ON FREQUENCY LOCK DETECTION FOR LOW SIGNAL-TO-NOISE RATIO QAM SIGNALS

Doan Nguyen Vo
Ultra Electronics – Tactical Communication System
Montreal, Quebec, Canada

The premier event for bringing next generation radio technologies to life.

30 November - 3 December 2010 • Washington, DC

Agenda

- **MOTIVATIONS**
- **NEW FREQUENCY LOCK DETECTION**
  - **The Proposed Techniques**
  - **Approximations of the Detector Metric at lock**
  - **Bounds of the Detector Metric at unlock**
- **SIMULATION**
- **HARDWARE IMPLEMENTATION**

Motivations

- The new HCR design applies different techniques for carrier recovery and coding.
- LDPC code can only provide a valid BER measurement after a few codeword => slow feedback response from the backend (in the order of milliseconds or seconds).
- LDPC allows the radio to operate at much lower SNR, which makes some detection mechanisms become unreliable.
- A fast, reliable mechanism for controlling the carrier recovery process should be proposed.

	HCR @ LDPC, coded 1E-3 (1E-5)					HCLOS @ coded 1E-5
	QAM4	QAM16	QAM32	QAM64	QAM128	32TCM
Es/No (dB)	1.6	12	14.4	18.2	21.1	18.1
Raw Eb/No (dB)	-1.4	5.98	7.41	10.42	12.65	11.2
Raw BER	1.16E-1	2.85E-2	3.3E-2	2.2E-2	2E-2	4.5E-3

A NEW FREQUENCY LOCK DETECTION
Introduction

- A traditional CFAR (Constant False Alarm Rate) technique is used in the burst preamble detection for TDMA applications.
- The technique exploits the correlation properties between the received symbols and the corresponding expected ones (training sequence).
- For BPSK, and the training sequence is carefully selected in order to maximize the gap in probability of lock and unlock.

$$F = \frac{\left(\sum_{k=1}^{N} a_I(k) z_I(k)\right)^2 + \left(\sum_{k=1}^{N} a_Q(k) z_Q(k)\right)^2}{\sum_{k=1}^{N} \left\| z(k) \right\|^2} > \alpha$$

A NEW FREQUENCY LOCK DETECTION Introduction

- **PROs**
  - **The metric will be reduced as noise increases compared with the signal.**

$$F_{lock,\min} = F_{lock,\min\,SNR} > F_{unlock,\max\,SNR} = F_{unlock,\max}$$

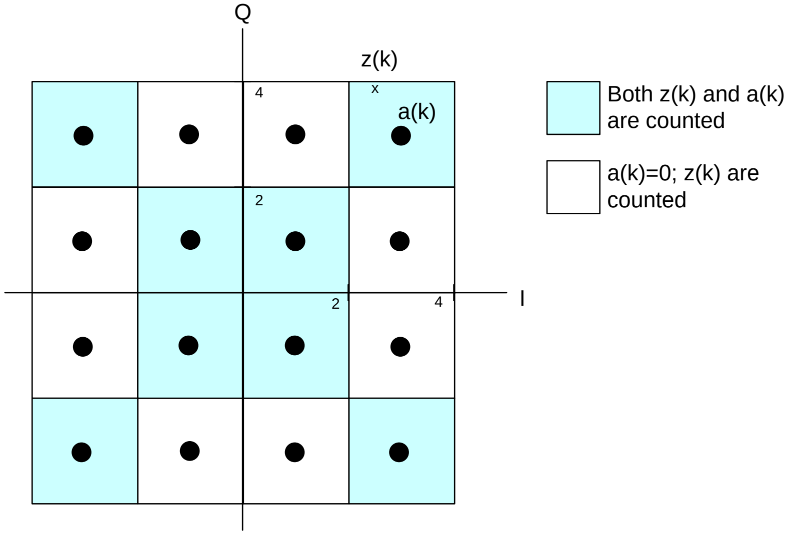
  - **The metric *F* is only a representative notation to ease the mathematical analysis.**
- **CONs**
  - **The sequence a(k) is no longer known, but random.**
  - **The correlation values become even weaker for higher QAMs.**

⇒ **These problems result a small difference between lock and unlock metric. This makes the detection being not reliable. Therefore this technique has been proposed so far only with BPSK training sequence.**

- **We could modify the technique so that it could be used for high QAM applications.**

A NEW FREQUENCY LOCK DETECTION
Proposed techniques (QAM-4,16, 64)

