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A Performance Analysis of Multi-GNSS Receiver with Various Intermediate Frequency Plans Using Single RF Front-end

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ABSTRACT

In this study, to design a multi-GNSS receiver using single RF front-end, the receiving performances for various frequency plans were evaluated. For the fair evaluation and comparison of different frequency plans, the same signal needs to be received at the same time. For this purpose, two synchronized RF front-ends were configured using USRP X310, and PC-based software was implemented so that the quality of the digital IF signal received at each front-end could be evaluated. The software consisted of USRP control, signal reception, signal acquisition, signal tracking, and C/N0 estimation function. Using the implemented software and USRP-based hardware, the signal receiving performances for various frequency plans, such as the signal attenuation status, overlapping of different systems, and the use of imaginary or real signal, were evaluated based on the C/N0 value. The results of the receiving performance measurement for the various frequency plans suggested in this study would be useful reference data for the design of a multi-GNSS receiver in the future.

Keywords: multi-GNSS receiver, RF front-end, frequency plan, USRP

1. INTRODUCTION

The Global Navigation Satellite System (GNSS) is a system that can measure a position on the globe, and it provides various measurements such as velocity and time as well as position. The position, velocity, and time information can be used for various services in the private sector and national defense, and thus the demand for GNSS has increased every year (Dovis 2015). The United States, the European Union, China, and Russia have developed and operated GPS, Galileo, Beidou Navigation Satellite System (BDS), and GLONASS, respectively, which can provide services all over the globe. Among these, GPS, BDS, and GLONASS are actively used in Korea because an average of more than six satellite signals can be received in Korea (Park et al. 2016a).

The various GNSS signals operated by each country are focused on the L1 and L2bands. In the case of the L1 band, GPS is operated at 1575.42 MHz, BDS at 1561.098 MHz, and GLONASS at 1602.0 MHz. In each system, multiple access techniques such as CDMA and FDMA are used, and thus Pseudo Random Noise (PRN) code is applied to every signal. It is assumed that different PRNs are theoretically orthogonal to each other and have no influence. However, they actually act as noise, and cause intra-system noise or inter-system noise. Thus, when there are many satellite signals, the noise of each satellite signal increases (Dovis 2015).

On the other hand, the availability increases when many satellite signals are received, and the accuracy and precision increase when the satellites are appropriately distributed. Due to this advantage, multi-GNSS signal receiving techniques have been developed and applied to

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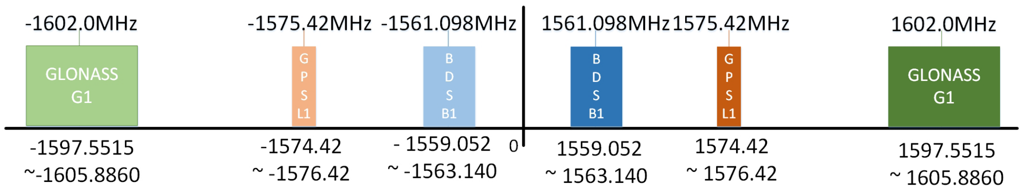

Fig. 1. The spectrum of GNSS signals on L1 band.

commercial GNSS receivers. The M8 receiver of Ublox uses a multi-GNSS receiving technique using dual front-ends, and supports GPS, Galileo, BDS, and GLONASS (Ublox 2015). However, the Ublox receiver has a dual front-end structure where a maximum of two systems can be selected and received (e.g., GPS/BDS or GPS/GLONASS). Also, when multiple front-ends (e.g., dual or triple) are applied, the structure is complicated as a synchronization module for the time and phase synchronization between the front-ends is separately required.

On the other hand, when multi-GNSS signals are received using single front-end that supports a wide band, all the GNSS signals in the L1 band can be received depending on the bandwidth, and separate synchronization between front-ends is not required. In a previous study, we found that the GPS, GLONASS, and BDS signals in the L1 band could be simultaneously received using single front-end based on Universal Software Radio Peripheral (USRP). In the above study, the Local Oscillator (LO) of the USRP mixer was set to 1584 MHz, and down conversion was performed to 8.85 MHz in the case of GPS, 18.0 MHz in the case of GLONASS, and approximately 20 MHz in the case of BDS. As a result, the signals of all the three systems could be received at a sampling rate of 50 Msps, and the signal sensitivity showed a 2 dB difference compared to a commercial receiver (Park et al. 2016a).

In the aforementioned study, the frequency plan was designed so that the three GNSS signals would not be overlapped for the maximum sampling rate that can be used in USRP and PC. If there are performance comparison data for various Intermediate frequency (IF) plans, (e.g., the overlapping of the signals of different systems, disposal of some signals due to bandwidth limitation, and the use of imaginary or real signal), optimum LO frequency can be established considering the calculation performance and usage of the receiver, and the RF front-end of a multi-GNSS receiver can be designed.

In the present study, the multi-GNSS receiving performances of single RF front-end depending on various frequency plans were examined and analyzed through an experiment. For the fair comparison of the receiving performances of different frequency plans, synchronized two-channel front-ends were configured using USRP X310. The two front-ends are synchronized using the same clock source, and the same sampling rate can be selected. Also, different LO can be established, and thus two frequency plans can be compared simultaneously. The signals received based on different frequency plans are transmitted to PC in real time, and receiver signal processing (e.g., signal acquisition, signal tracking, and bit extraction) is performed. In this regard, to measure the GNSS signal receiving performance, the Carrier to Noise Ratio (C/N0) of each satellite signal was estimated. Using this information, experiments were conducted for various frequency plans, and the results were compared and summarized.

