Dual-frequency Spreading Waveform and Multiplexing Joint Design for Satellite-based Navigation Signals

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Abstract

With the flourish development of global navigation satellite systems (GNSS), to study the high performance navigation signal spreading modulation in limited bandwidth, as well as the high efficiency constant envelope multiplexing technique has been being an emergent task. In this paper, multiple navigation signal components in two different carriers are taken as a whole. The concept and method of dual-frequency spreading waveform and multiplexing joint design are proposed, and the unified representation and reconstructed subcarrier are investigated to resolve the contradiction between radio frequency compatibility, ranging accuracy, and multiplexing efficiency. Analysis results show that under the dual-frequency spreading waveform and multiplexing joint design, composited signal can achieve both high ranging performance and high multiplexing efficiency under the constraint of radio frequency compatibility. The proposal offer a new idea for the updating of the existing GNSS signal and the further study of next generation navigation signal design.

1. Introduction

In the next generation GNSS signal design, the technique of spread spectrum modulation and constant envelope multiplexing are among the essential topics. Since the ranging accuracy, anti-multipath, anti-interference, radio frequency (RF) compatibility and other navigation performances are largely determined by the spreading modulation technique, the design of spreading code waveform is one of the key aspects for the potential receiving performance of the navigation signal. Meanwhile, due to the limitation in GNSS transmitting power and the nonlinearity of signal transmitting channel, multiple spreading signals should share a carrier frequency and multiplex into a composite signal with constant envelope in the signal generator [1]. Until now, the design and optimization of modulation and multiplexing are practically independent in the signal design. Although in the recent years, the booming constructing of modern GNSS, including GPS III, Galileo and Beidou, greatly promotes the development of modulation and multiplex technology especially for the field of navigation, the growing expanded GNSS application and refined service require the new generation GNSS to have more signals [2] and higher quality of the navigation performance. On one hand, the crowding of the spectrum available for GNSS is exacerbated, thus restricting the performance improvement under the limited bandwidth. On the other hand, the power efficiency of existing constant envelope multiplexing is reduced, while the complexity of the satellite payload is increased. This situation makes the modern GNSS signal design meet a dilemma in the tradeoff of the ranging accuracy, RF compatibility, multiplexing performance and other essential performances.

In order to solve the aforementioned problems in the system constructing, the concept and generating approach of dual-frequency spreading waveform and multiplexing joint design is proposed in this paper. Performance analysis for the designed signal is also given. Results show that the proposed method achieves the joint optimization of spreading spectrum modulation and multiplexing, and the designed signal allows for not only the separate narrowband receiving of the two frequencies with low complexity, but also the joint receiving as a wideband integral signal with enhanced processing performance. The work in this paper provides an effective access to resolve the conflicts of number of signal, RF compatibility and multiplexing efficiency for the GNSS signal design.

2. Dilemma in Satellite-based Navigation Signal Design

In the optimization of modulation, the key to enhancing ranging performance is to increase the root mean square (RMS) bandwidth [3], which can be achieved by adding high-frequency component to the baseband signal. In order to promote the ranging performance while maintain the required spectral separation, spectrum-split spreading modulation such as binary offsite carrier (BOC) modulation [4] is a feasible option. However, the larger RMS bandwidth requires the spectrum-split signal to have higher subcarrier rate, which means larger receiver RF bandwidth and the increment of complexity of the receiving. Although the sophisticated receiving strategy is acceptable for high-end applications such as surveying and mapping, the cost and complexity is hardly to bear for the low-end consumer electronics devices. To address this problem, some systems transmit multiple signals on the satellite, providing the high-end users with wideband signal while allowing the low-end users to have simple receiving strategy for narrowband signal. Unfortunately, the increment in the number of signals at the same frequency degrades the multi-access interference (MAI) between the system and the inter-system signals, which leads to the deterioration in the receiving performance.

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On the other hand, in the constant envelope multiplexing on the navigation satellite, as the number of multiplexing signal increases, more inter-modulation terms power should be added to keep the envelope of multiplexed signal constant [5]. Since the information carried on inter-modulation terms is redundant for the receiving, the more proportion of the inter-modulation means the less proportion of useful power, which is expressed as lower multiplexing efficiency, thus reducing the received carrier to noise ratio (CNR). Though increasing the transmit power can compensate the multiplexing loss, it will further deteriorate MAI between the system and the inter-system signals.

Therefore, in the independent design of modulation and multiplexing, it is difficult to reconcile the contradictions among number of signal, RF compatibility and multiplexing efficiency.

