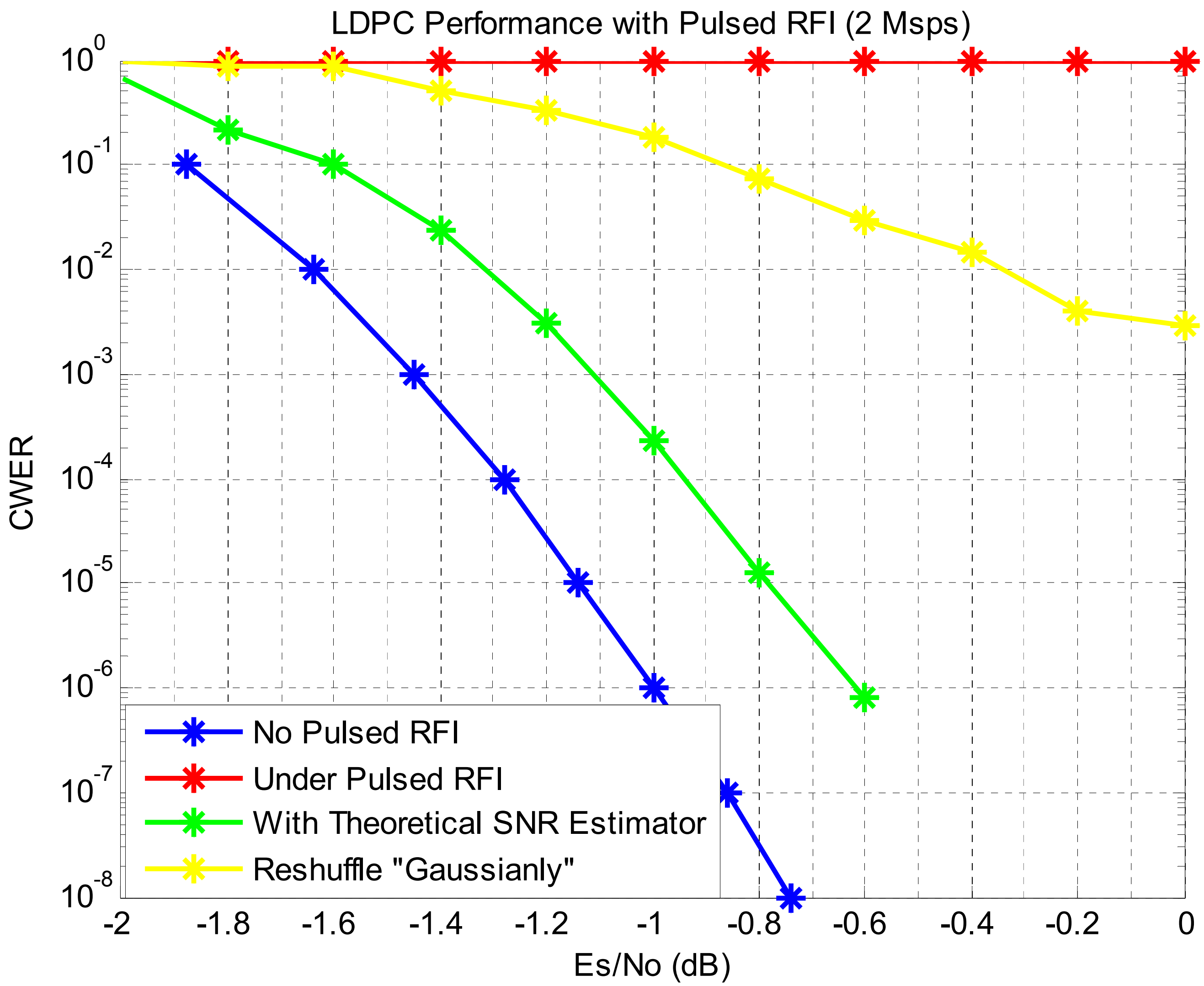
- **It is observed that the performance of Reshuffle to “Zero” closely matches with the performance with Theoretical ‘SNR’ Estimator when Es/No is low (below -1 dB) while two performance curves diverge when Es/No increases and the performance curve of Reshuffle to “Zero” floored out at CWER 1E-4.**

- **One speculation is that when Es/No is low, the scaling factor “combining ratio” is small (close to zero) with strong pulsed RFI, Reshuffle to “Zero” is same as scaling it with a factor of zero, therefore it does the same thing as the Theoretical ‘SNR’ Estimator does. However, when Es/No increases, the scaling factor increases too and “walks” away from zero, Reshuffle to “Zero” provides an inaccurate scaling factor, hence the performance curve starts to diverge from the curve with Theoretical ‘SNR’ Estimator.**

