Research on Bandwidth Limit of Multi-channel Signal Splicing

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Abstract. Multi-channel narrowband signal through the splicing to synthesis a single channel wideband signal is an effective way to expand the signal bandwidth. At present, the multi-channel signal bandwidth splicing is basically achieved, and the error in splicing process has also been in-depth analysis. However, the bandwidth of the signal obtained by splicing the multi-channel signal has yet to be analyzed and demonstrated. In this paper, according to the principle of multi-channel signal splicing, the bandwidth limit of multi-channel signal splicing is analyzed theoretically. Secondly, the upper limit bandwidth of multi-channel signal splicing is analyzed from the engineering realization of multi-channel signal splicing. From the analysis results, the bandwidth of multi-channel signal splicing can be extended with the increase of channel number and single-channel signal bandwidth. In the engineering realization, the signal bandwidth of splicing can only be effectively expanded in RF splicing, while it will be limited by the clock frequency of mixer.

1. Introduction
Modern radar can not only complete the target location, speed and other information obtain, but also image and identify the target. This requires that the radar transmit signal has a large instantaneous bandwidth, thus obtaining a sufficiently high distance resolution to excite the details of the target. The digital compression method has become a commonly used waveform synthesis method for modern radar. However, the pulse compression signal produced by monolithic DDS can not meet the requirement of signal bandwidth of modern radar. Therefore, it is of great practical significance to study the wideband radar signal source based on multi-splicing. Multi-channel signal splicing is a multi-channel narrowband signal spliced into a broadband signal method. At present, the research on the bandwidth splicing technology for multi-channel signals is more mature. The literature [1] proves the problem of multi-channel signal splicing, the literature [2], [3] on the multi-channel signal splicing, multi-channel signal The problem of error control in the process of splicing is analyzed deeply and the better results are obtained. This is also one of the two important problems in the field of multi-channel signal splicing. However, multi-channel splicing of the signal bandwidth can be infinitely expanded to be analyzed and demonstrated. In this paper, this paper will be from the theory and engineering to achieve two aspects of analysis and research.

2. Factors that limit the bandwidth of multi-channel signal splicing
From the first section, we can see that in the signal splicing scheme, according to the timing of signal
splicing, can be divided into baseband splicing, intermediate frequency splicing and RF splicing. For different signal splicing scheme, difficulty is different. In general, the baseband splicing is less, relatively simple, the signal is easier to control, the signal quality of the splicing is relatively high; and RF splicing relative to the baseband splicing, the increase in the modulation and mixing process, in this process Not only will introduce noise, but also increase the difficulty of synchronization, and ultimately lead to splicing the signal quality is relatively low. In addition to the quality of the signal obtained by splicing, different designs will also affect the splicing bandwidth of the signal, the following analysis of this.

First of all, for the baseband signal splicing, DDS or FPGA can be directly generated by the signal, and then for each piece of DDS or FPGA signals generated by DAC conversion, direct synthesis. One of the key metrics for evaluating DAC performance is the slew rate / settling time. The conversion rate is measured by the settling time, which refers to the time at which the data must reach an effective logic level relative to the DAC clock transition. Different models of DAC setup time are typically between nanoseconds and order of microseconds. For the baseband splicing scheme, the bandwidth of the spliced signal can be increased by increasing the number of channels. However, with the increase in the number of channels, so that the time of splicing signal reached or even exceeded the maximum settling time of the DAC, then no matter how many channels, the final splicing of the signal bandwidth is still limited, so that the splicing program can not get the signal In the bandwidth expansion on a breakthrough. The significance of the scheme is that the basic experimental verification can be carried out on the feasibility of multi-channel signal splicing technology.