3. Dual-frequency Modulation and Multiplexing Joint Design

In order to break the cycle of measurement accuracy, services variety, RF compatibility, as well as multiplexing efficiency in satellite-based navigation signal design, in this paper, a dual-frequency joint modulation and multiplexing (DJMM) technique is proposed. In this technique, several types navigation signals located at two different central frequencies are treated as a whole, and the modulation and multiplexing of them are designed and optimized jointly. The key of DJMM is how to combine several flexible signals located at two different central frequencies with arbitrary power, chip rate, and spreading waveform into an integral signal with constant envelope.

Taking the design of four signals DJMM for example, in which four different baseband spreading signals are denoted as g_1, g_2, g_3, and g_4, respectively, the spreading code of which are orthogonal to each other, and each is designed to carry different service data. Each channel can be represented as $s_i(t)=A_ig_i(t)d_i(t)$, where A_i is the amplitude of each channel, the equality of them is not required, d_i is data modulated in channel i. When considering combining these four channels into an integrated signal in which s_1 and s_2 are located on the upper sideband I and Q phases, s_3 and s_4 are located on the lower sideband I and Q phases, the center angular frequencies of two sidebands are $2\omega_{sc}$ apart, the simplest form of subcarrier is complex sinusoid, with which the combined complex envelope signal can be expressed as

$$\begin{aligned} s_l(t) &= \left(s_1 + \mathrm{j}s_2\right)\mathrm{e}^{\mathrm{j}\omega_{sc}t} + \left(s_3 + \mathrm{j}s_4\right)\mathrm{e}^{-\mathrm{j}\omega_{sc}t} \\ &= -\left(s_{13,+}^2 + s_{24,-}^2\right)^{1/2}\sin\left(\omega_{sc}t - \operatorname{atan}2\left(s_{24,-}, s_{13,+}\right)\right) + j\left(s_{13,-}^2 + s_{24,+}^2\right)^{1/2}\sin\left(\omega_{sc}t + \operatorname{atan}2\left(s_{13,-}, s_{24,+}\right)\right) \end{aligned} \tag{1}$$

where $s_{ij,\pm} \triangleq s_i \pm s_j$, and atan2(·,·) is four-quadrant arctangent. However, the envelope of (1)

$$\left|s_l\right| = \left\{\sin^2\left(\omega_{sc}t + \varphi_1\right) + \sin^2\left(\omega_{sc}t + \varphi_2\right) + 2\left(s_1s_3 - s_2s_4\right)\left[\sin^2\left(\omega_{sc}t + \varphi_1\right) - \sin^2\left(\omega_{sc}t + \varphi_2\right)\right]\right\} \tag{2}$$

is varying with time, which means that the satellite HPAs do not operate with high efficiency. In order to keep it constant, we need to reconstruct the subcarrier in (1) to equate the value of $\sin^2\left(\omega_{sc}t + \varphi_i\right)$ with i=1 or 2, and remains them to be invariant with time.

In subcarrier reconstruction, the spectrum structure of the signal should not changed significantly, and a receiver which still use signal (1) or a single channel $s_i(t)$ as the local replica signal ought obtain high enough power at correlation output when processing the reconstructed signal. For generation complexity, we use 2-level waveform to reconstruct the subcarrier. The reconstructed subcarrier waveform is denoted as $\gamma(t)$, value of which is confined to $\pm K$. Without loss of generality, we assume the local replica is the in-phase component of $s_l(t)$, and the received signal is $\gamma(t)$, then the output of prompt correlator can be expressed as

$$R = \alpha_1\int_0^T \sin\left(\omega_{sc}t + \varphi_1\right)\gamma(t)\,dt \le \alpha_1\int_0^T \left|\sin\left(\omega_{sc}t + \varphi_1\right)\right|\left|\gamma(t)\right|dt = K\alpha_1\int_0^T\left|\sin\left(\omega_{sc}t + \varphi_1\right)\right|dt \tag{3}$$

Equality holds if $\gamma(t) = K\,\mathrm{sgn}\left[\sin\left(\omega_{sc}t + \varphi_1\right)\right]$. In order to keep the invariant subcarrier power before and after waveform reconstruction, let $K=\sqrt{2}/2$. Consequently, the optimal 2-level waveform reconstruction is replacing all of those sin(·) in (1) with $(\sqrt{2}/2)\,\mathrm{sgn}\left[\sin(\bullet)\right]$. And the integrated baseband complex signal after reconstruction is

$$\tilde{s}_l(t) = \left(\sqrt{2}/2\right)\alpha_1\,\mathrm{sgn}\left[\sin\left(\omega_{sc}t + \varphi_1\right)\right] + \mathrm{j}\left(\sqrt{2}/2\right)\alpha_2\,\mathrm{sgn}\left[\sin\left(\omega_{sc}t + \varphi_2\right)\right] \tag{4}$$

