DESIGN AND IMPLEMENTATION OF DIFM ALGORITHM IN FPGA

S. Sandhyarani¹, T. Kavitha ²

¹M.E, Department of Electronics & Communication Engineering
²Asst.Professor, Department of Electronics & Communication Engineering
³M.V.S.R.E.C, Nadergul, Hyderabad.

Abstract: - This paper outlines two different processing techniques to resolve ambiguities in broadband digital instantaneous frequency measurement (DIFM) receivers using an array of “n” phase correlate’s. The phase error margins in both cases are analyzed. The usefulness of each processing algorithm vis-à-vis the ratio of delay line lengths is shown. Closed loop equations for practical implementation of the processing algorithms are derived. Segmented processing of the data to increase the robustness of the algorithm in practical implementations is qualitatively explained.

I. INTRODUCTION

The DIFM receiver is the basic building block of any wide open electronic sup-port measure (ESM) system. It has the unique features of good sensitivity, good frequency measurement accuracy, high dynamic range and high speed. Exhaustive analyses of frequency accuracy, temperature effects, sensitivity and microwave component performance required for DIFM, including a general description of the DIFM receiver, are given in the literature. This article is aimed at providing insight into some of the processing algorithms used to resolve ambiguity, their related phase error margins and their respective advantages.

The principle used in a DIFM receiver centers around the conversion of the frequency information into an equivalent phase delay. Consider an RF signal that is passed through a transmission line (a coaxial cable for instance). The specific difference between the signal at the input of the transmission line and that at the output is the phase delay undergone by the signal.

is phase delay is given by

\[ \psi = \frac{2\pi L \epsilon}{c} \]  

(1)

Where

- \( \psi \) = total phase delay
- \( L \) = length of the transmission line
- \( f \) = carrier frequency
- \( c \) = velocity of electromagnetic waves (in free space)

\( \epsilon \) = dielectric constant of the medium used in the cable

Thus, if the value of \( \psi \) is known, it is possible to compute the frequency of the input RF signal as

\[ f = \frac{c \psi}{2\pi L \epsilon} \]  

(2)

If good frequency measurement accuracy is required in the presence of large phase errors, a long delay line must be used. Since the measurement of a phase delay is always within modulo \( 2\pi \), this will result in reduced unambiguous bandwidths. To provide a broadband, high accuracy, frequency measurement capability in spite of large errors in phase measurement, it is essential to have an array of phase measurements using different lengths of delay lines. This ensures that the ambiguity in the frequency estimate from the measured phase delay corresponding to the longest delay line can be re-solved.

In order to prevent wrong frequency estimates due to inaccuracies in phase measurement, a sufficient error margin must be provided in the algorithm. This article gives the details of the algorithms used to resolve the ambiguity in frequency estimates of a broadband DIFM receiver, with simultaneous good frequency accuracy capability and broad frequency coverage, along with phase error margin performance.

The generic building block of a broadband DIFM receiver is shown in Fig 1. It consists of an array of delay lines of different lengths followed by phase correlators. It is assumed that sufficient pre-amplification of signals has been carried out to achieve the specified system sensitivity and that suitable filtering is done to eliminate the undesired signals be-fore they enter the 2n-way power divider. The phase correlators are used to measure the progressive phase delays at their inputs at any given frequency.

In the analysis given below, it is assumed that the sine and cosine out-puts of the phase correlators have been suitably processed to give a phase angle between 0 and \( 2\pi \) in a digital format commensurate with the accuracy and resolution requirement. The delay line lengths are chosen such that each delay line is longer than the previous one, implying that their phase delays will be proportional.

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Fig 1: Generic block diagram of DIFM receiver

The shortest delay line is chosen so that the phase shift over the unambiguous bandwidth (f_{min} to f_{max}) is 2π. The longest delay line determines the achievable frequency accuracy. The shorter delay lines are used primarily to resolve the ambiguities in the longest delay line. In this article the term “delay line length” refers to the differential length between the two RF cables or transmission lines at the input of the correlators.

The length of the shortest delay line is given by

$$L_1 = \frac{C}{\sqrt{E(U_{max} - f_{min})}}$$  \hspace{1cm} (2)

The following analysis assumes that only one frequency signal is present at the input of the DIFM receiver. Two algorithms for resolving the ambiguity have been studied and are discussed in this paper. The first algorithm uses the measured phase delay in the longest delay line as the reference, and comparison is made with each of the shorter delay lines in order to progressively reduce the number of ambiguities in the longest delay line. Once the comparison between the measured phases delays between the longest and shortest de-lay lines is made, the ambiguity is to-tally resolved.