- **For the square QAMs such as QAM-4, 16, and 64, only diagonal points (i.e., $|a_I|=|a_Q|$) are considered. Points not on the diagonals will be forced to have a(k) = 0.**



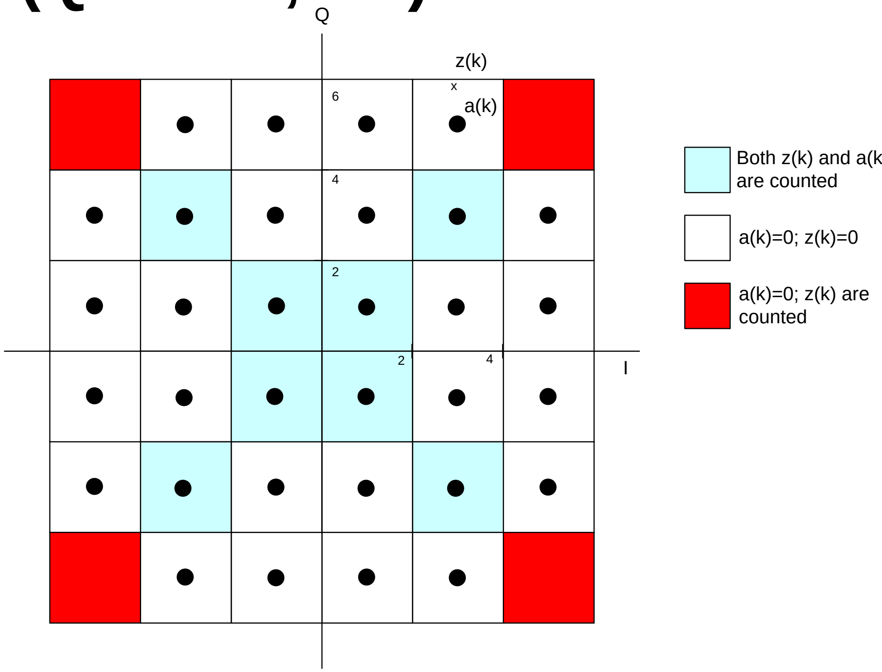
$$F_{squareQAM}=\sqrt{QAM}\,\frac{\left(\sum_{k=1}^{N}a_I(k)z_I(k)\right)^2+\left(\sum_{k=1}^{N}a_Q(k)z_Q(k)\right)^2}{\sum_{k=1}^{N}\|a(k)\|^2\sum_{k=1}^{N}\|z(k)\|^2}$$

A NEW FREQUENCY LOCK DETECTION Proposed techniques (QAM-4,16, 64)

- **The important point of this trick is that it considers the constellation points not on the diagonal axes as noise adding up to the energy portion of the metric. It does not impact much when it is locked, but it helps when it is unlock. When it is unlock, the diagonal points will be rotated and it has less percentage of staying in the right location; other rotating points can get into the diagonal axes, but has less probability compared with the probability of the good diagonal points rotating out their location. It will provide (1) the average power of the measured diagonal points is reduced, and (2) the energy of noise-like power is increased. These impacts will make the metric significantly smaller compared with the metric when locked.**

A NEW FREQUENCY LOCK DETECTION
Proposed techniques (QAM-32,128)

- **The above trick can work only with squared QAMs.**
- **For cross QAMs, only diagonal points (i.e., $|a_I|=|a_Q|$) will be considered, the points at the 4 corners will have a(k) = 0. The other points not on these axes will be ignored in all computations.**



$$F_{crossQAM} = 2\frac{\left(\sum_{k=1}^{N} a_I(k) z_I(k)\right)^2 + \left(\sum_{k=1}^{N} a_Q(k) z_Q(k)\right)^2}{\sum_{k=1}^{N}\|a(k)\|^2 \sum_{k=1}^{N}\|z(k)\|^2}$$

A NEW FREQUENCY LOCK DETECTION Proposed techniques (QAM-32,128)

- In this trick, the points at the corners help to reduce the metric when the system is unlocked. These points are considered as noise-like power as in the previous trick. The power at these corners is significantly large and it can be seen as a weighting factor. We currently use the actual measured energy, but it can be replaced by a predefined average energy.

