Decision Feedback Equalizer (DFE) combined with Carrier Recovery

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1. Introduction

The need to increase the channel data rate in data communication systems without increasing the signal bandwidth drives the development toward more spectrally efficient modulation systems (or formats). QAM modulation is widely used in digital wireless communication systems for achieving high data transmission rates over relatively narrow signal bandwidth. Digital radio systems designed using such modulation schemes must balance the effects of phase noise from local oscillators with the demodulator parameters in determining overall performance. In an M-QAM system each symbol transmitted contains k bits, where M = 2^k. In contrast, BPSK (binary phase shift keying) system transmits 1 bit per symbol and QPSK (quadrature phase shift keying) system transmits 2 bits per symbol while requiring the same RF (radio frequency) bandwidth for a given symbol rate.

The M states in a high order M-QAM constellations are more closely spaced than those in BPSK or QPSK constellations, and therefore require lower noise relative to the average carrier power to eliminate errors. The RMS (root mean square) phase noise of the local oscillators, after being filtered by demodulator, must be sufficiently low to not cause bit errors. For a QPSK or M-PSK schemes (or formats), a multitude of carrier recovery algorithms exist that provide a high phase noise tolerance. However, those algorithms fail when applied to most of the higher order QAM constellations because these lack equidistant phases. Additionally, it has been shown that most of decision-directed carrier recovery is also not a viable option for higher order QAM constellations due to the inevitable relatively long feedback delay (or latency) in practical systems.

Phase noise is one of the most critically destructive noises affecting the performance of wireless high speed communication systems. In the general application area, a higher speed communication system requires the use of a higher order QAM (quadrature amplitude modulation) system. There is need to use more accurate and more recently measured (i.e., low latency) phase noise estimates for a higher order QAM to mitigate the phase noise effect on the signal. The GScom's solution, DFE combined with Carrier Recovery, provides an effective phase noise mitigation approach with good accuracy and very low latency. "DFE combined with Carrier Recovery" will be referred as "DFE-CR" in this document.

The DFE-CR provides a phase noise tolerant method with very low latency by combining the decision feedback equalizer (DFE) and the carrier recovery loop effectively.

2. Equalization

Equalization is used to mitigate the channel effect on the received signal for clear communication. The equalizer estimates the communication channel distortion (such as amplitude distortion, phase distortion, fading, and channel interference, etc.) and mitigates the channel effect.

In micro-wave or millimeter wave communications which uses high carrier radio carrier frequency, the equalizer combined with carrier recovery is one of the most powerful solutions to combat the phase noise through the latency reduction between the phase noise estimation and correction.

GScom uses a fractional spaced decision feedback equalizer (DFE) to mitigate the channel effect and inter-symbol interference. The DFE consists of two sections in the equalizer: one is Feed Forward Filter (FFF) and the other is Feedback Filter (FBF). The FFF consists of 24-tap T/2 spaced finite impulse response (FIR) filter. The FBF is consists of 1-tap or 2-tap T spaced FIR filter. In general, the number of taps used is determined by the modulation order (or symbol rate) used.

Figure.1 is the function block diagram of the DFE which gets the phase noise estimate from carrier recovery loop. The input signal of the DFE, u(n) , is the transmitted signal through the noisy communication channel from the transmitter and is the signal received at the receiver. This is a noisy signal. The output signal, q(n), of the DFE is the summation of the output signal of the FFF and the output signal of the FBF in the adder. The output signal, $\hat{\mathrm{d}}(\mathrm{n})$, of the DD is used in the decoder.

The phase noise correction (or compensation) is obtained by multiplying the respective input signal of the DFE, u(n), and the output signal, q(n), of the DFE with the negative value of the phase noise estimate, which is obtained from the carrier recovery DPLL (digital phase locked loop) in the multipliers, respectively. The phase noise compensated signal, Q(n), is the input of the DD. The DD uses the input signal, Q(n), to find its output from M QAM constellation by finding one of the M signal constellation points which is closest to the input signal, Q(n), and selects the closest signal point to Q(N) as the output signal, $\hat{d}(\mathbf{n})$, of the DD. The error signal, e(n), is obtained by subtracting the output signal, $\hat{d}(\mathbf{n})$, from the input signal, Q(n), of the DD. We also obtain the SNR estimate by applying signal and noise energy measurement algorithm at the output of DD in DFE.

For equalizer operation perspectives, GScom uses preamble symbols which are in Acquisition Frame as a training sequence for equalizer during Acquisition mode before data mode operation (Pease refer to Acquisition Frame Format in section 3.4.3.2 in the system description document).