The second algorithm uses the measured phase delay in the shortest delay line as the reference. This un-ambiguous measured phase delay is used to completely resolve the ambiguity in the measured phase delay in the next longer delay line. Each un-ambiguous phase delay is in turn used to resolve the ambiguity in the measured phase delay of the next longer delay line. This process is continued until the ambiguity in the measured phase delay of the longest delay line is completely resolved.

II. PHASE RELATIONSHIPS IN THE GENERIC DIFM

Let n be the number of delay lines used. Let the measured phase angles (modulo 2π) by the n correlators be given by φ_1, φ_2, ..., φ_n and the corresponding total phase angles be ψ_1, ψ_2, ..., ψ_n.

The following analysis is carried out by assuming, without loss of generality, that it is necessary and sufficient to estimate modulo integers, only for frequencies within the band of interest. That is, at the starting frequency f_{min} the value of all the modulo 2π integers m_i to m_n is zero. In practice, the value of all the measured phase delays φ_i at f_{min} are not all necessarily zero and must be normalized to zero for the algorithms to be effective. It may be noted that the phase delay for a given length of delay line is dependent only on the frequency propagation and not on the absolute values of the starting and ending frequencies. Hence, normalizing the phase data to zero does not in any way affect the ambiguity resolution algorithm. After normalization, m_1 = 0.

a) Algorithm no. 1
(Using the measured phase for the longest delay line as reference)

For this algorithm to be effective the primary condition is that the ratio of any two successive delay line lengths should be 1 : k (where k is an exact integer). Since the ratios of length of delay lines is 1 : k the phase delays in the subsequent phase correlators outputs will be k, k^2, k^3 times ψ_1, and therefore their measured values will be ambiguous. That is n will give k^{n-1} ambiguous aliases in frequency estimation, only one of which is correct. All the k^{n-1} – 1 incorrect aliases in ψ_n (corresponding to the longest delay line) have to be eliminated to estimate the correct frequency.

$$\psi_{n-1} = \psi_n + 2\pi m_{n-1}$$  \hspace{1cm} (4)

$$\psi_n = \phi_n + 2\pi m_n$$  \hspace{1cm} (5)

Let

$$\psi_{n-1} : \psi_n = 1 : k$$  \hspace{1cm} (6)

Then

$$k(\phi_{n-1} + 2\pi m_{n-1}) = \phi_n + 2\pi m_n$$  \hspace{1cm} (7)

$$k\phi_{n-1} - \phi_n = m - k m$$  \hspace{1cm} (8)

Where R1 is the integer which can be computed from the measured values \phi_n and \phi_{n-1}. Due to errors in measurement of the phase angles, an exact integer value
of LHS of Equation 9 may not be obtained. In such a case it is rounded off to the nearest integer to get R1.

\[ m_n - k m_{n-1} = R_1 \]  
(10)

or

\[ m_n = k m_{n-1} + R_1 \]  
(11)

The term R1 is expressed as the sum of two components

\[ R_1 = P_1 + k Q_1 \]  
(12)

where

\[ P_1 \text{ integer such that } 0 \leq P_1 < k \]  
\[ Q_1 \text{ any integer} \]

Substituting for R1 in Equation 11

\[ m_n = k m_{n-1} + (P_1 + k Q_1) \]  
(13)

Since \( m_{n-1} \) and \( Q_1 \) are also integers let

\[ (m_{n-1} + Q_1) = M_1 \]

\[ 4 m_n = P_1 + k M_1 \]

Substituting for \( m_n \) in Equation 5

\[ \phi_n = \phi_n + 2\pi (P_1 + k M_1) \]  
(15)

or

\[ \phi_n = \xi_1 + 2k\pi (M_1) \]  
(16)

where

\[ \xi_1 = \phi_n + 2\pi P_1 \]  
(17)

The range of values of \( \xi_1 \) is from 0 to \( 2k\pi \).