A NEW FREQUENCY LOCK DETECTION
Analytical metric when locked (QAM-4,16, 64)

$$F_{lock} = \sqrt{QAM}\,\frac{\left(\sum_{k=1}^{N} a_I(k)\left(a_I(k)+n_I(k)\right)\right)^2 + \left(\sum_{k=1}^{N} a_Q(k)\left(a_Q(k)+n_Q(k)\right)\right)^2}{\sum_{k=1}^{N}\left\|a(k)\right\|^2 \sum_{k=1}^{N}\left\|z(k)\right\|^2}$$

$$\cong \sqrt{QAM}\,\frac{\left(\sum_{k=1}^{2N/\sqrt{QAM}} a_{I,diag}^2(k)\right)^2 + \left(\sum_{k=1}^{2N/\sqrt{QAM}} a_{Q,diag}^2(k)\right)^2}{\sum_{k=1}^{2N/\sqrt{QAM}} \left\|a_{diag}(k)\right\|^2 \sum_{k=1}^{N}\left\|a(k)+n(k)\right\|^2}$$

$$= \sqrt{QAM}\,\frac{2\left(\frac{2N}{\sqrt{QAM}}\right)^2 \frac{E_s^2}{4}}{\frac{2N}{\sqrt{QAM}} E_s \cdot N\left(E_s+\sigma_n^2\right)} = \frac{1}{1+\frac{\sigma_n^2}{E_s}}$$

$$F_{lock} = \frac{1}{1+1/SNR} \xrightarrow{SNR>>1} 1$$

A NEW FREQUENCY LOCK DETECTION
Analytical metric when locked (32, 128)

$$F_{lock} = 2\frac{\left(\sum_{k=1}^{N} a_I(k)\left(a_I(k)+n_I(k)\right)\right)^2 + \left(\sum_{k=1}^{N} a_Q(k)\left(a_Q(k)+n_Q(k)\right)\right)^2}{\sum_{k=1}^{N}\|a(k)\|^2\sum_{k=1}^{N}\|z(k)\|^2}$$

$$\cong 2\frac{\left(\sum_{k=1}^{L} a_{I,diag}^2(k)\right)^2 + \left(\sum_{k=1}^{L} a_{Q,diag}^2(k)\right)^2}{\sum_{k=1}^{L}\|a_{diag}(k)\|^2\sum_{k=1}^{N}\|a(k)+n(k)\|^2}$$

$$= 2\frac{2\left(L\frac{E_{diag}}{2}\right)^2}{LE_{diag}\cdot\left(L\left(E_{diag}+\sigma_n^2\right)+(N-L)\left(E_{corner}+\sigma_n^2\right)P(x\_at\_corner)\right)}$$

$$F_{lock} \cong \frac{\left(LE_{diag}\right)^2}{LE_{diag}\cdot\left(L\left(E_{diag}+\sigma_n^2\right)+\frac{L}{2}\left(E_{corner}+\sigma_n^2\right)2P(x>1)\right)}$$

$$= \frac{1}{1+\frac{\sigma_n^2}{E_{diag}}+\left(4+\frac{\sigma_n^2}{E_{diag}}\right)P(x>1)}$$

$$= \frac{1}{1+\frac{2}{SNR}+\left(4+\frac{2}{SNR}\right)Q\left(\sqrt{\frac{3SNR}{QAM-1}}\right)}$$

$$F_{lock} \cong \frac{1}{1+1/SNR}\left(\frac{1}{1+4Q\left(\sqrt{\frac{3SNR}{QAM-1}}\right)}\right) \xrightarrow{SNR>>1} 1$$

A NEW FREQUENCY LOCK DETECTION
Bound of metric when unlocked

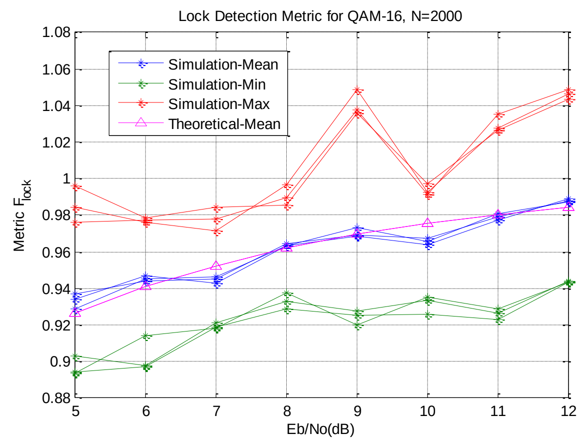
$$F_{unlock,squareQAM} = \sqrt{QAM}\,\frac{\left(\sum_{k=1}^{N} a_I(k) z_I(k)\right)^2 + \left(\sum_{k=1}^{N} a_Q(k) z_Q(k)\right)^2}{\sum_{k=1}^{N} \|a(k)\|^2 \sum_{k=1}^{N} \|z(k)\|^2}$$