It can be noted that the envelope $\left|\tilde{s}_l\right| \equiv 1$, so that $\tilde{s}_l(t)$ achieves the constant envelope combination of several independent navigation signals located at two frequencies. More importantly, no power ratio limitation and constraint is imposed to the proposed technique, and every baseband signal can employ any kind of binary coded symbol(BCS) spreading waveform [6]. That means in this integral signal, those channels can have arbitrary power allocation and any spreading modulation, which implies more proportion of the transmission power can be allocated to pilot channels, and each channel's spreading waveform can be optimized independently, depending on the specific application requirement.

4. Performance Analysis

Compared with the existing techniques, the proposed DJMM have the following advantages:

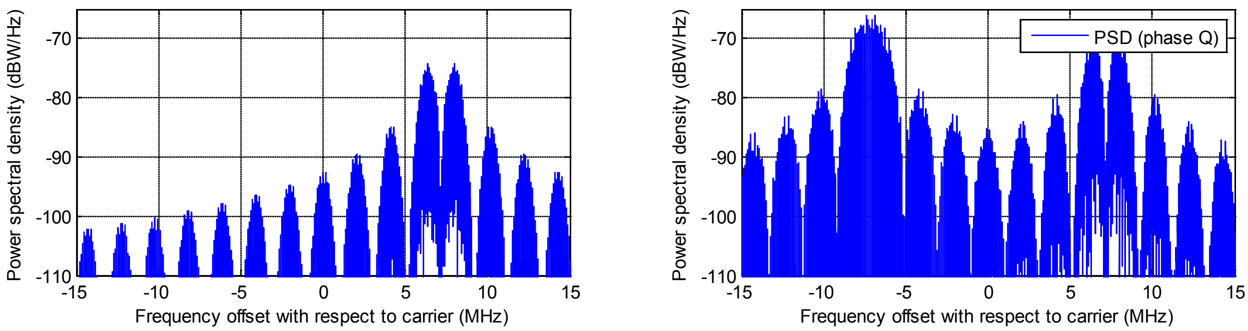
(1) Firstly, the increasing crowded GNSS frequency band is hardly to accommodate additional wideband signals, while among the existing signals of GNSS there still leaves some unoccupied narrow band. It is possible to modulate two narrowband signals at two adjacent spectral gaps, and then combine them into a wideband integral signal by DJMM technique. The designed signal keeps the required spectral separation to the existing signals, while feasible for not only the narrowband receivers with low processing complexity, that treat the signal as two narrowband signals at different frequency separately, but also the wideband receivers to jointly process the two frequency as a wideband composite signal, which will achieve higher RMS bandwidth.

(2) Secondly, the multiple narrowband signals on the two adjacent frequency gaps are allowed to utilize different optimized spreading code waveform, power ratio, data structure and different service carried on the signal, which is a possible solution for the demand of diversified services in the future GNSS.

(3) Thirdly, in the existing multiplexing techniques, the information and power carried on the inter-modulation terms are not well utilized, which is one of the main sources of the multiplexing loss. In fact, however, the constant envelope multiplexed signal can not only be received separately for the composed signals, but also treated as a whole for the receiving and processing. The DJMM takes advantage of the inter-modulation power, thus can reach the joint optimal solution of the ranging accuracy and multiplexing efficiency.

(4) Besides, DJMM can combine the digital baseband part of the signals on the two frequency together and shares the same transmitting chain, which considerably reduces the mass and volume of the satellite payload. Moreover, DJMM technique can efficiently resolve the smooth transition issue in the upgrade process of GNSS systems. For instance, in both of B1 band and B3 band of Beidou systems, the central frequencies of Phase II (regional) signals and Phase III (global) signals are different, in transition period between these two Phases, it is necessary to allow the regional signals and global signals to coexist over a period of time. The DJMM allows the multiple signals on the two frequency share the transmitting devices, and the possible future closure of services on a frequency can be easily achieved by letting the amplitude A_i to be zero for the corresponding component.