Equation 16 indicates that \( \phi_n \) which was originally measured as a modulo \( 2\pi \) quantity is now available as modulo \( 2k\pi \). This also means that the number of ambiguous frequency estimates obtained from \( \phi_n \) is only \( kn-3 \). The range of values of \( i \) is from 0 to \( 2ki\pi \). In practical implementation of the algorithm, only the term \( i \) in Equation 28 assumes significance. The other term \( 2(k-i-1)\pi \) in the general equation is ignored while implementing the algorithm in hardware, without affecting the final result. Equation 28 indicates that \( \phi_n \), which was originally measured as a modulo \( 2\pi \) quantity, is now available as a modulo \( 2k\pi \) after \( i \) steps of the algorithm. The number of ambiguous frequency estimates obtained from \( \xi_1 \) is only \( kn-i-1 \). Repeated application of the above algorithm to \( (n-1) \) steps yields \( \xi_{n-1} \) will give an unambiguous frequency estimate. Note that for any value of \( M_{n-1} > 0 \), Equation 28 will result in \( \phi_n > 2\pi kn-1 \), which violates the original conditions.

b) Phase error margins for algorithm

The phase error margin is defined as the limiting value of the phase measurement error below which the algorithm will be effective. In general, if the phase error exceeds this limiting value this algorithm is likely to fail. The integer nearest to \( R_i \) can be correctly computed if the errors in \( \phi_{n-1} \) and \( \xi_{i-1} \) are such that

\[
\frac{k \delta\phi_{n-1} - \delta\xi_{i-1}}{2k(1-i)\pi} < 0.5
\]  
(29)

Assuming that the phase error statistics are independent of the individual delays, it can be seen that the phase error margin for the \( i^{th} \) step in the algorithm is given by it can be also seen that each step gives a progressively higher error margin compared to the previous step. The above analysis was carried out assuming that the ratios of delay line lengths are in the form \( 1 : k \). A similar analysis can be carried out for integer ratios of delay line lengths in the form \( k_1 : k_2 : k_3 \ldots kn-1 \) where \( k_i : k_{i+1} \) is a mutually prime integer ratio. Analysis for different integer ratios for different delay lines can also be carried out and appropriate ratios chosen for an improved
system design which emphasizes accuracy vs. error margin performance. In such a case, the error margin for any step is given by

\[ \delta \phi < \frac{H_1 H_2 H_3 ... H_{n-1}}{H_1 H_2 H_3 ... H_n} \]  

(30)

c) Algorithm no. 2

(Using the measured phase for the shortest delay line as reference)

In this case also, (n–1) steps are involved. In the previous algorithm (longest to shortest line) of ambiguity resolution, the primary condition was that the delay line ratios should be strictly integers. In the present algorithm (shortest to longest line) it is not necessary that the delay line ratios be strictly integers. It is only necessary that as in the first algorithm, the shortest delay line be unambiguous over the frequency range \( f_{\text{min}} \) to \( f_{\text{max}} \). Let

\[ j_i : j_{i+1} = 1 : k_i \]  

(31)

Here, \( f_n \) will have \( (k_1 . k_2 ... k_{n-1}) \) ambiguous aliases including the correct estimate. The major difference between the previous and the present algorithms is that, in the previous case, ambiguities in \( f_n \) were resolved partially at every step and finally the unambiguous estimate of frequency was obtained. In the present case, each step results in an unambiguous frequency estimate.

Step 1

\[ \phi_1 : \phi_2 = 1 : k_1 \]  

From Equation 3:

\[ k_1 \phi_1 = \phi_2 + 2\pi m_2 \]  

(33)

Note that \( \phi_1 \) is unambiguous after normalization.

In case of errors in phase measurement the RHS of Equation 34 will not give a perfect integer. In such a case, it is rounded off to give a unique solution for \( m_2 \). Substituting for \( m_2 \) in Equation 33, let

\[ \phi_2 + (k_1 \phi_1 - \phi_2)/2\pi = \zeta_1 \]  

(34)

\( \zeta_1 \) gives an unambiguous estimate of frequency and the range of \( \phi_1 \) is from 0 to \( 2k_1\pi \). The major difference between the previous and the present approaches is that in the previous case, ambiguities in \( \phi_1 \) were resolved partially at every step and finally the unambiguous estimate of frequency was obtained. But in the present case, each step results in an unambiguous frequency estimate. In the next step of the algorithm, the unambiguous \( \phi_1 \) is compared with the measured \( \phi_3 \) to resolve the ambiguity in \( \phi_3 \).