For equalizer operation perspectives for data mode, GScom uses preamble symbols and pilot symbols which are in Data Frame for channel estimation and mitigation purpose (Pease refer to Data Frame Format in the system description document).

GScom uses a least mean square (LMS) algorithm for filter coefficient update in both of FFF and FBF. The step size (μ) used for the filter coefficient update in LMS algorithm is programmable.

The following Figure 1 is the equalizer function block diagram.

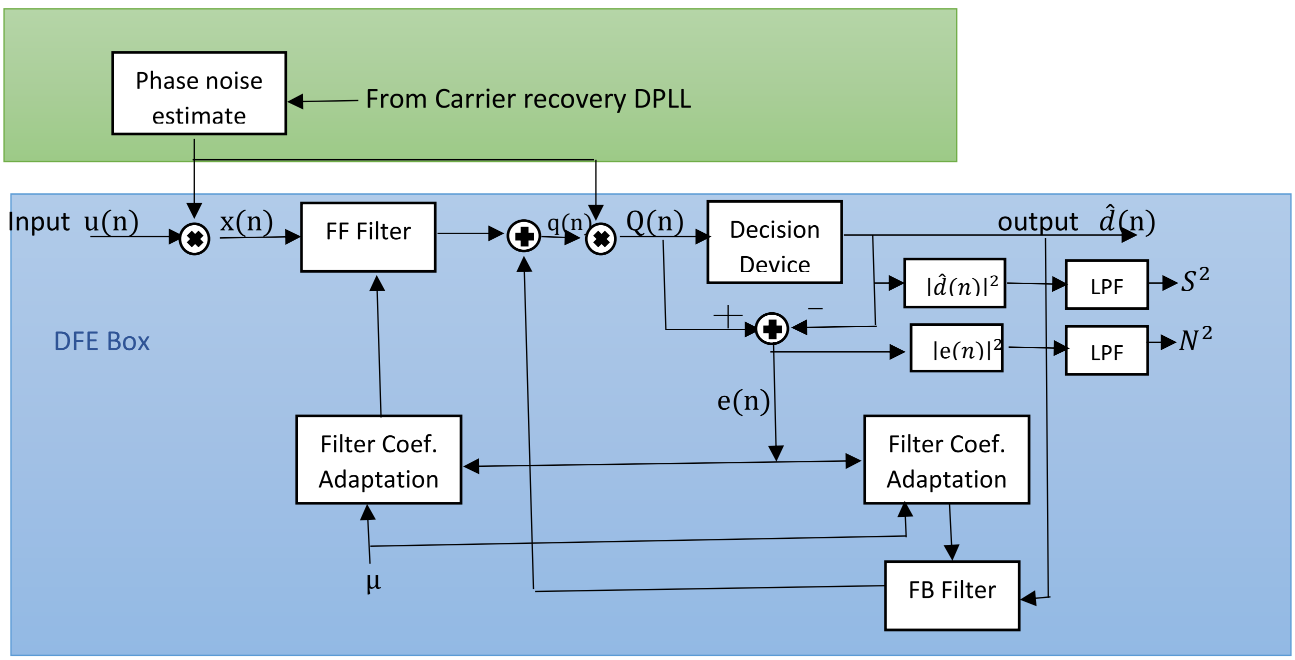

Figure 1. Function Block Diagram of Decision Feedback Equalizer

The Feed Forward Filter (FFF) is T/2 spaced complex asymmetric FIR filter (where T is a symbol interval). The FFF performs decimation by 2; two symbols are shifted in for each symbol produced at the output of FFF. The FFF supports 24 complex coefficients. The Feedback Filter (FBF) is an adaptive T spaced complex filter. The filter has one or two complex filter coefficients depends on modulation order used.

The input and output of DFE, phase noise compensated DFE output signal $\mathrm{Q(n)}$, data estimate, and its error can be calculated as follows (as can be seen in the above figure);

Output of DFE; $\mathrm{q(n)} = \sum_{k=1}^{K} f_k(n)x_k(n-k) + \sum_{l=1}^{L} b_l(n)\hat{d}_l(n-l)$

Phase noise compensated DFE output; $\mathrm{Q(n)} = \mathrm{q(n)}\ e^{-j\hat{\theta}_n}$

Data estimate; $\hat{d}(n) = \text{ Demap (Q(n))}$

Error estimate; $\mathrm{e(n)} = Q(n) - \hat{d}(n)$,

where K and L are filter order of FFF and FBF, respectively, and $\hat{\theta}_n$ is the phase noise estimate obtained from carrier recovery loop.

