TWO SIGNAL HIGH DYNAMIC RANGE AND HIGH RESOLUTION WIDEBAND DIGITAL RECEIVER USING BEAT FREQUENCY

David. M. Lin and Lihyeh L. Liou,
Sensor Directorate, Air Force Research Laboratory
Wright-Patterson AFB, OH

BIOGRAPHY

David M. Lin received the B.S.E.E. from Tatung Institute of Technology, Taiwan, 1970, the M.S.E.E. and the M.E.M.E. from Tennessee Technological University, Cookeville, Tennessee, 1977, 1978 respectively and the M.S.C.S. from Wright State University, Dayton, Ohio, 1984. From 1979 to 1985, he was a software engineer at System Research Laboratories, Inc., Dayton Ohio. Since 1985 he has been an Electronics Engineer at the Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio. His work involves Electronic Warfare, radar and GPS receivers. He has received 10 patents

Lee L. Liou received a B. S. degree in physics, a M. S. degree in geophysics, and a Ph. D. degree in physics from University of Southern California, Los Angeles, in 1985. He was a technical staff working on CMOS process development for Hewlett-Packard, Ft. Collins, CO. from 1985 to 1986. Since then he was a research physicist working for Air Force Research Laboratory in Wright-Patterson Air Force Base, OH. His work includes modeling of semiconductor devices, electromagnetic simulations and GPS-related projects.

ABSTRACT

This paper describes how to build a wideband digital receiver using 2 FFTs with bit-reduced kernels and beat frequency resulting from the square of the sampled input data. It reduces the computation time, increases the instantaneous dynamic range, and improves the frequency resolution if compared with a typical fix point FFT approach. Without losing the generality, a 10 bit A/D converter, 2.56 GHz sampling rate, and 256 points of data processing are used for illustration of this approach. The Matlab simulations are used to compare the new approach with the approach using a 10-bit fix point FFT. The simulation results are tabulated.

INTRODUCTION

A typical approach to detect more than one signal for a wideband digital receiver is to use the FFT (Fast Fourier Transformation). If high dynamic range is a requirement for this wideband receiver, the number of the bits of the A/D converter has to be increased and a proper window function has to be applied. The typical FFT approach needs a great amount of firmware area and significant computation time. In general, the required computational time and the area of firmware will increase with the number of bits. For the receiver with a high dynamic range, even the most current and most advanced FPGA technology can't meet the needs of the computational speed and memory load of the firmware. The other disadvantage of the FFT approach is the frequency resolution will adversely be reduced as the side lobe level of the window function decreases. Two signals with a small frequency difference can't be detected individually even when they have almost the same strength. This paper discusses an approach to reduce the computation and firmware load and also resolves two signals even when they have a very small difference in the frequency and a very large difference in the amplitude. Compared with regular 10-bit FFT approach, from Case 3 table below, the dynamic range improvement can be as large as 5db and the frequency resolution improvement can be from 30MHz(3 frequency bins) of typical approach to 0.2 MHz (0.2 frequency bit) of the new approach. If the requirements for the dynamic range and the frequency resolution are reduced, it can still work well for more than two input signals