The algorithm is repeatedly applied step by step so that each step results in a reduced number of ambiguous frequency estimates.

\[ \phi_i = \phi_i + 2\pi m_i = \zeta_i \]  

(35)

Fig. 2 Generic block diagram of the DIFM processor

Where \( \zeta_i \) is obtained after \((i-1)\) steps of sequential implementation of the algorithm on \( \phi_1, \phi_2, \ldots \phi_i \).

\[ \phi_{i+1} = \phi_{i+1} + 2\pi m_{i+1} \]  

(36)

Since \( \phi_i : \phi_{i+1} = 1 : k_i \)

\[ k_i (\phi_i + 2\pi m_i) = \phi_{i+1} + 2\pi m_{i+1} \]  

(37)

\[ k_i \zeta_i = \phi_{i+1} + 2\pi m_{i+1} \]  

(54)

\[ m_{i+1} = (k_i \phi_i - \phi_{i+1})/2\pi \]  

(38)

Substituting for \( m_{i+1} \) the unambiguous estimate for frequency is obtained. The algorithm is repeated for \( i = 1 \) to \( n-1 \). The value of \( \zeta_n \) so obtained will give the correct and unambiguous frequency estimate.

Error margin for \( i_{th} \) step

It can be shown that the error margin for \( i_{th} \) step is given by unlike in the previous approach, there is no progressive increase in the phase margin at each step, but it is governed by the value \( k_i \).

Practical Implementation - A Comparative Study

Practical implementation of the algorithm can be done by using decoder logic for finding the integer values of \( m_n \). After implementation of each step the value of the modulo integer so obtained (\( P_i \) or \( m_i \) as the case may be) is fed to the subsequent decoder for the next step of the ambiguity resolution algorithm. A generic block diagram is given in Fig2. The final estimated frequency in both the above algorithms will range from 0 to \( (f_{\text{max}} - f_{\text{min}}) \), since the original were normalized to zero before implementation of the actual algorithms. Therefore, the actual frequency estimate must be derived by restoring \( f_{\text{min}} \) to the estimated frequency.

\[ f_{\text{actual}} = f_{\text{estimated}} + f_{\text{min}} \]  

(39)

The frequency estimator in the block diagram implements equation 56 to obtain the correct frequency estimate of the input signal. The delay lines ratio plays a key role in both above algorithms. While practically mounting the delay lines in the DIFM receiver, there could be a marginal change in their electrical lengths due
to the contouring of the delay lines. This change in the electrical lengths of the delay lines will in turn have an impact on their ratios. The variation in the SWR over the frequency range will also appear as a change in electrical length of the delay lines. In addition, the nonlinearity in the phase correlate’s, the signal to noise ratios, dynamic range effects in the RF front-end and the quantization errors (1 LSB) contribute to the overall phase errors. In the first algorithm, the condition that the delay lines bear integer ratios with each other may be seriously affected by the previously mentioned factors. Even a small deviation in the integer ratios may result in the breakdown of the algorithm. Therefore, considerable efforts must be made while fine tuning the cables and in-situ adjustments of the delay lines must be carried to realize the integer ratios. The second algorithm lends itself to a more practical implementation of the algorithm in the system design. This is because the ratios of the delay line lengths can be measured in-situ and fitted into the algorithm. In general, the performance of both algorithms will be better if the phase data is quantized to a larger number of bits, as long as the 1 LSB errors in the quantizer data is a dominant contributor to the total phase error. The robustness of the second algorithm can be further improved by segmented implementation of the algorithm. In this, the marginal variations in the ratio of delay line lengths over frequency range of interest (due to SWR, temperature effects and phase imbalance in the microwave components) can be fitted into the algorithm. The quantizer data set is unique for any given frequency within the bandwidth. This fact is exploited to estimate the exact ratios and the algorithm can be implemented using the appropriate ratios for each unique and discrete set of data. Hence, the chances of the algorithm breaking down due to wrong assignment of the delay line ratios are minimized drastically. A second major advantage of using the second algorithm is that it gives ambiguous frequency estimates (after the appropriate step in the algorithm has been implemented), each with progressively increasing accuracy. This fact can be used to incorporate graceful degradation in system performance.

III. RESULTS

DIFM design designed in VHDL code simulated and synthesized by Xilinx ISE tool. It is shown in below fig3

IV. CONCLUSION

The ambiguity resolution algorithms in broadband DIFM receivers have been presented in a practical implementation and hardware realizable form. Two algorithms to resolve modulo 2p ambiguities have been discussed. The error margins in each case were derived. The essential conditions for which the algorithms will work satisfactorily have been given in each case. The progressive improvement in error margin for the first algorithm has been shown and can be exploited for better system design. The inherent advantages of the second algorithm for a practical design have also been explained.
V. REFERENCES