The signal to noise ratio (SNR) estimate is obtained by applying time average of data estimate, $\hat{d}(n)$, and error estimate, $\mathrm{e(n)}$, using 1-pole IIR (infinite impulse response) filter as follows;

Signal energy; $S^2(n) = \alpha S^2(n-1) + (1-\alpha)\hat{d}(n)\hat{d}^*(n) = \alpha S^2(n-1) + (1-\alpha)|\hat{d}(n)|^2$

Noise energy; $N^2(n) = \alpha N^2(n-1) + (1-\alpha)e(n)e^*(n) = \alpha N^2(n-1) + (1-\alpha)|e(n)|^2$

SNR estimate; $\mathrm{SNR} = 10 * \log10 (S^2(n)/N^2(n))$,

where α is average parameter and is pole of 1-pole IIR filter. Its value is $0 < \alpha < 1$ and is close to 1.

The decision directed LMS, where the filter coefficients are adapted to minimize the Mean Squared Error (MSE) at the Decision Device (DD) input, is used in this application. The filter coefficient adaption (or update) are performed as follows;

$$f_k(n+1) = f_k(\mathrm{n}) + \mu * \mathrm{e(n)} * x_k(\mathrm{n}), \qquad \mathrm{k} = 1,2,\ldots,\mathrm{K}$$

$$b_l(n+1) = b_l(\mathrm{n}) + \mu * \mathrm{e(n)} * \hat{d}_l(\mathrm{n}), \qquad l = 1,2,\ldots,\mathrm{L}$$

for FF filter and FB filter, respectively.

Where f_k(n) and $f_k(n+1)$ are present k^{th} FF filter coefficient and next k^{th} FF filter coefficient, respectively, and

b_l(n) and $b_l(\mathrm{n}+1)$ are present l^{th} FB filter coefficient and next l^{th} FB filter coefficient, respectively, and

x_k(n) and $\hat{d}_l$(n) are the input of k^{th} filter coefficient of the FFF and the input (or the output of FFF) of l^{th} filter coefficient of the FBF, respectively.

3. Carrier Recovery

The carrier synchronization loop tracks the phase error at the input of decision device (DD) in the decision feedback equalizer (DFE). The carrier synchronization loop is a 2nd order type II digital phase locked loop (DPLL) operating at the symbol rate. The phase error estimate is obtained from the phase difference between the input and output of the decision device and is decision directed. The following Figure 2 is the function block diagram of the carrier recovery loop (CRL) combined with the part of the DFE that is designed for joint detection, estimation, and compensation of the phase noise. The CRL tracks the phase error at the input of the DD in the DFE.

