A high phase stability transmitter clock domain design

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Abstract. Satellite microwave communication transmitters mainly evaluate the transmitted signal quality through EVM indicator. In this paper, we used the mathematical derivation result between phase noise and signal EVM, then proposed a high phase stability transmitter clock domain design scheme, based on the design process of a spaceborne transmitter. After testing, compared with the traditional transmitter clock domain, the new transmitter clock domain achieved an 6% increase in the EVM indicators.

1. Introduction
With the rapid development of space application technology, satellite navigation, satellite timing, satellite remote sensing and other applications have gradually penetrated into various fields of military and civilian use [1-2]. Satellite microwave communication technology can provide means of information transmission. On the other hand, it can provide wide-area beacons and measurement methods for the satellite point visible area, through the transmission characteristics of microwave signal space and the synchronization strategy of both transmitters and receivers [3]. The error vector magnitude (EVM) of the beacon signal used for accurate measurements is one of the most important performance parameters. EVM reflects the combined effect of amplitude and phase imbalance of the signal, characterizing the total noise/defects present in the signal transmission path [4-6]. In this paper, a high-phase stability signal clock domain design was implemented for satellite signal transmitter (hereinafter referred to as transmitter), and a high phase stability clock domain design parameter ratio was given. The measured broadcast signal EVM was better than 4%, the phase error was better than 2%, which improved the EVM and phase error indicators compared with the traditional transmitter design.

2. EVM and local oscillator phase noise

2.1. Error vector magnitude (EVM)
EVM is an important performance metric of the modulation precision, and EVM is a measure of errors between the measured symbols and expected symbols. EVM represents the dispersion degree of constellation points, and is defined by the following formula:

\[
EVM_{rms} = \left( \frac{1}{N} \sum_{n=1}^{N} \frac{|S_n - S_{0,n}|^2}{\frac{1}{N} \sum_{n=1}^{N} |S_{0,n}|^2} \right)^{1/2} \times 100\%
\]  

(1)
Where \( E_{rms} \) represents the root-mean-square (rms) EVM, \( S_n \) is the actual normalized constellation point of \( n \)th symbol in the stream of measured symbols, is the corresponding ideal normalized constellation point of the \( n \)th symbol, \( S_{0,n} \) is the corresponding ideal normalized constellation point of the \( n \)th symbol, and \( M \) is the number of constellation points for different modulation types. For example, \( M = 4 \) for quadrature phase shift keying (QPSK) [7].

2.2. Local oscillator phase noise

LO phase noise is known as random frequency fluctuations around its center frequency. Phase noise is measured in the frequency domain. There are several ways of defining LO phase noise. The common definition is expressed as a ratio of noise power to carrier signal power, and the noise power is measured in a 1 Hz bandwidth at a given offset from the carrier frequency, and the unit is dBC/Hz. Another definition is the rms phase noise, which can be calculated by the integration of single-sideband phase noise spectrum density in a certain extent of frequency, and the unit is degree. The latter indicates the total phase stability of the LO within the information bandwidth (BW)[8].

The ideal transmitting radio frequency signal without LO phase noise can be expressed as follows:

\[
S_{\text{ideal}}(t) = I(t)\cos(\omega_ct) + Q(t)\sin(\omega_ct)
\]

(2)

Where \( I(t) \) is the in-phase baseband signal, \( Q(t) \) is the quadrature baseband signal, and \( \omega_c \) is carrier frequency. If the LO phase noise exists, the transmitting radio frequency signal can be expressed as follows:

\[
S_{\text{phase-noise}}(t) = I(t)\cos(\omega_ct + \theta(t)) + Q(t)\sin(\omega_ct + \theta(t))
\]

(3)

Equation (3) indicates the phase offset \( \theta(t) \), which introduces a phase shift in the in-band frequencies. In Reference [9] an equation relating EVM and LO phase noise is given:

\[
E_{rms} = \left( \frac{N_0}{E_s} + 2 - 2\exp\left(-\frac{\sigma^2}{2}\right) \right)^{1/2}
\]

(4)

where \( E_s/N_0 \) represents the SNR, \( E_s \) is the energy per symbol, \( N_0 \) is the noise power spectral density, \( \sigma \) represents the rms phase noise. Approximating \( \exp\left(-\sigma^2/2\right) \) by 2-order Taylor series expansion, Equation (4) is simplified to:

\[
E_{rms} = \left( \frac{N_0}{E_s} + \sigma^2 \right)^{1/2}
\]

(5)

Figure 1 shows the EVM variation with the LO phase noise by Equation (5) at different SNR.
3. A high phase stability clock domain design

3.1. Composition of the transmitter

The transmitter used a once up-conversion architecture, the transmitter comprised a baseband module, a RF module and a power amplifier module, and the baseband module was responsible for generating a navigation message and generating an IF signal of QPSK modulation. After the IF signal was mixed with the RF local oscillator by the RF module, the RF signal was generated and passed through the bandpass filter, and then the power amplifier module was used for power driving, and output to the antenna unit. The block diagram of the transmitter was as follows:

![Block Diagram of Transmitter](image)

Figure 2. Composition of the transmitter block diagram.

3.2. Traditional transmitter clock domain design

The transmitter used an up-conversion architecture, and the IF signal was generated by the baseband module. In the traditional transmitter clock domain design, taking into account the availability and development convenience of spaceborne product components, the frequency synthesizer chip was usually used to provide the working clock for the signal processing FPGA. The clock domain design block diagram was as follows:

![Block Diagram of Traditional Clock Domain](image)

Figure 3. traditional transmitter clock domain design block diagram.