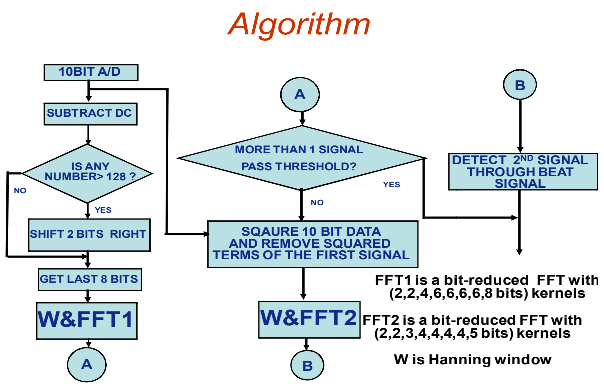


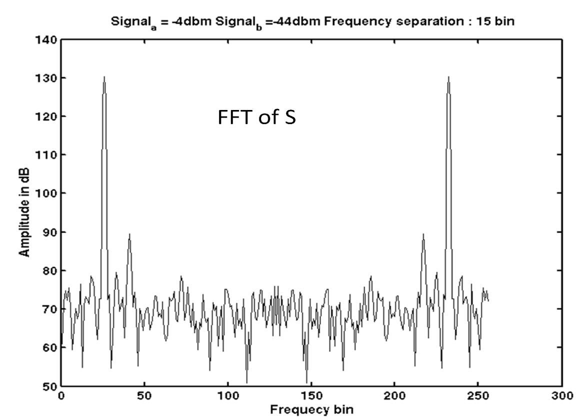
Figure 1 Receiver Algorithm

DESCRIPTION

Without losing the generality, we use a 10-bit A/D converter sampled at 2.56 GHz, and a batch processing of 256 points of data for the illustration of this approach. As shown in the figure 1, after the A/D converter, the DC offset of the A/D converter has to be removed. This corresponds to subtract the sampled data by the mean value. After subtraction, the data will become a 2's complement number. One copy of the data is buffered for later usage and the other copy of data is checked for its' maximum. If the maximum of the data is greater than 128, they are shifted right 2 times to remove the 2 least significant bits. 8 bits of data are multiplied by the Hanning window and then perform a bit-reduced FFT (a bit-reduced FFT is an FFT whose kernel functions are quantized with less bits than that of the data. For example, data for the FFT is 8 bits but the kernel functions could be 4 bits). However, use the maximum number of the bits for the kernel functions so long as the FPGA or the VLSI programmable memory can afford. After the FFT, the amplitudes of the FFT results are compared against the detection thresholds. All the amplitudes above the thresholds are analyzed for the local peaks. Each local peak is considered as a detected signal. The amplitude and the frequency of the local peak are those of the signal. If more than one signals are detected or no signal is detected, the receiver reports the result and the process completes. If only one signal detected, the process continues and the copy of the data in the buffer are squared. In this case, there are three possibilities: (1) There is only one signals, (2) the 2nd signal is below the threshold, or (3) the 2nd signal is very close to the first signal in frequency but appears as one signal in the first FFT spectrum. If only one signal exists, the following process will detect no more signals. If there are two signals, If there are 2 signals, let x be the strong signal which was detected in the bit-reduced FFT, let y be the weak signal which is below the threshold and missed the detection or mixed in the spectrum of the x, let n be noise, and let w_1 and w_2 are the frequencies of x and y respectly.

$$\begin{aligned}
&x = A\sin(w_1 t+\theta_1); \qquad y = B\sin(w_2 t+\theta_2); \qquad s = x+y+n \\
&s^2 = A^2\sin(w_1 t+\theta_1)^2 + 2AB\sin(w_1 t+\theta_1)\sin(w_2 t+\theta_2) + B^2\sin(w_2 t+\theta_2) \\
&\quad + 2n(x+y) + n^2 \\
&\approx \frac{A^2+B^2}{2} - \frac{A^2\cos(2w_1 t+2\theta_1) + B^2\cos(2w_2 dt+\theta_2)}{2} \\
&\quad + AB\cos((w_1-w_2)t+(\theta_1-\theta_2)) - AB\cos((w_1+w_2)t+(\theta_1+\theta_2)) + 2n(x+y)
\end{aligned} \tag{1}$$

Case I $|w_1 - w_2| \geq 4$ frequency bins



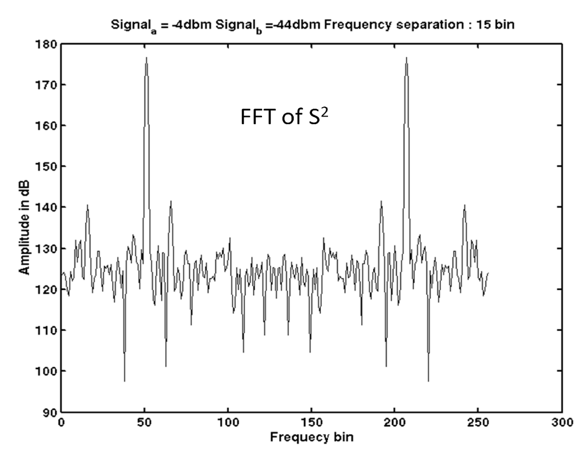


Figure 2 (a) FFT spectrum of x+y+n if frequencies of two signal are widely separated . (b) FFT spectrum of (x+y+n)^2