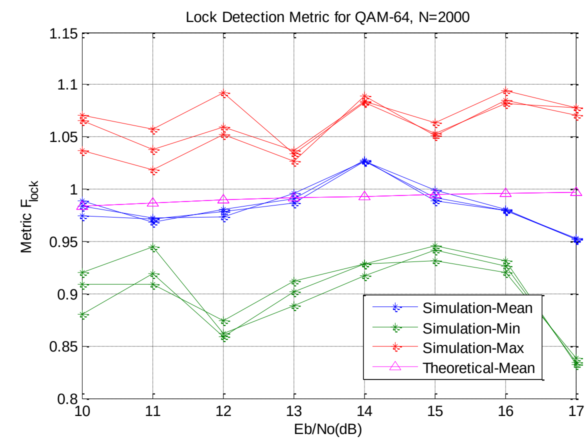
$$= \sqrt{QAM}\,\frac{\left(\sum_{k=1}^{L} a_I(k) z_I(k)\right)^2 + \left(\sum_{k=1}^{L} a_Q(k) z_Q(k)\right)^2}{\sum_{k=1}^{L} \|a(k)\|^2 \sum_{k=1}^{N} \|z(k)\|^2} < \sqrt{QAM}\,\frac{\left(\sum_{k=1}^{N} a_I(k) z_I(k)\right)^2 + \left(\sum_{k=1}^{N} a_Q(k) z_Q(k)\right)^2}{\sum_{k=1}^{N} \|a(k)\|^2 \sum_{k=1}^{L} \|a(k)\|^2 \frac{\sqrt{QAM}}{2}}$$

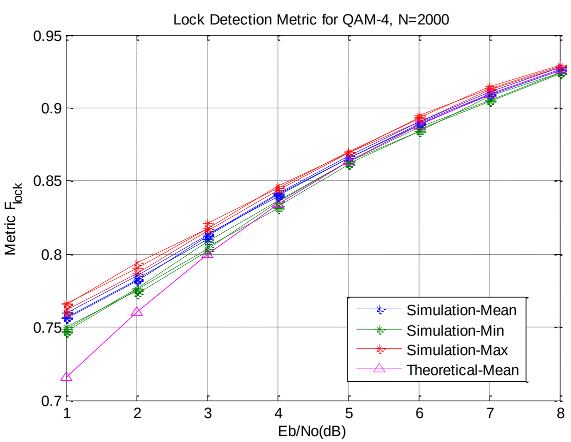
$$= 2\,\frac{\left(\sum_{k=1}^{L} a_I(k) z_I(k)\right)^2 + \left(\sum_{k=1}^{L} a_Q(k) z_Q(k)\right)^2}{\left(\sum_{k=1}^{L} \|a(k)\|^2\right)^2} = F_{unlock,crossQAM}$$

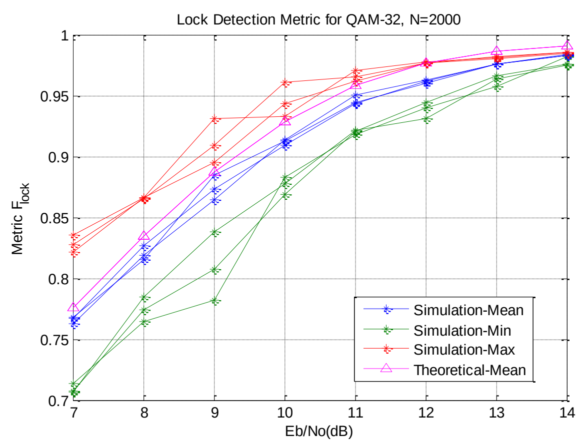
$$F_{unlock,QAM} < 2\,\frac{2\left(\frac{E_S}{2}\,\frac{2\sqrt{2}}{\pi}\right)^2}{E_S^2} = \frac{8}{\pi^2} \cong 0.81$$

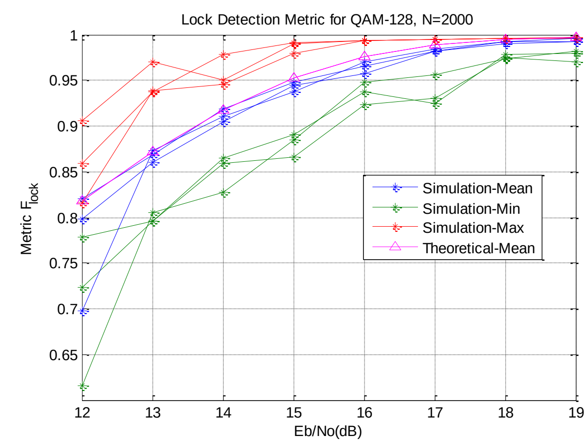
A NEW FREQUENCY LOCK DETECTION
Simulated metric when locked