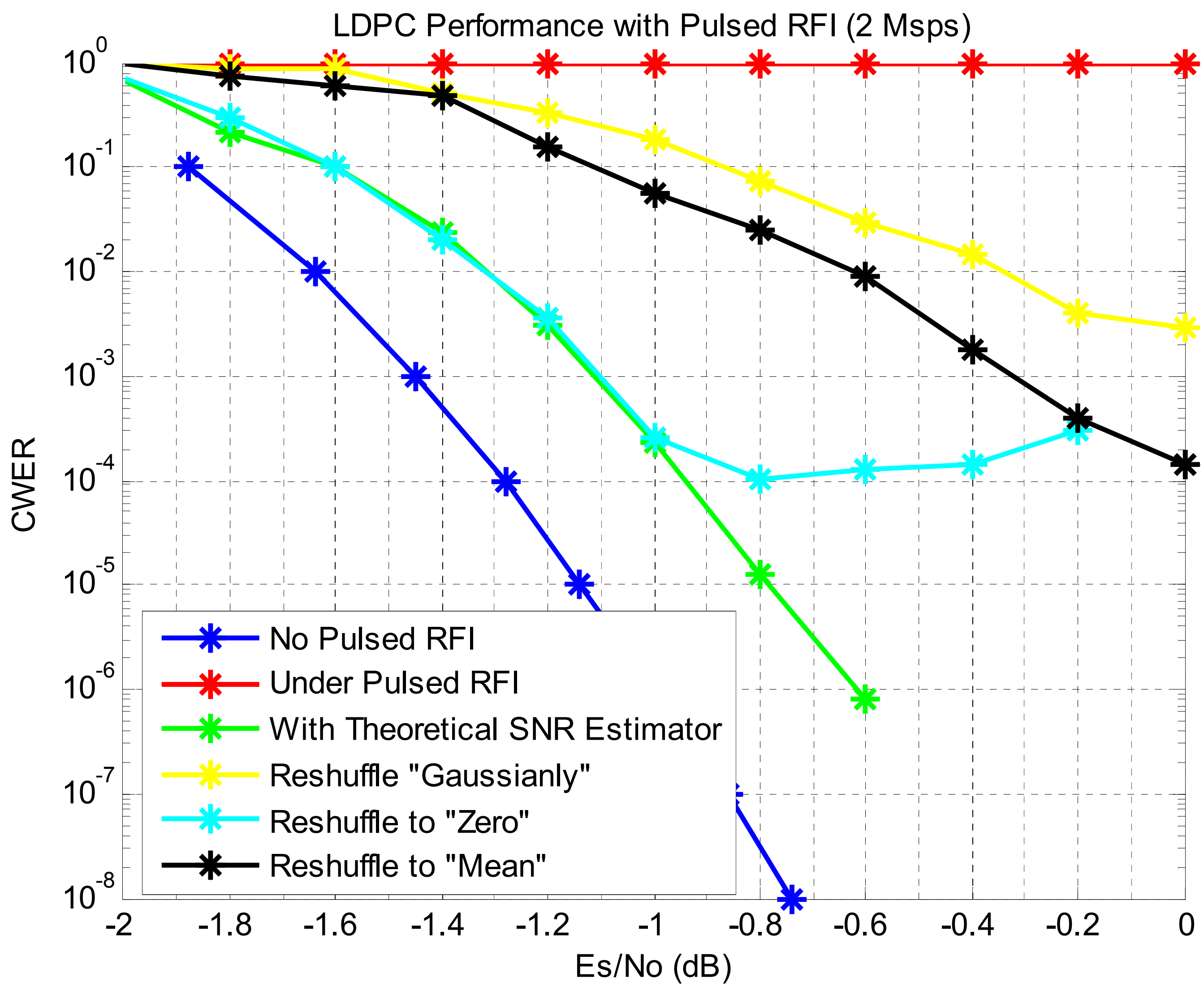
Reshuffle "Gaussianly"



Reshuffle "Gaussianly"