If A and B are close, x and y can be detected in the first FFT and process completed, therefore, we can assume A>>B in this case

$$
\begin{aligned}
s^2 &\approx A^2\sin(w_1t+\theta_1)^2 + 2AB\sin(w_1t+\theta_1)\sin(w_2t+\theta_2) + 2nx \\
&= \frac{A^2(1-\cos(2w_1t+2\theta_1))}{2} + AB\cos((w_1-w_2)t+(\theta_1-\theta_2)) - \\
&\quad AB\cos((w_1+w_2)t+(\theta_1+\theta_2)) + 2nx
\end{aligned} \tag{2}
$$

The frequency of the strong signal, w_1, can be estimated very accurate by comparing the first FFT amplitude results of the peak and those of its adjacent frequency bins. After w_1 is determined, 256 points of $\boldsymbol{e}^{-j2mw_1\Delta t}$ can be generated from a complex exponential function table.

First, remove the DC constant $A^2/2$ from the squared data sequence s_m^2 by following step

$$x'_m = s_m^2 - \frac{1}{256}\sum_{m=1}^{256} s_m^2$$

(3)

Here x'_m is s_m^2 with the DC removed

Second, to remove the strongest term, $A^2\cos(2w_1t+2\theta_1)/2$ from x'_m by following steps

$$
\begin{aligned}
b_1 + jb_2 &= \frac{1}{256}\sum_{m=1}^{256} x'_m \times e^{-j(2mw_1\Delta t)} \approx \frac{1}{256}\sum_{m=1}^{256}\frac{-A^2}{2}\cos(2mw_1\Delta t+2\theta_1)e^{-j(2mw_1\Delta t)} \\
&\approx \frac{A^2}{4}e^{2j\theta_1} = \frac{A^2}{4}(\cos(2\theta_1)+j\sin(2\theta_1));
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
y'_m &= x'_m + 2(b_1\cos(2w_1m\Delta t) - b_2\sin(2w_1m\Delta t)) \\
&= x'_m + \frac{A^2\cos(2w_1m\Delta t+2\theta_1)}{2} \\
&= AB\cos(m(w_1-w_2)\Delta t + \theta_1 - \theta_2) \\
&\quad + AB\cos(m(w_1+w_2)\Delta t + \theta_1 + \theta_2) + 2n_m x_m + R_m
\end{aligned} \tag{5}
$$

y'_m is the final squared data with dc and the strongest term removed. The R_m is the residues of the strongest term and $2n_mx_m$ is the dominant noise. We multiply y'_m with a Hanning window and perform 2nd reduced bit FFT. After the FFT, we use half of the spectrum (1st 128 frequency bins) to detect the signals against threshold. From (5) above, the amplitudes of the signals of the sum and the difference frequency are the same. If they are detected they should be detected together. If only one signal detected above threshold, it is a false detection. If two signals detected above the thresholds. The detected signals are these two signals. We assume the 1st signal detected under 2nd FFT is at the frequency w_a, and the 2nd signal detected above thresholds is w_b. Since w_a and w_b are smaller than frequency bin 128, w_a or w_b could be difference frequency. For sum frequency, the following 4 frequency bins, bin 256- w_a , bin 256- w_b , w_a, and w_b, are all possible frequency bins. Since the sum of the sum frequency and the difference frequency should be $2w_1$. (If $w_1 > w_2$, $|w_1 - w_2| + w_1 + w_2 = 2w_1$. If $w_1 < w_2$, $w_1 + w_2 - |w_1 - w_2| = 2w_1$) after pairing and testing, the right sum and different frequencies can be determined and w_2 can be solved.