Secondly, for the intermediate frequency splicing, the signal through the FPGA and other devices after the baseband signal, and then through the DDS and other devices to achieve quadrature modulation, and complete the digital-analog conversion, the final output IF signal. In this process, the same baseband splicing, baseband signal generation link generated by a single signal bandwidth will be limited by the FPGA clock. After the baseband signal enters the DDS, the signal needs to be quadrature modulated. During the modulation process, its output signal bandwidth will be limited by the clock frequency of the DDS. Even if the signal bandwidth is expanded by the increase in the number of channels, its maximum bandwidth But also by the DDS clock frequency decision. Therefore, IF splicing can only increase the DDS clock frequency to increase the way the bandwidth of the signal obtained by splicing. However, from Table 1 can be intuitively seen, due to process factors, DDS series chip clock frequency is limited. Therefore, the IF splicing scheme eventually outputs the signal bandwidth is limited by the DDS clock frequency.

| Type     | CLK (MHz) | DAC Bits | Type     | CLK (MHz) | DAC Bits |
|----------|-----------|----------|----------|-----------|----------|
| AD5930   | 50        | 10       | AD9910   | 1000      | 14       |
| AD5932   | 50        | 10       | AD9914   | 3500      | 12       |
| AD9830   | 50        | 10       | AD9951   | 2500      | 12       |
| AD9834   | 75        | 10       | AD9953   | 400       | 14       |
| AD9850   | 125       | 10       | AD9957   | 400       | 14       |
| AD9854   | 300       | 12       | AD9958   | 500       | 10       |
| AD9858   | 1000      | 10       | AD9959   | 500       | 10       |

Finally, for RF splicing, this approach differs from IF splicing in that it adds a mixing session before signal synthesis. From the mixer output signal and the input signal relationship can be seen, for the frequency signal, the output signal frequency is the sum of the two input signal frequency. Thus, in the case where the bandwidth of the intermediate frequency signal is constant, the frequency spectrum can be moved by the high frequency clock, and the signal spectrum can be moved to the desired frequency range so as to jump out of the devices such as the FPGA and the DDS, Band splicing. For the splicing scheme, the factors that affect the quality of signal splicing are mainly from three parts:

In the baseband signal generation, the baseband signal is generated, and the quality of the resulting signal is affected by the following aspects: First, caused by its own structure, such as phase truncation,
amplitude quantization and conversion, etc., will be introduced in the baseband signal.

The second is in the synchronization problem, if not between the work, then, will cause the baseband signal phase, frequency and other inconsistencies, resulting in the signal before reaching the RF switch phase, frequency error.

In the quadrature modulation, the signal is output by the quadrature modulator, its quality is mainly affected by the following factors: First, for the IQ baseband signal amplitude and phase consistency; second, the two orthogonal modulator initial phase whether the same, the reference clock center frequency is accurate, these two factors will directly affect the output of the IF signal quality, the final performance of the RF input signal phase, the frequency is affected.

In the mixing process, the output quality of the RF output is mainly affected by the following factors: First, the consistency of the initial phase of the two mixers, and the accuracy of the reference clock center frequency; second, in the final synthesis, Switch the switching time. They will cause the final splicing out of the signal phase, frequency, time deviation.

In general, the main factors that affect the multi-channel signal splicing bandwidth expansion can be summarized as three aspects: one is the amplitude error, the second is the delay error, the third is the frequency error. And these three aspects of the error factors are from the three aspects of the project, namely the baseband signal generation link, quadrature modulation link, RF output link. The following will be analyzed from the ideal situation (regardless of any error), the theoretical situation (considering the amplitude, delay and frequency error) and engineering conditions (from the baseband signal generation, quadrature modulation and RF output three links analysis) Multi-channel signal splicing ideal bandwidth, theoretical bandwidth and engineering bandwidth.

3. Theoretical Limitation of Bandwidth of Multi-channel Splicing Signal

Multi-channel signal splicing technology is a way to synthesize signals with narrower bandwidths to a larger bandwidth signal. To LFM signal (LFM), for example, multi-channel signal splicing principle as shown in Figure 1.