To help readers better understand the benefits presented above of DJMM technique, we take the design scenario of Beidou B1 band open service (OS) signals as an example. In Phase II, the spectra of the regional OS B1I signal with the center frequency of 1561.098MHz. In Phase III, out of the consideration for interoperability, the spectra of the global OS B1C signals updated will employ a new modulation with the same center frequency of 1575.42MHz as that of the GPS C/A, GPS L1C and Galileo E1 OS signal. We assume that B1I uses BPSK-R(2) modulation while both pilot channel and data channel of B1C use BOC(1,1) modulation. The power ratio of B1I, B1C pilot channel, and B1C data channel is 4:3:1. By using the proposed technique, we can combine these 3 components into a dual-frequency constant envelope composed signal, and use one transmitter to broadcast it, where the subcarrier frequency is $\omega_{sc}/(2\pi)$=7.161 MHz, and RF carrier frequency is1568.259 MHz. Under the aforementioned assumptions, the spectrum of the multiplexed signal is shown in Fig.1, separated for the in-phase and quadrature-phase.



(a) in-phase components

(b) quadrature component

Figure 1 Spectrum of proposed constant envelope integral signal;

From Fig. 1 we can see, taking the multiplexed signal as a whole, it has a spectrum-split structure and reflects the original designed spectral characteristic of the three components. We can also see that the main lobes of all the three signal components occupy narrow frequency band, requiring less processing complexity. Narrowband receivers only need to set the receiving frequency at 1561.098MHz or 1575.42MHz and reproduce the corresponding local replica to make correlation. Meanwhile, the multiplexed signal as a whole has large RMS bandwidth. For the high-end receivers with stringent requirement on the ranging accuracy and anti-multipath performance, the central frequency can be set at 1568.259 MHz and reproduce the wideband composite replica to make correlation with the received signal.

Figure 2 shows the equivalent RMS bandwidth [7] under the narrowband separate receiving with local replica of BPSK(2) and BOC(1,1) signal, and the dual-frequency joint receiving with the local replica of wideband composite signal.

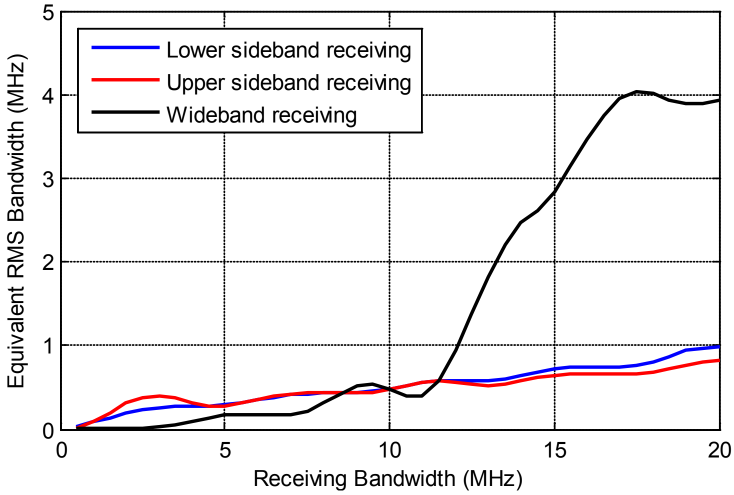


Figure 2 Equivalent RMS bandwidth with different receiving strategies

From Fig.2 we can see, that the equivalent RMS bandwidth under the wideband joint receiving is significantly higher than that under the separate receiving, which means considerable improvement in the ranging accuracy and anti-multipath performance can be achieved for the high-end receivers by using the dual-frequency joint design in multiplexing or modulation. Moreover, when the designed signal is received as a whole, the inter-modulation terms in the multiplexed signal can be well utilized, thereby promoting the upper bound of multiplexing efficiency to reach 100% theoretically.

5. Conclusion

With the upgrade and emerging of future GNSS, it is possible that more and more signals are transmitted and further occupy the L band. DJMM is applicable to combine two narrowband signals at adjacent frequencies into an integral wideband signal. Since the composed narrowband signals can be located in the gaps among the main lobes of existing spectrum, thus reducing the interference to the operating signals, while providing the high-end users with wideband signal and enhanced performance. Therefore, the proposed DJMM can not only achieve outstanding ranging accuracy without significant increasing the RF interference to the existing signals in the same band, but also provide users with diversified and targeted service without noticeably deteriorated the multiplexing efficiency on satellite. It provides a promising technique solution for the next generation GNSS signal design.

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7. References

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