Case II. $|w_1-w_2| < 4$

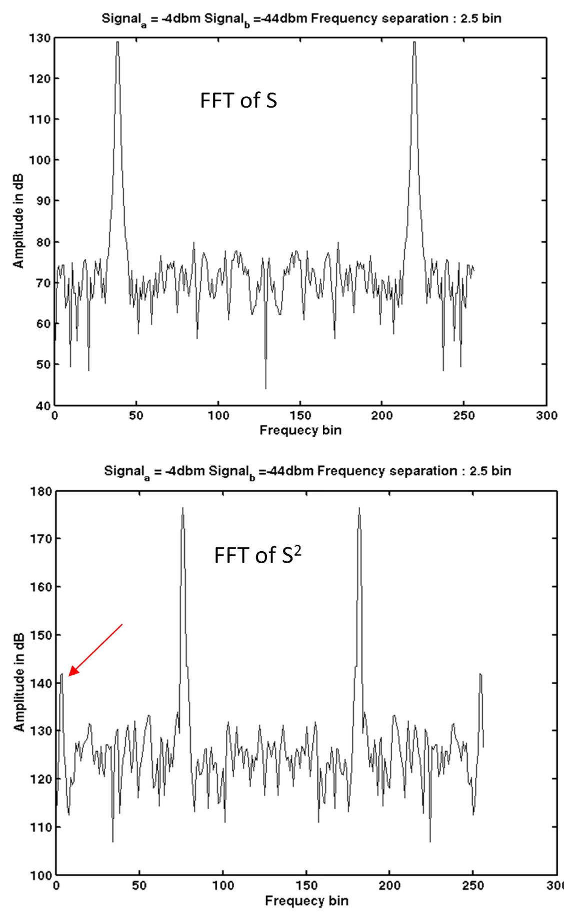


Figure 3 (a) FFT spectrum of x+y+n if frequencies of two signal are very close. (b) FFT spectrum of (x+y+n)^2

In this case, w_1 and w_2 are very close. As shown in Figure 3a, the spectrum of x and y are mixed together. The frequency measured in the first bit-reduced FFT spectrum is the frequency of the combined signal. Because the frequencies of x and y are very close, so are the frequencies of the signals they generate in the s^2 which are $2w_1$, $2w_2$ and $w_1 + w_2$. As shown in Figure 3b, the spectrum of the signals s^2 are all mixed together. Since procedures are the same for case I and II, the frequency of the strong signal measured in this case is the frequency of the mixed signal of x and y and the step 'REMOVE SQUARED TERM OF FIRST SIGNAL' in the algorithm remove the DC term and great part of combined signals of $2w_1$, $2w_2$ and $w_1 + w_2$. (For the Case I, this step will almost completely remove the signal of the frequency $2w_1$) This step will reduce the dynamic range requirement of the FFT and that is the reason a further bit-reduced FFT can be used. In the algorithm of Figure 1, after the 2nd bit-reduced FFT, the first step is to check if there is a signal detected in the first 3 frequency bins of the spectrum, if there is, the following procedure will continue, otherwise the procedure of the case I mentioned above will enter.

We assume the frequency of the detected signal is at w_d, which is below frequency bin 4. Since it is so small, we can assume w_d is the difference frequency and $| w_1 - w_2 | = w_d$. If the amplitude A of x is significantly greater than the amplitude B of y. The frequency measured in the 1st bit-reduced FFT of the combined signal is very close to w_1. The sum frequency $w_s = w_1 + w_2$ could be $2w_1 - w_d$ or $2w_1 + w_d$. The amplitudes of the frequency bins at $2w_1 - w_d$ and $2w_1 + w_d$ are compared. The strong one determines the frequency bin of $w_1 + w_2$. Since $2w_1$, $w_1 + w_2$, $| w_1 - w_2 |$ are known, w_2 can be solved.

If the amplitude A of x is very close to the amplitude B of y. The frequency of the strong signal measured in 1st FFT is the average of w_1 and w_2. The removal of the strong signal in the s^2 is very limited. The determination that either $2w_1 - w_d$ or $2w_1 + w_d$ is the sum frequency can be wrong. The same problem will occur when B is very small and contaminated by noise. Wrongly determine the sum frequency can cause the frequency measurement error as high as $2w_d$.

SIMULATION RESULT

The following tables are simulation results. In the simulation, a 10- bit ADC is sampled at 2.56 GHz. The full scale of ADC: 0.5v p-p (-2dbm). The data length for each batch processing is 256 data points (100ns). The noise floor is set at -62dbm which is strong enough to toggle one bit. The 10-bit fix point FFT with Hanning window is used to compared with the new approach. The 1st signal detection threshold is 14 dB above the average of the noise floor ($FAR=10^{-7}$). The 2nd signal detection threshold is 50 dB below the 1st signal peak but greater than 1st threshold.

Case 1. Two signals with different strength are used as inputs for 10-bit FFT the simulation. The table 1 shows the different power level and their frequency separation requirement for 95% detection of the weak signal.