Comparison of Three Reshuffles

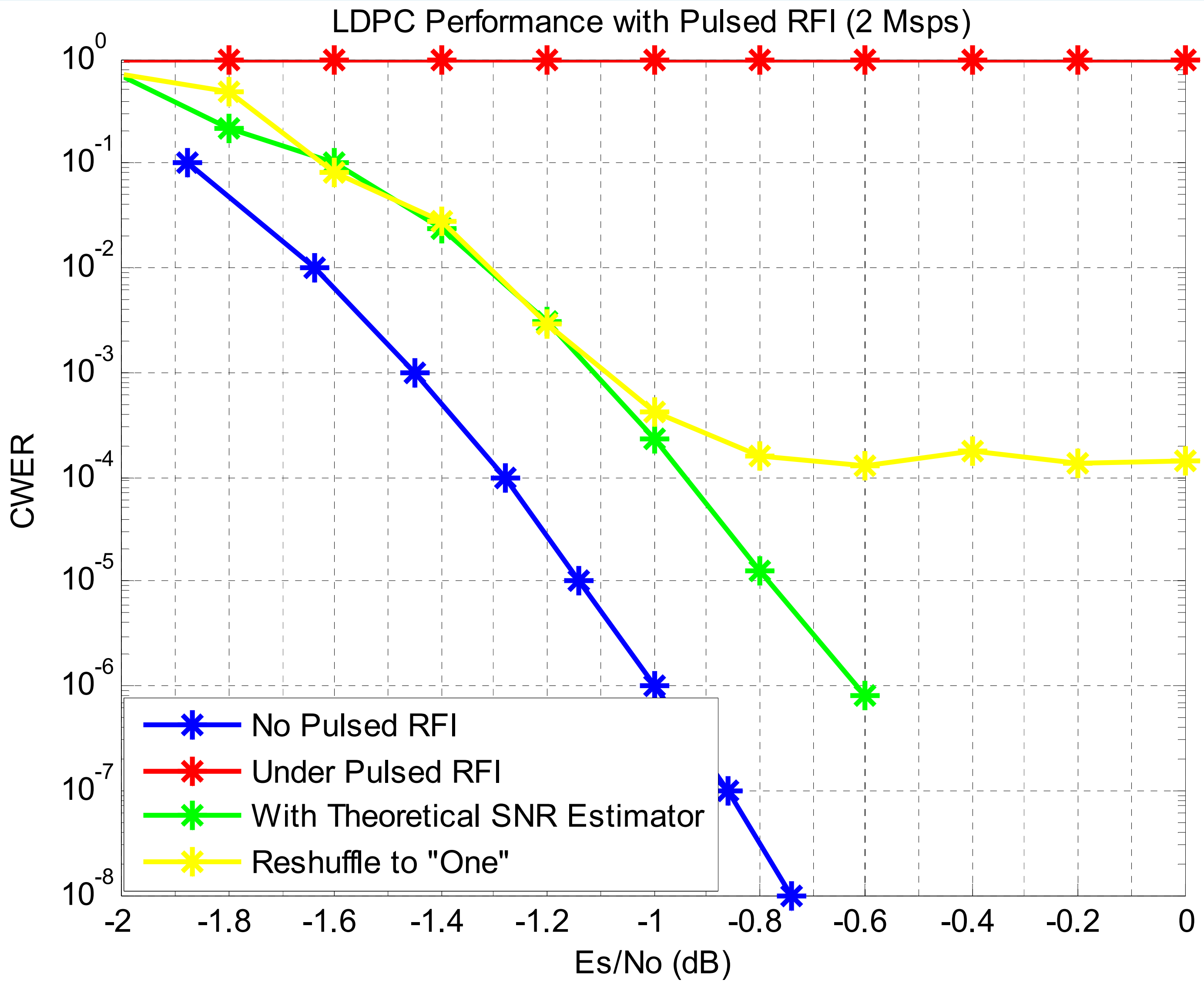


One More Try: Reshuffle to "One"

- **Thoughts: when the method Reshuffle to "Zero" is applied, it literately changes the pulsed RFI channel into an eraser channel since those symbols effected by pulsed RFL have been completely erased out. LDPC code is designed for the AWGN channel, not the eraser channel. So, is the performance floor of Reshuffle to "Zero" is due to the erasure effect? How about reshuffle to some bins close to "Zero" bin, not completely "erase-out"?**

- **A method Reshuffle to "One" (shuffle to Bin "-1" and Bin "+1") has been evaluated and the results (see next page) show that the performance is almost the same as Reshuffle to "Zero" and the floor still appears at CWER 1E-4. The mechanism causing this error floor remains unknown**

Reshuffle to "One"



Summary

- Test results and simulation data show that the performance of the LDPC decoder is severely degraded when exposed to the pulsed RFI specified in some spacecraft's transponder specifications.
- An analysis work (through modeling and simulation) has been conducted to evaluate a few implemental techniques to mitigate the pulsed RFI impact by reshuffling the soft-decision-data. The simulation results show that the LDPC decoding performance (CWER) under pulsed RFI can be improved up to four order of magnitude (from 1E0 to 1E-4) through a simple soft-decision-data reshuffle scheme "Reshuffle to 'Zero'".
- This study reveals that an error floor of LDPC decoding performance appears at CWER=1E-4 when the proposed technique is applied to mitigate the pulsed RFI impact. The mechanism causing this error floor remains unknown, further investigation is necessary.