In the actual test, EVM indicators and Phase Error (phase error) indicators were about 9% and 5°, far exceeded the technical requirements. Therefore, the system clock domain was re-designed to obtain a high-stability transmitter clock domain design.

3.3. A high phase stability clock domain design

In this scheme, the factors affected the EVM and Phase Error specifications include phase noise introduced into the baseband RF multiplex device, FPGA internal DCM, and local oscillator signal phase noise. Therefore, started from the above aspects, we first eliminated the phase noise introduced by the baseband frequency integrated chip, replaced the chip with an analog quadruple frequency circuit, and used the higher harmonic components generated by the amplifier in the nonlinear region to made the fourth harmonic. The wave was filtered out used a bandpass filter and amplified again to serve as the main operating clock of the FPGA, which eliminated the phase noise introduced by the integer and fractional division of the digital synthesizer chip. In addition, the internal working clock domain of the FPGA was re-planned, and the FPGA working clock, the IF signal carrier generator, and the pseudo-code generator were processed in the same phase. The reference was unified to an integer multiple of f0/2, and the quality of the broadcast signal was significantly improved.
4. Transmitter test result

4.1. Test of traditional transmitter clock domain design through baseband
In order to measure and analysis of traditional clock domain design baseband signals, we used VSA (89601B) analysis software in Agilent N9010A spectrum analyzer, EVM was 8.76%, phase error was 3.89°. Test result was shown in figure 5 and figure 6.

4.2. Test of high phase stability clock domain design through baseband
In order to measure and analysis of high phase stability design baseband signals, we used VSA (89601B) analysis software from Agilent N9010A spectrum analyzer, EVM was 2.15%, phase error was 0.86°. Test result was shown in figure 7 and figure 8.
4.3. Test of high phase stability clock domain design through RF and power amplifier

Measurement and analysis of high phase stability design through RF and power amplifier signals using VSA (89601B) analysis software from Agilent N9010A spectrum analyzer, EVM was 3.9%, phase error was 1.72°. Test result was shown in figure 9 and figure 10.

![Figure 9. Constellation of high phase stability clock domain design through RF and power amplifier.](image1)

![Figure 10. EVM of high phase stability clock domain design through RF and power amplifier.](image2)

Measurement and analysis again of high phase stability design through RF and power amplifier signals using Agilent E4440A, EVM was 3.89%, phase error was 1.75°, test result was same as using Agilent N9010A.

![Figure 11. EVM and constellation of high phase stability clock domain design through RF and power amplifier.](image3)

4.4. Test summary

According to the measured results, when the digital frequency synthesizer was used to provide the baseband clock before the improvement, the signal output EVM and Phase Error result were not ideal, resulting in constellation offset, which affected the receiving performance of the ground receiving system. After used the improved high-stability transmitter clock domain, the signal quality was significantly improved by 6%, and the Phase Error was increased by 3°.

| EVM    | Phase error |
|--------|-------------|
| 8.76%  | 3.89°       |
| 2.15%  | 0.86°       |
| 3.9%   | 1.72°       |
| 3.89%  | 1.75°       |

Table 1. Test summary.
5. Conclusions
Using the improved high phase stability transmitter clock domain design, the output signal EVM index can be greatly improved about 6%, which has reference significance in the transmitter design.

References
[1] ZHAO, Y. (2017) Brief probe on application of compass navigation satellite system in the fields of sea, land and air. Proceedings of 2017 2nd International Conference on Materials Science, Machinery and Energy Engineering. Dalian, China. pp. 212-217.
[2] ENGE, P., WALTER, T., PULLEN, S. (1996) Wide area augmentation of the Global Positioning system. Proceedings of the IEEE, 84(6): 1063-1088.
[3] Shen, D.H., Meng, Y.S., Bian, L. (2019) A global navigation augmentation system based on LEO communication constellation. Journal of Terahertz Science and Electronic Information Technology, V01.17, NO.2: 209-215.
[4] Hassun, R., Flaherty, M., Matreci, R. (1997) Effective evaluation of link quality using error vector magnitude techniques. Proceedings of 1997 Wireless Communications Conference (WCC’97). Boulder, CO, USA. Piscataway, NJ, USA. pp. 89-94.
[5] Wang, A.K., Ligmanowski, R., Castro, J. (2006) EVM simulation and analysis techniques. Proceedings of IEEE Military Communications Conference (Milcom’06). Washington, DC, USA. Piscataway, NJ, USA. pp. 1-7.
[6] Wara, M.T., Raghavendra, M.R., Kodandaram, M., Bhuvaneshwari, M.S. (2018) Measurement, analysis, and understanding of the error vector magnitude (evm) of navigation signals. IETE Journal of Research, 64(6): 1-12.
[7] Tan, X.H., Li, T.J. (2009) EVM simulation and analysis in digital transmitter. The Journal of China Universities of Posts and Telecommunications, 16(6): 43-48.
[8] Liu, R.F., Li, Y.M., Chen, H.Y. (2006) EVM estimation by analyzing transmitter imperfections mathematically and graphically. Analog Integrated Circuits and Signal Processing, 48(3): 257-262.
[9] Georgiadis, A. (2004) Gain, phase imbalance, and phase noise effects on error vector magnitude. IEEE Transactions on Vehicular Technology, 53(2): 443-449.