![Figure 1 Multi-channel signal splicing schematic diagram](image)

First, we analyze the ideal conditions of multi-channel signal splicing can be extended to achieve the signal bandwidth, and called the ideal bandwidth. The ideal bandwidth for multi-channel signal splicing is to take into account the limitations of the performance of components in all aspects of signal splicing, the presence of errors, and the introduction of interference in the environment, so that the analysis can be achieved through multi-channel splicing The maximum bandwidth of the signal. From the previous analysis, we can find that the LFM signal belongs to a typical spliced signal. So the following will LFM signal as an example, multi-channel splicing signal obtained by the ideal bandwidth of the upper limit analysis. The expression of the chirp signal is as follows:
In equation (1), let the pulse width of the signal to take the real part (i.e., take $u(t)=1$), then the linear FM signal can be expressed as:

$$x(t) = \cos \left[ 2\pi \left( f_0 t + \frac{B}{2T} t^2 \right) \right]$$

(2)

The following is the time-domain analysis of the chirp signal in (2), which is divided into four segments in one sweep cycle, $0 \sim \frac{T}{4}, \frac{T}{4} \sim \frac{T}{2}, \frac{T}{2} \sim \frac{3T}{4}, \frac{3T}{4} \sim T$.

In the first paragraph: Let $t \in \left[ 0, \frac{T}{4} \right]$, then

$$x(t) = \cos \left[ 2\pi \left( f_0 t + \frac{B}{2T} t^2 \right) \right] = \cos \left( 2\pi f_0 t + \frac{\pi B}{T} t^2 \right)$$

Set the center carrier frequency $f_0$, quadrature modulation carrier $\cos(2\pi f_0 t)$ and $\sin(2\pi f_0 t)$, in the FPGA to achieve I and Q two baseband data, $I(t) = \cos \left( \frac{\pi B}{T} t^2 \right), Q(t) = \sin \left( \frac{\pi B}{T} t^2 \right), t \in \left[ 0, \frac{T}{4} \right]$.

Similarly, in the second paragraph, take $t \in \left[ \frac{T}{4}, \frac{T}{2} \right]$, let $t_1 = t - \frac{T}{4}$, then $t_1 \in \left[ 0, \frac{T}{4} \right]$, let $f_1 = f_0 + \frac{B}{4}$.

bring $f_1$ and $t_1$ to $x(t)$, there are

$$x(t_1) = \cos \left[ 2\pi f_0 \left( t_1 + \frac{T}{4} \right) - 2\pi \frac{B}{4} \left( t_1 + \frac{T}{4} \right) + \frac{B}{T} \left( t_1 + \frac{T}{4} \right)^2 \right]$$

$$= \cos \left( 2\pi f_0 \left( t_1 + \frac{T}{4} \right) - \frac{\pi B T}{16} + \frac{\pi B}{T} t_1^2 \right)$$

$$= \cos \left( 2\pi f_1 \left( t_1 + \frac{T}{4} \right) - \frac{\pi B T}{16} \cos \left( \frac{\pi B}{T} t_1^2 \right) - \sin \left( 2\pi f_1 \left( t_1 + \frac{T}{4} \right) - \frac{\pi B T}{16} \sin \left( \frac{\pi B}{T} t_1^2 \right) \right) \right)$$

(4)

Set the center carrier frequency $f_1 = f_0 + \frac{B}{4}$, quadrature modulation carrier $\cos \left( 2\pi f_1 t - \frac{\pi B T}{16} \right)$, $\sin \left( 2\pi f_1 t - \frac{\pi B T}{16} \right)$ to achieve baseband data,

$I(t_1) = \cos \left( \frac{\pi B}{T} t_1^2 \right), Q(t_1) = \sin \left( \frac{\pi B}{T} t_1^2 \right), t_1 \in \left[ 0, \frac{T}{4} \right]$.