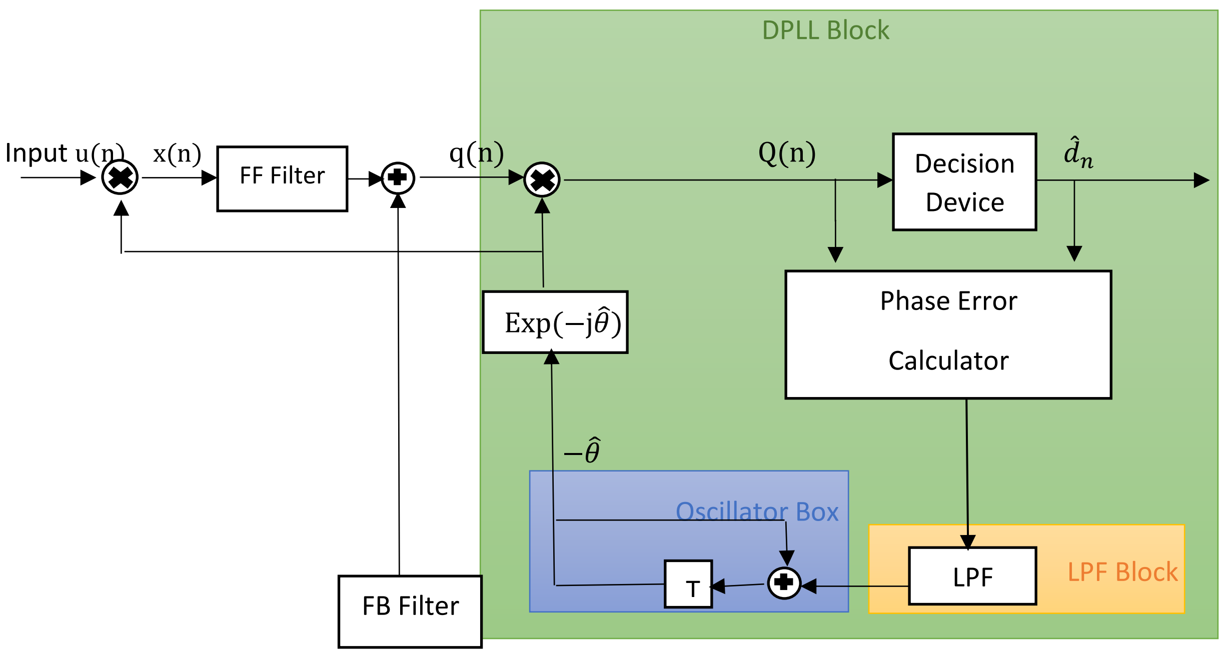

Figure 2. Carrier Synchronization Loop block diagram

The input signal of the DFE, u(n) , is the transmitted signal through the noisy communication channel from the transmitter and is the signal received at the receiver. This is a noisy signal. The q(n) in the above Figure is the output of DFE and is supposed to be transmitted data symbol, d, in no noise communication environment. However, it is a data estimate which may include the noise components in it. The phase noise correction (or compensation) is obtained by multiplying the respective input signal of the DFE, u(n), and the output signal of the DFE, q(n) , with the negative value of the phase noise estimate, which is obtained from carrier recovery DPLL (digital phase locked loop). The phase noise compensated signal, Q(n), is the input of the DD.

The Q(n) is the phase noise compensated version of q(n) and can be represented as

Q(n) = q(n) $e^{-j\hat{\theta}_{n-\Delta}} = \hat{d}_n e^{j\hat{\theta}_n}$, where $\hat{d}$ is data estimate and $e^{j\hat{\theta}_n}$ is phase noise.

As can be seen from the above Figure, the phase error estimate is obtained by taking the phase error sample and then low pass filtering of the phase error.

The LPF in the Digital Phase Locked Loop (DPLL) in the above Figure has two signal paths in it; one is proportional path and the other is integration path as shown in Figure in the section of Carrier Synchronization of section 3.4.7 in system document. As discussed before, the proportional path gain K_p and integration path gain K_i in the LPF determines the bandwidth of the carrier synchronization loop filter.

The carrier synchronization loop supports a range of loop bandwidths designed to maximize phase noise tracking capability and minimize the effect of additive white Gaussian noise (AWGN). There is need to optimize the loop bandwidth based on the expected signal to noise ratio (SNR) and on the expected amount of the phase noise.

4. Performance Evaluation

GScom carried out a performance test of the DFE-CR (DFE combined with Carrier Recovery) in the dynamic range of SNR using additive white Gaussian noise and phase noise. GScom used two phase noise masks in the performance evaluation: one is the one in the DVB-S2 specification and the other is obtained from the system development division of a tier-1 backhaul equipment vendors. The followings are the phase noise masks of those of two phase noise masks.

– **Phase Noise Mask for DVB-S2 (ETSI EN_302307)**

Frequency	100 Hz	1 KHz	10 KHz	100 KHz	1 MHz	> 10 MHz
Agg1 (typical) (dBc)	-25	-50	-73	-93	-103	-114
Agg2 (critical) (dBc)	-25	-50	-73	-85	-103	-114

– **Phase Noise Mask for Backhaul (tier-1 company)**

Frequency	100 Hz	2 KHz	10 KHz	100 KHz	100 MHz
Agg (critical) (dBc)	-37	-37	-58	-88	-148

As seen from the above two noise masks, the tier-1's phase noise mask was more aggressive than those used in the ETSI specification. GScom illustrated the performance result which GScom obtained from using the tier-1's phase noise mask in a various level of SNR in this section.

GScom carried out the performance test of the DFE-CR (DFE combined with Carrier Recovery) in the six levels of QAM modulation schemes (or formats); 4QAM, 16QAM, 64QAM, 256QAM, 1024QAM, and 4096QAM. GScom used several levels of the signal to noise ratio to test the performance in each of the QAM modulation scheme. The following table shows the performance improvement obtained through the usage of the GScom's DFE-CR when compared to the performance of the conventional system which uses DFE only at the reference of the SNR point where one can achieve 10^{-6} bit error rate (BER).

- **Performance Improvement due to the combination of DFE and Carrier Recovery**

4QAM	16QAM	64QAM	256QAM	1024QAM	4096QAM
0 dB	1 dB	7 dB	6 dB	8 dB	7 dB

4.1 Performance Evaluation Summary

- GScom used 1 DPLL to take care of phase noise (PN). In practical communication system, GScom will use analog PLL on top of the DPLL in the commercial system, which will provide a few more dB performance improvement.
- Excellent performance of phase noise mitigation from combining DFE and Carrier Recovery in terms of the signal quality recovery and latency.