References

- [1]. S.L. Bernstein; "Theory Of The Effects Of Pulsed RFI On Coded Communication", Technical Note 1977-34, Massachusetts Institute of Technology Lincoln Laboratory, July 22 1977.
- [2]. Marvin K. Simon, K. T. Woo; "The Performance of Suppressed Carrier Receivers in a Pulsed RFI Environment", IEEE Transaction On Communications, VOL. COM-28, No. 5, May 1980.
- [3]. Aaron Weinberg; "The Impact of Pulsed RFI on the Coded BER Performance of the Nonlinear Satellite Communication Channel", IEEE Transaction On Communications, VOL. COM-29, No. 5, May 1981.
- [4]. "Performance and Design Requirements and Specification for the Fourth Generation TDRSS User Transponder", Goddard Space Flight Center, Greenbelt, Maryland, REVIEW COPY (dated 10/24/96).
- [5]. "International Space Station Program Communications and Tracking Equipment-Development Specification Standard TDRSS Transponder", Document Number 10033011, Revision J, 21 May 1997.
- [6]. "Performance Specification Integrated Receiver", Interstate Electronics Corporation, 1994.
- [7]. David Ni; ""Pulsed Radio Frequency Interference Impact on Low Density Parity Check Code AR4JA (2048, 1024) Decoding Performance", report EV7-10-4586, ESCG/JSC, June 25, 2010.
- [8]. David Ni "Pulsed Radio Frequency Interference Impact on Frame Synchronizer Performance", report EV7-10-4560, ESCG/JSC, April 23, 2010.
- [9]. Kenneth Andrews, et al; "Symbol Scaling for LDPC Decoders", JPL, February 6, 2008.

Backup Slides

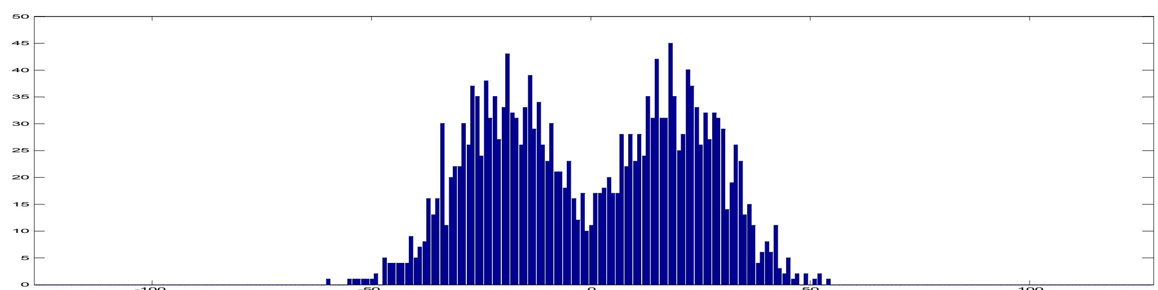
Gaussian Mixture Distribution

- **Received signal in AWGN Channel**
- **Y = X + N**
- **Conditioned Y|X is under Gaussian distribution**
- **Unconditioned Y is Gaussian mixture distribution**
- **Probability density function,**