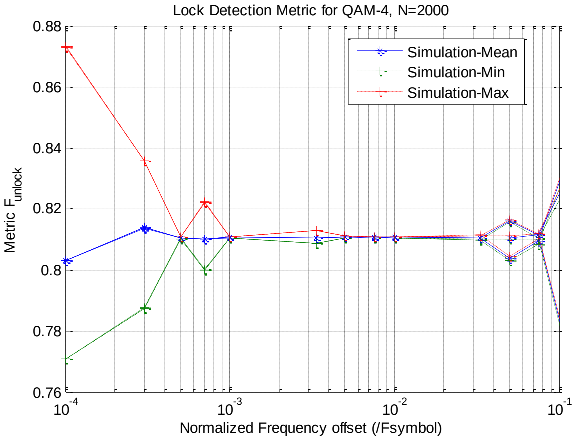


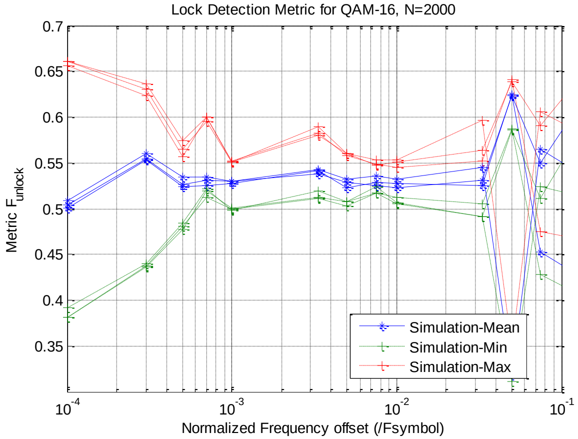


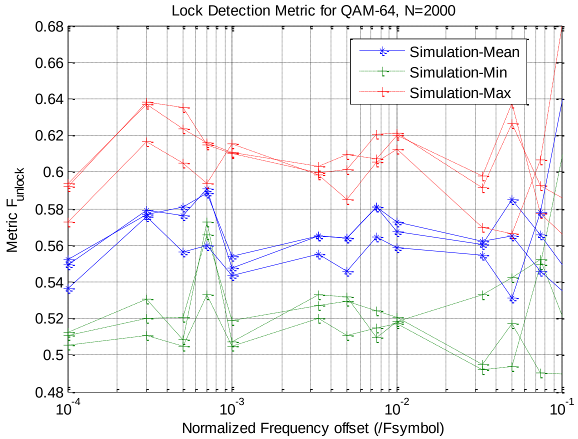


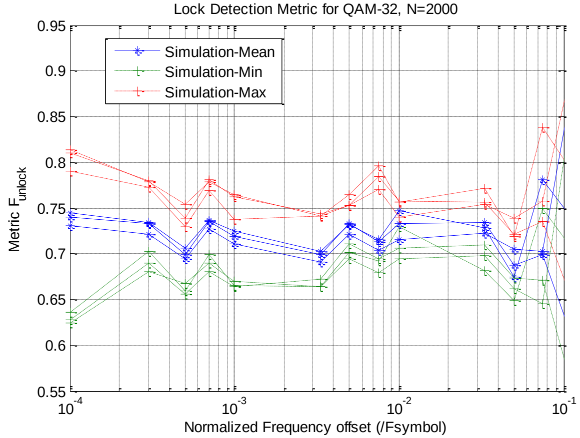
SDR`10
Wireless Innovation Conference
and Product Exposition

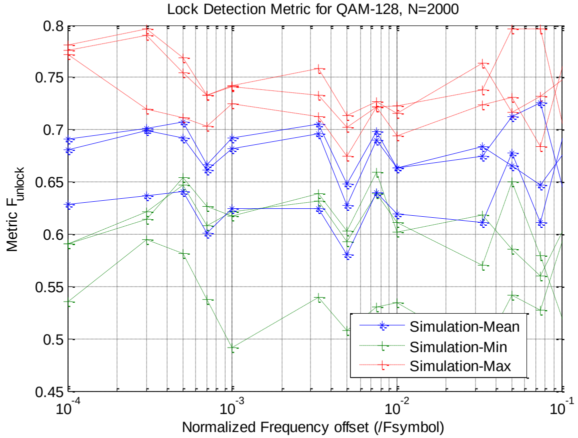
A NEW FREQUENCY LOCK DETECTION
Simulated metric when unlocked