Similarly, in the second paragraph, take $t \in \left[ \frac{T}{2}, \frac{3T}{4} \right]$, let $t_2 = t - \frac{T}{2}$, then $t_2 \in \left[ 0, \frac{T}{4} \right]$, let $f_2 = f_0 + \frac{B}{2}$.

bring $f_2$ and $t_2$ to $x(t)$, get,
\[
x(t_j) = \cos \left\{ 2\pi f_c \left( t_j + \frac{T}{4} \right) - 2\pi \frac{B}{4} \left( t_j + \frac{T}{4} \right) + \frac{B}{T} \left( t_j + \frac{T}{4} \right)^2 \right\}
\]

\[
= \cos \left\{ 2\pi f_c \left( t_j + \frac{T}{2} \right) - \pi \frac{BT}{4} + \frac{\pi B}{T} t_j \right\}
\]

\[
= \cos \left\{ 2\pi f_c \left( t_j + \frac{T}{2} \right) - \pi \frac{BT}{4} \cos \left( \frac{\pi B}{T} t_j \right) - \sin \left\{ 2\pi f_c \left( t_j + \frac{T}{2} \right) - \pi \frac{BT}{4} \sin \left( \frac{\pi B}{T} t_j \right) \right\} \right\}
\]

Set the center carrier frequency \( f_c = f_c + \frac{B}{2} \), quadrature modulation carrier \( \cos \left( 2\pi f_c t - \frac{\pi BT}{4} \right) \), \( \sin \left( 2\pi f_c t - \frac{\pi BT}{4} \right) \) the realization the baseband data of I, Q. I \((t_j) = \cos \left( \frac{nB}{T} t_j \right), \ Q(t_j) = \sin \left( \frac{nB}{T} t_j \right), t_j \in \left[ 0, \frac{T}{4} \right].\)

Similarly, in the fourth paragraph, take \( t \in \left[ \frac{3T}{4}, T \right], t_j = t - \frac{3T}{4} \), then there is \( t_j \in \left[ 0, \frac{T}{4} \right] \), take \( f_c = f_c + \frac{3B}{4} \), then there are:

\[
x(t_j) = \cos \left\{ 2\pi f_c \left( t_j + \frac{T}{4} \right) - 2\pi \frac{B}{4} \left( t_j + \frac{3T}{4} \right) + \frac{B}{T} \left( t_j + \frac{3T}{4} \right)^2 \right\}
\]

\[
= \cos \left\{ 2\pi f_c \left( t_j + \frac{T}{2} \right) - \pi \frac{9BT}{16} + \frac{\pi B}{T} t_j \right\}
\]

\[
= \cos \left\{ 2\pi f_c \left( t_j + \frac{T}{2} \right) - \pi \frac{9BT}{16} \cos \left( \frac{\pi B}{T} t_j \right) - \sin \left\{ 2\pi f_c \left( t_j + \frac{T}{2} \right) - \pi \frac{9BT}{16} \sin \left( \frac{\pi B}{T} t_j \right) \right\} \right\}
\]

Set the center carrier frequency \( f_c = f_c + \frac{3B}{4} \), quadrature modulation carrier: \( \cos \left( 2\pi f_c t - \frac{9\pi BT}{16} \right) \), \( \sin \left( 2\pi f_c t - \frac{9\pi BT}{16} \right) \), to achieve the baseband data:

\[
I(t_j) = \cos \left( \frac{nB}{T} t_j \right), Q(t_j) = \sin \left( \frac{nB}{T} t_j \right), t_j \in \left[ 0, \frac{T}{4} \right].
\]

From the derivation results of (3), (4), (5) and (6), it can be seen that the baseband data are consistent after the four-way signal is decomposed from the time domain, and the bandwidth of the baseband data keep the same, the four-band signal carrier frequency are \( f_c, f_c + \frac{B}{4}, f_c + \frac{B}{2}, f_c + \frac{3B}{4}. \)

From the time domain analysis results can be seen in the frequency domain is also equivalent to the signal is divided into four bands.