1st signal power (dbm)	2nd signal power (dbm)	Frequency separation in MHz
-8	-8	30
-3	-13	40
-3	-23	40
-3	-33	50
-3	-43	60
-3	-50	70

Case 2. The frequency of 1st signal varies from 50MHz to 1130 MHz with 1 MHz increment and 2nd signal frequency is random. The table 2 is the cases that the two signals have the same strength

1st signals Power (dbm)	2nd signal Power (dbm)	New method 2nd signal	10-bit FFT 2nd signal miss
-60	-60	66	60
-30	-30	1	43
-20	-20	2	46
-8	-8	2	32

Case 3. The frequency of 1st signal varies from 50MHz to 1130 MHz with 1 MHz increment and 2nd signal frequency is random. The table 3 is the cases that two signals have very different strength.

1st signals Power (dbm)	2nd signal Power (dbm)	New method 2nd signal miss	10-bit FFT 2nd signal
-3	-50	19	85
-3	-53	28	780
-3	-55	89	1065

Case 4. The frequency of the 1st signal varies from 50MHz to 1130 MHz with 1 MHz increment and 2nd signal has frequency 5MHz apart(0.5 frequency bin) apart from that of the first signal

1st signals Power (dbm)	2nd signal Power (dbm)	New method 2nd signal miss	10-bit FFT 2nd signal miss
-3	-47	75	1081
-3	-40	14	1081
-8	-8	8	1028
-30	-30	45	1032

Case 5. The frequency of the 1st signal varies from 50MHz to 1130 MHz with 1 MHz increment and 2nd signal has frequency 2MHz(0.2 frequency bin) apart from that of the first signal

1st signals Power (dbm)	2nd signal Power (dbm)	New method 2nd signal miss	10-bit FFT 2nd signal miss
-8	-8	7	1072
-20	-20	9	1069
-23	-23	136	1075
-3	-33	39	1081

Case 6. The frequency of the 1st signal varies form 50MHz to 1130 MHz with 1 MHz increment and 2nd signal has frequency 20MHz(2 frequency bin) apart from that of the first signal

1st signals Power (dbm)	2nd signal Power (dbm)	New method 2nd signal miss	10-bit FFT 2nd signal miss
-3	-47	15	1081
-3	-40	16	1023
-8	-8	7	898
-30	-30	12	907

Case 7. The frequency of the 1st signal varies from 50MHz to 1130 MHz with 1 MHz increment and 2nd signal has frequency 100MHz(10 frequency bins) apart from that of the first signal

1st signals Power (dbm)	2nd signal Power (dbm)	New method 2nd signal	10-bit FFT 2nd signal miss
-3	-55	45	1074
-3	-52	13	156
-3	-47	12	0
-3	-40	9	0
-3	-38	0	0
-8	-8	0	0
-30	-30	0	0

Case 8. The frequency of the 1st signal varies from 50 MHz to 1130 MHz with 1 MHz increment and 2nd signal has random frequency between 50 MHz to 1130 MHz

1st signals Power	2nd signal Power	New method 2nd signal	10-bit FFT 2nd signal
-4	-300	1081	1081
-8	-300	1081	1081
-20	-300	1081	1081
-40	-300	1081	1081

CONCLUSION

Compared with regular 10-bit FFT approach, from Case 3 table below, the new approach can improve the dynamic range as large as 5db and the frequency resolution from 30MHz(3 frequency bins) to 0.2 MHz (0.2 frequency bit). If the requirements for the dynamic range and the frequency resolution are reduced, it can still work well for more than two input signals. The determination of sum frequency in the Case II , $|w_1 - w_2| < 4$ frequency bins, could be wrong as mentioned before but the difference frequency measured in the Case II is very accurate. In a complete receiver design, there is encoder after this algorithm. The encoder will produce PDW (Pulse Description Word). It collects all batches processed in the pulse duration to determine the pulse carrier frequency. We assume two pulse trains received by the receiver, as long as there are stagger between two pulses, the knowledge of 2nd signal existence and the accuracy of the difference frequency measurement are only two things needed to determine the frequency of 2nd signal.

REFERENCE

Jame Tsui "Digital Techniques for Wideband " 2nd edition Receiver"Artech House, Boston London