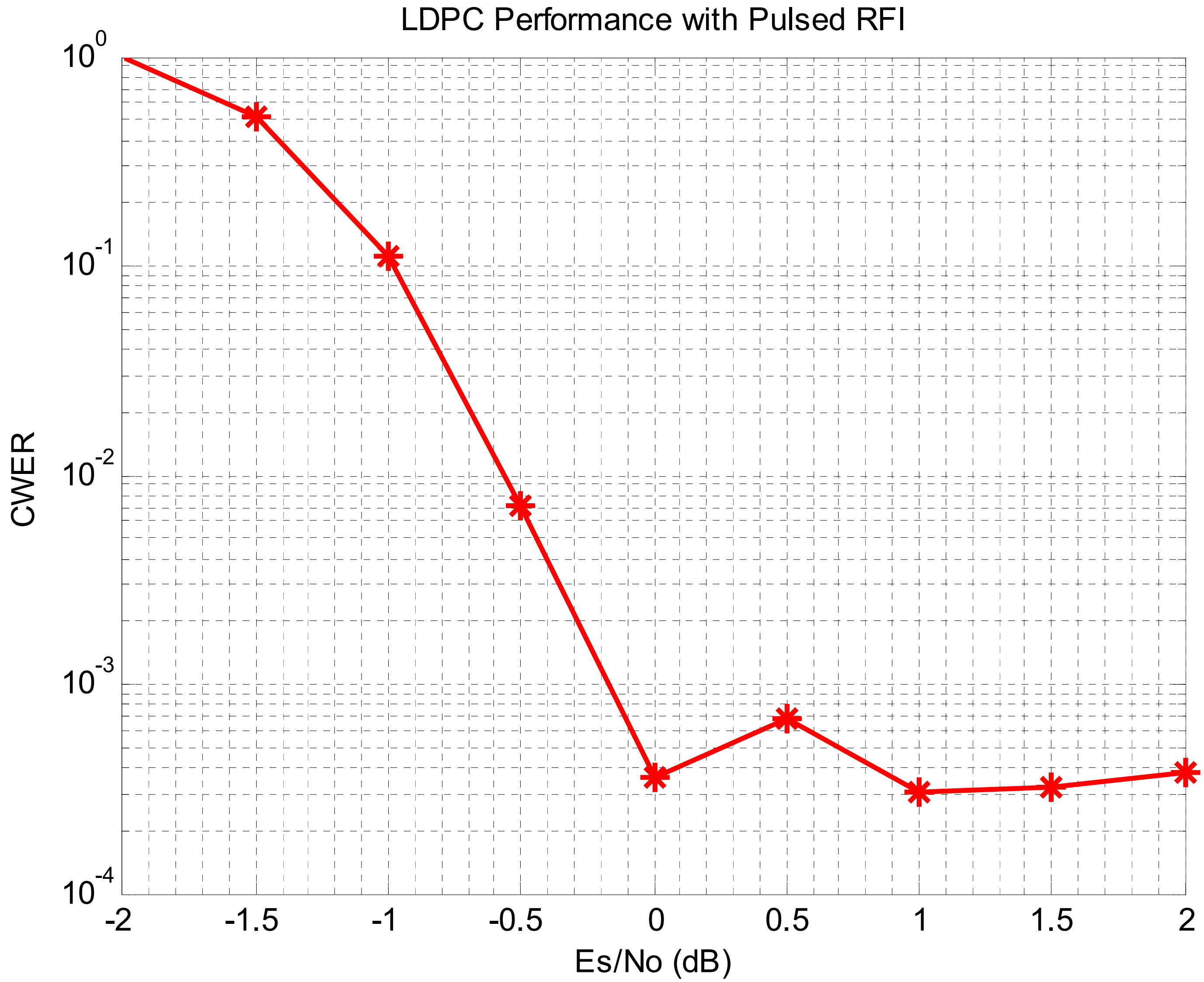
$$f(y;\vec{\mu},\vec{\sigma}) = (1-p)\frac{1}{\sqrt{2\pi\sigma_1^2}}e^{-\frac{(x-\mu_1)^2}{2\sigma_1^2}} + p\frac{1}{\sqrt{2\pi\sigma_2^2}}e^{-\frac{(x-\mu_2)^2}{2\sigma_2^2}}$$

For random binary equal probablity and equal engergy signal in AWGN channel, it becomes

$$f(y;\vec{\mu},\vec{\sigma}) = \frac{1}{2\sqrt{2\pi\sigma^2}}\left(e^{-\frac{(x-\mu)^2}{2\sigma^2}} + e^{-\frac{(x+\mu)^2}{2\sigma^2}}\right).$$