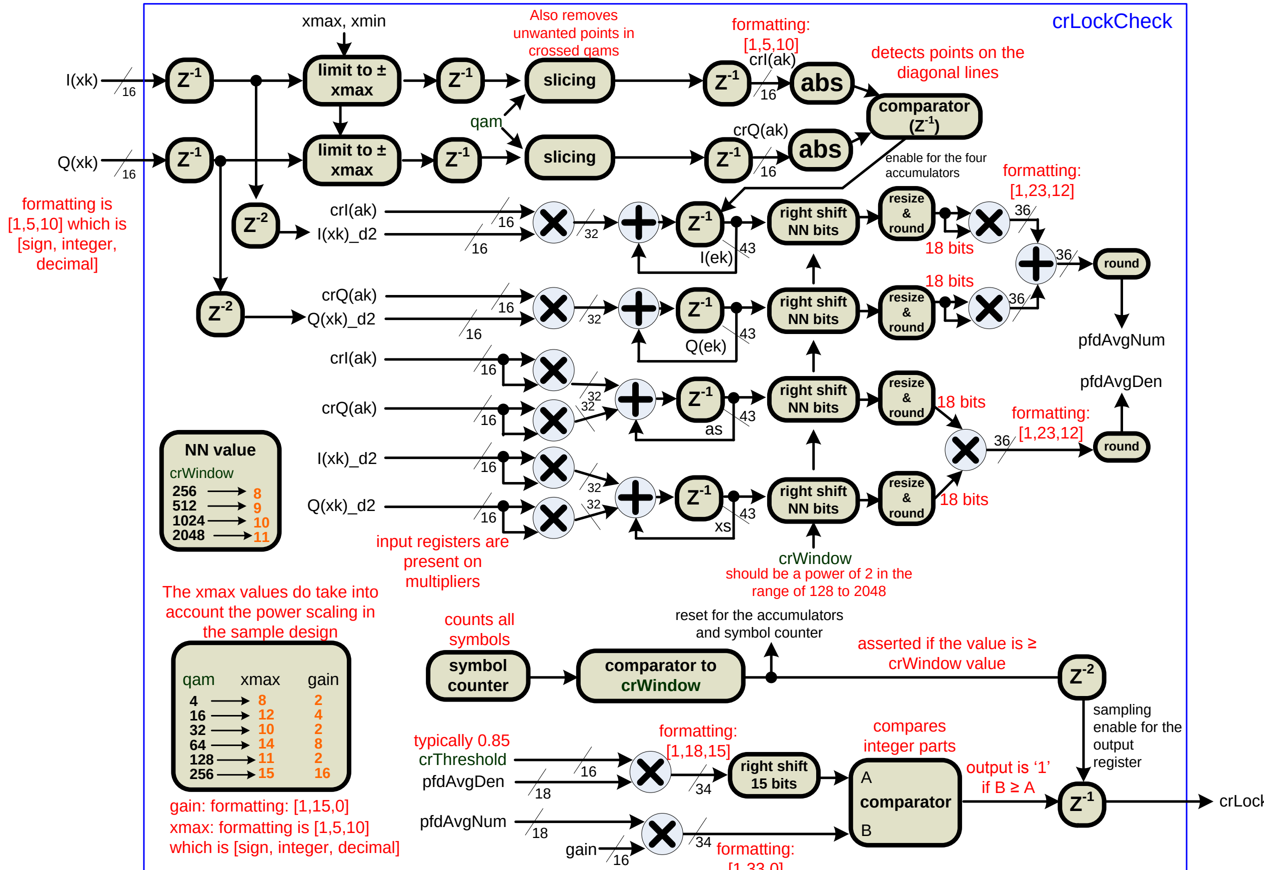






SDR`10
Wireless Innovation Conference
and Product Exposition

A NEW FREQUENCY LOCK DETECTION
Implementation



Rules for the accumulators:

For square qam → xs cumulates the energy of every symbols, as, I(ek) and Q(ek) cumulate values for the diagonals only.

For cross qam → xs cumulates the energy for all diagonals, including the points that would be on the diagonal extensions. I(ek), Q(ek) and cumulate values for the diagonals only.

Thank you