Thus, by increasing the bandwidth of the single signal and the number of channels of the signal, the instantaneous bandwidth of the signal can be greatly extended in theory. The signal bandwidth obtained by splicing can be expressed as:

1. When the N-way baseband signal bandwidth is exactly the same: \( B = B_0 \times N, \ N \in Z, \ B_0 \) represents the single baseband signal bandwidth;

2. When the N-way baseband signal bandwidth is not exactly the same: \( B = \sum_{i=0}^{N-1} B_i, \ N \in Z, \ B_i \) represents the \( i \) baseband signal bandwidth.

Of course, the final size does not depend entirely on the baseband signal bandwidth and the number of splice channels, but also with the mixer carrier frequency \( (f_c, f_c, 0 < \cdots < f_c, < \cdots < f_c, N-1) \) there is
contact.

For the \(\text{①}\) case, \(f_{c,N-1} = B_0 \times (N - 1) + B_0 / 2\) then:

As can be seen from the above analysis, when \(N \to \infty, B \to f_c\), the size of the bandwidth obtained by splicing approaches the carrier frequency. Therefore, by increasing the maximum carrier frequency \((f_{c,N-1})\), the bandwidth of the spliced signal can be effectively expanded.

For the \(\text{②}\) case, \(f_{c,N-1} = \sum_{i=0}^{N-2} B_i + B_{N-1} / 2\) then:

\[
B = f_{c,N-1} + B_{N-1} / 2
\]  

(8)

Thus, by increasing \(f_{c,N-1}\) or increasing \(B_{N-1}/2\), the bandwidth of the spliced signal can be effectively expanded. However, in general, the increase of \(B_{N-1}/2\) is often limited by the hardware.

In summary, the signal splicing bandwidth can be expanding effectively by increasing \(f_{c,N-1}\), specifically to what extent the size of the approximation with the approximate linear relationship of \(f_{c,N-1}\). Considering the ideal situation, the carrier frequency is not limited by hardware (ie, the carrier frequency can be any desired size), then, through the signal splicing technology, will be able to synthesize any desired bandwidth size.

4. Conclusion

Through theoretical analysis, we have obtained the theoretical bandwidth of signal splicing, which can expand with the increase of the number of splicing channels and the increase of single channel bandwidth. Through the engineering analysis, we can see that different splicing scheme will have a great impact on the bandwidth expansion of the signal. In terms of baseband signal splicing and intermediate frequency signal splicing, these two schemes are limited by hardware, And can not get all the bandwidth of the signal, and for the RF splicing program, you can break through the digital-analog converter limit, get mixed with the frequency of the carrier frequency linear relationship between the instantaneous bandwidth. The next step is to focus on how to improve the quality of the signal obtained by splicing, mainly for the follow-up study on the influence of channel characteristic deviation and motion drift on the signal quality of splicing.

References

[1] Bangqian Wan, Zhiyong Yu, Jian Yang. Advances in Computer Science Research, Volume 70:Multi-channel Splicing Technology for Signal Bandwidth Expansion [C]//ICCCA. Beijing, China. Atlantis Press, 2017.
[2] Wang Wuheng. Research and implementation of broadband signal source based on low processing rate [D]. Changsha: National University of Defense Technology, 2010.
[3] Li Gang. Based on multi-splicing of broadband radar signal source [D]. Chengdu: University of Electronic Science and Technology.
[4] Xiang Yunlong. Design and implementation of multi-channel broadband signal generator [D]. Changsha: National University of Defense Technology, 2010.
[5] Fei Yuanchun, Su Guangchuan, etc. Broadband radar signal generation technology [M]. Defense Industry Press .2005.
[6] JIANG Nie-ti, JIANG Tao, CHEN Jian-jun. Preparation of multi-channel broadband DDS signals by parallel conversion method [J]. Radar and confrontation, 2009,4: 31-33.
[7] Li Chenlei, Zhu Xiaosong, Xu Zhuang. Design of a UWB Linear Frequency Modulation Signal Source [J]. Modern Radar, 2015,37 (8): 58-64.
[8] Li Xiang. DDS-based common mode signal generator design research [D]. Xi'an: Xi'an University of Electronic Science and Technology, 2011.