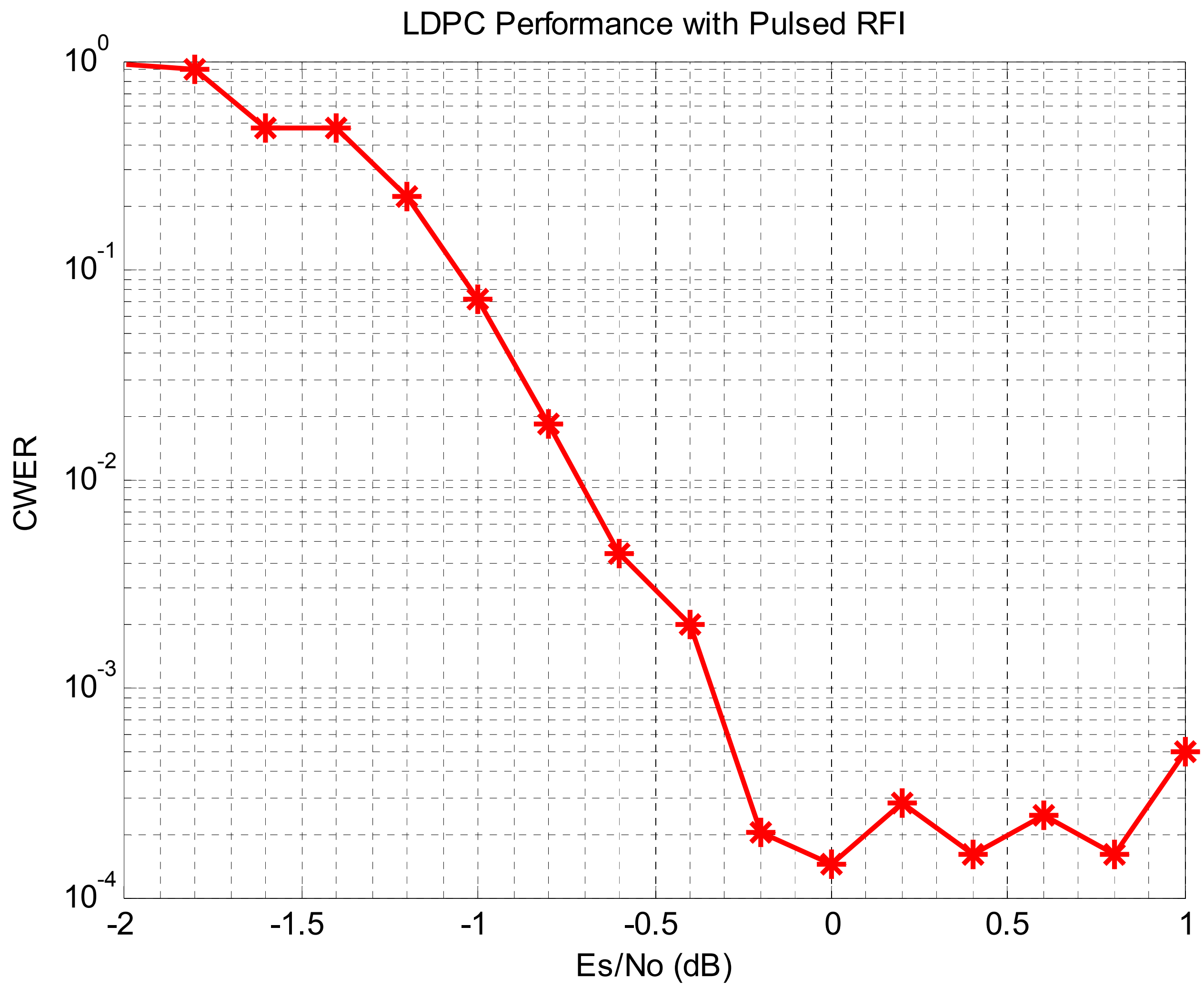


Reshuffle to “Mean” (2 Msps)

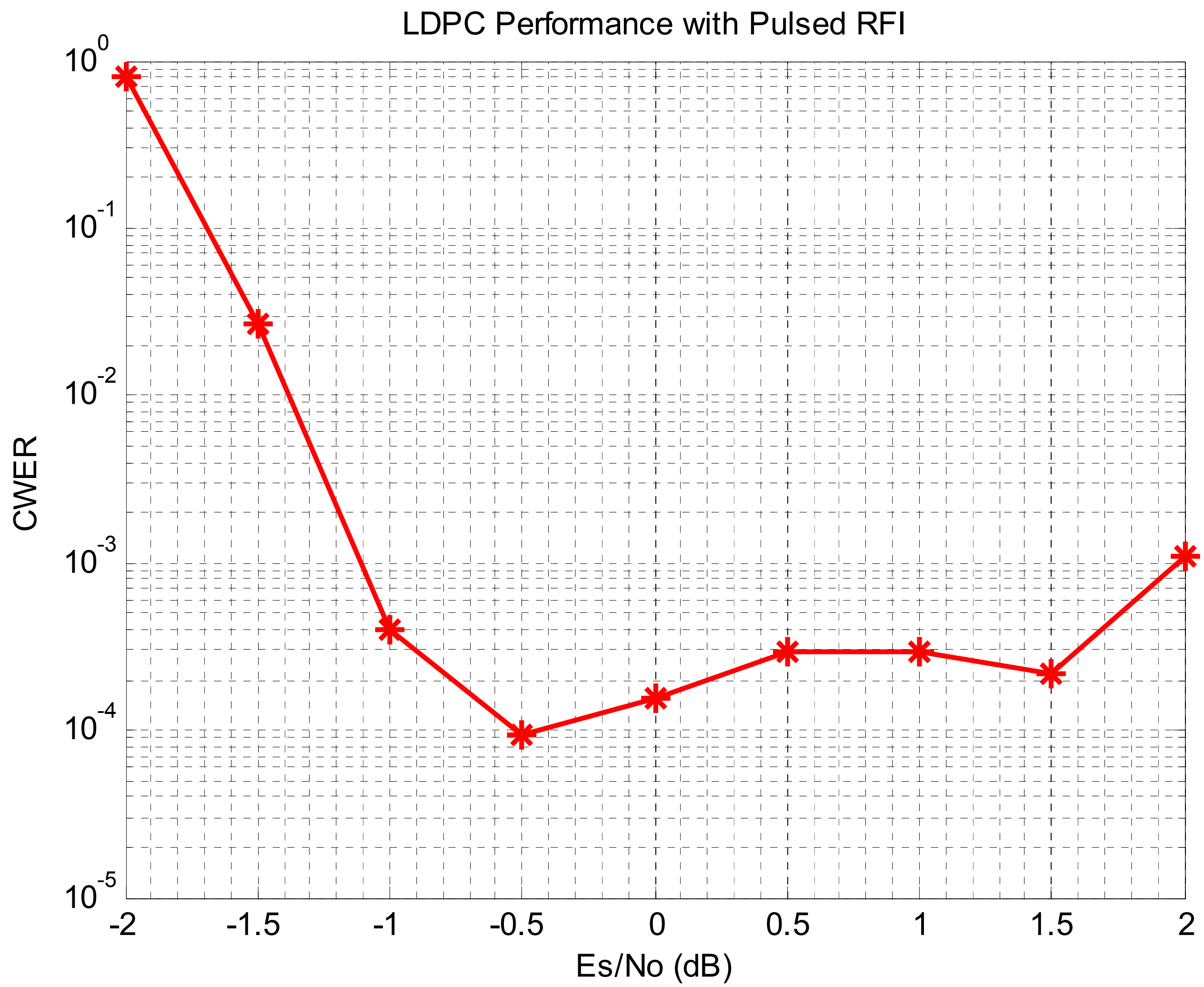


Avionic Systems Analysis

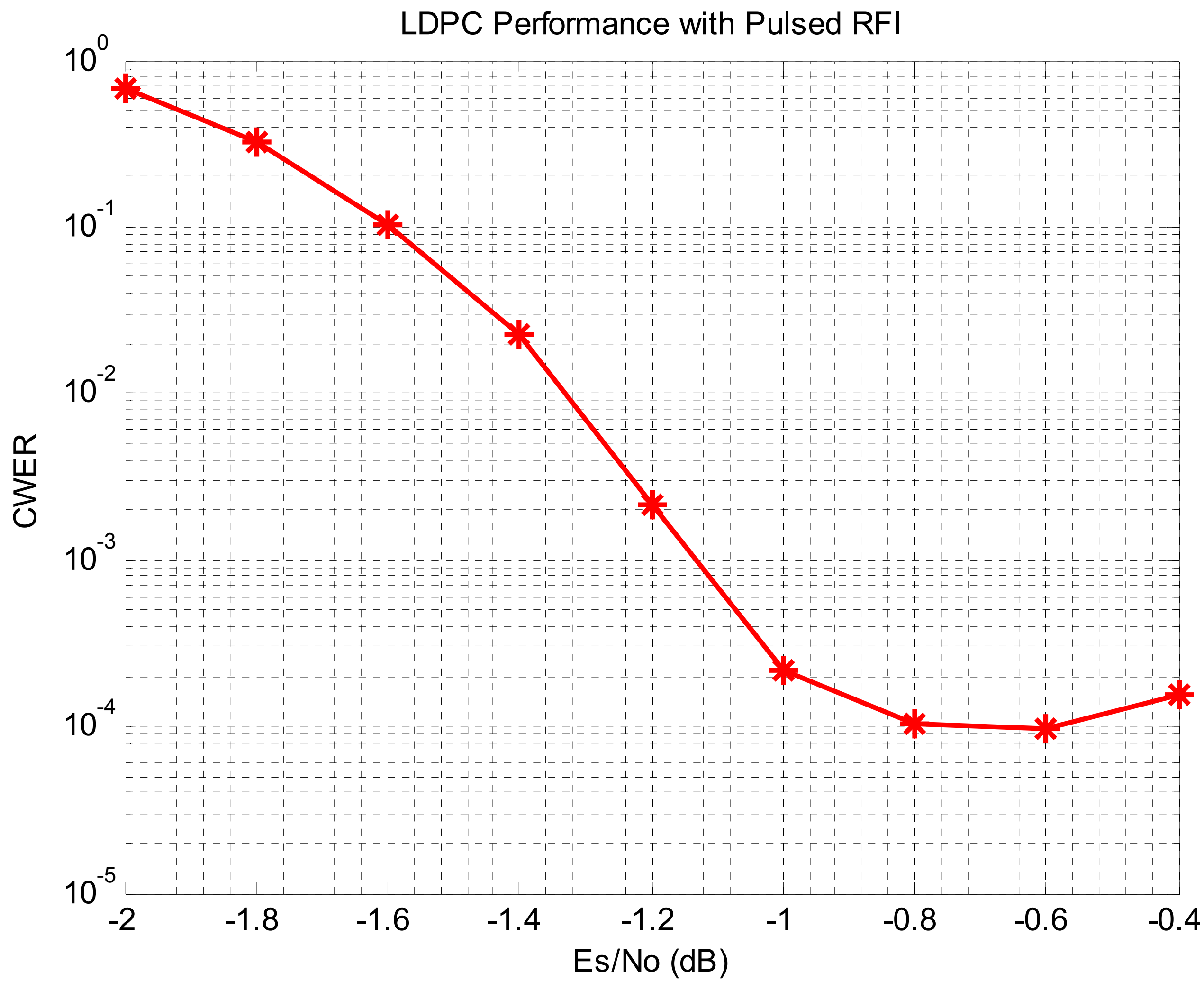
Reshuffle to “Mean” (200 Ksps)



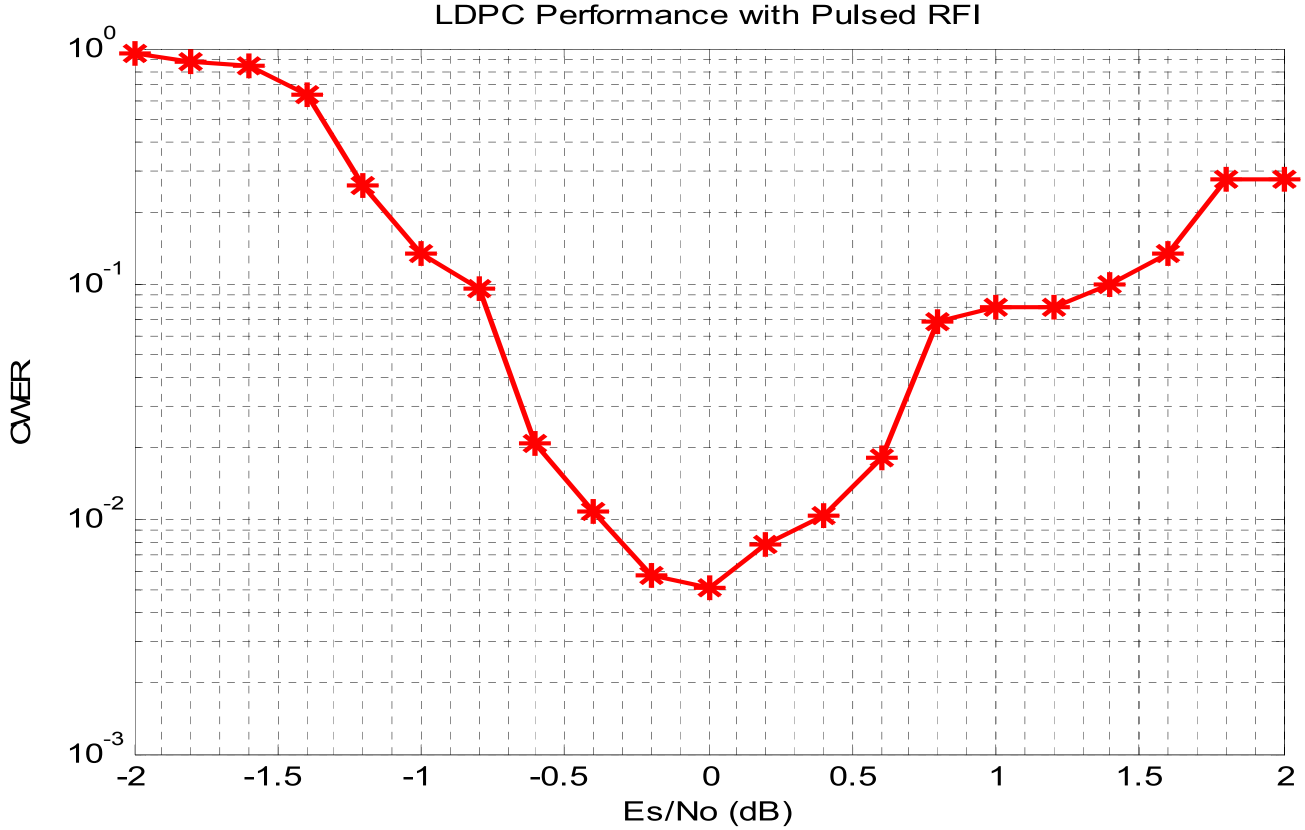
Reshuffle to "Zero" (2 Msps)



Reshuffle to "Zero" (200 Ksps)



Reshuffle “Gaussianly” (2 Msps)



- **Simulation data show that the performance curve of Reshuffle “Gaussianly” tails up from 0 dB as Es/No increases. The mechanism causing this performance behavior remains unknown, further investigation is necessary.**