The contents of this paper consist of four chapters. In Chapter 2, the GNSS signal and RF front-end of the L1 band, which is the target band of this study, are introduced. In Chapter 3, the implementation of RF front-end using USRP is described. In Chapter 4, the various frequency plans suggested in this study are introduced. Lastly, in Chapter 5, a method for the measurement of receiving sensitivity is introduced, and the receiving sensitivity measured based on each frequency plan was summarized and analyzed.

2. INTRODUCTION TO RF FRONT–END OF GNSS RECEIVER

In the L1 band, the GPS, GLONASS, and BDS signals exist at 1575.42 MHz, 1602 MHz, and 1561.098 MHz, respectively, as shown in Fig. 1. When only the public signals are considered, the bandwidths are about 2 MHz, 8.3 MHz, and 4 MHz, respectively. Also, the signals exist symmetrically in the real region and the imaginary region (Ziemer & Tranter 2006). In the figure, the imaginary signals are expressed in light color, and the real signals are expressed in dark color.

For a GNSS receiver that receives the aforementioned signals, a heterodyne method is used in general (Kaplan & Hegarty 2006). A heterodyne-type receiver performs the down conversion of an RF signal into an IF signal (several MHz), and thus a filter with low complexity can be used for the implementation of the receiver. Fig. 2 shows the RF front-end of a general heterodyne receiver. When an analog RF signal is entered from the antenna, only the target band

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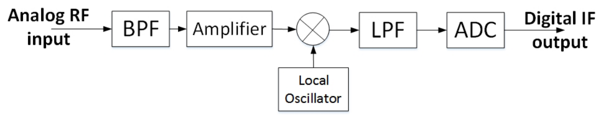

Fig. 2. The spectrum of GNSS signals on L1 band.

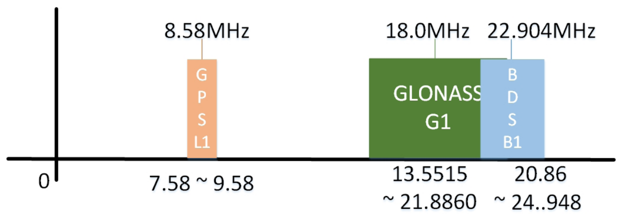

Fig. 3. A spectrum of frequency plan for GPS, GLONASS, BDS L1 band receiver.

is left through a band pass filter. The GNSS receiver passes the L band signal, and this signal is entered to the mixer, where down conversion and up conversion are performed by the frequency of the local oscillator. The high frequency element that has been up-converted is eliminated by the low pass filter, and only the down-converted signal is remained. This signal is an IF signal, and it is converted to a digital signal through Analog to Digital Convertor (ADC). For a general hardware receiver, down conversion could be performed again using a mixer with Phase Locked Loop (PLL) before the conversion through ADC in order to lower it to a baseband. On the other hand, for a software receiver, a digital IF signal is inputted, and the baseband signal is extracted from a general purpose microprocessor.

For RF front-end, the signal of the L1 band can be down-converted in various forms by the frequency of LO. Fig. 3 shows the examples, which are the spectra of the three GNSS systems when an LO frequency of 1584 MHz designed in the previous study is used (Park et al. 2016a). In this case, for GPS and BDS, the imaginary signals are located in the real region, and they have center frequencies of 8.58 MHz and 22.904 MHz, respectively. For GLONASS, the real signal has a center frequency of 18.0 MHz.

If the LO frequency is increased, the GPS signal will get close to the GLONASS signal, and the GLONASS signal will get close to the zero. Also, the BDS signal and the GLONASS signal get farther away from each other. However, when the maximum frequency of the BDS signal exceeds 25 MHz, a higher sampling rate is needed to restore the signal without a loss. On the other hand, when the LO frequency is lower than 1584 MHz, the GLONASS and BDS signals get closer to each other, and are completely overlapped. Instead, the maximum frequency decreases, and thus a lower sampling rate can be used. As mentioned above, the computation burden and receiving performance of a receiver can vary depending on the frequency of LO.

3. IMPLEMENTATION OF RF FRONT–END USING USRP

3.1 Hardware Configuration

To configure an environment that can experiment various frequency plans, USRP was used. In this chapter, the implementation of RF front-end using USRP is described. USRP is reconfigurable RF front-end developed by Ettus, and is a tool for supporting the development of a software receiver (Ettus research 2017). The frequency of LO, the gain of amplifier, and the sampling rate of ADC can be established, and various RF bands can be handled by replacing the D-board. Also, multiple front-ends can be operated by synchronizing a number of USRPs through an external clock source.

In the case of USRP, there are many versions (e.g., N, E, and X) depending on the purpose. Among them, for the X-series model, two D-boards can be installed on one mother board (Ettus research 2017). D-board consists of RF signal input, amplifier, LO, and mixer, which represents one front-end. Also, as one mother board is used, two D-boards operate in a synchronized manner without separate external hardware when internal oscillator or Global Positioning System Disciplined Oscillators (GPSDO) is used. In this regard, GPSDO refers to a clock source that provides OCXO-level precision using the clock information of GPS. Thus, dual RF front-ends can be easily configured using the X-series. In terms of disadvantage, the two front-ends should use the same sampling rate as the same mother board is used.

For the fair comparison of various frequency plans based on the same signal at the same time, more than two synchronized reconfigurable front-ends are needed. Thus, to configure dual RF front-ends in this study, hardware was organized using USRP X310, as shown in Fig. 4. For USRP X310, WBX D-board with a range of 50 Hz ~ 2.2 GHz was used so that the L1 and L2 bands could be received. A GNSS antenna (NovAtel 2013) and 20 dB LNA (GPSNETWORKING 2015a) were used so that the GNSS signal could be received. The GNSS signal amplified through the antenna and LNA is entered to the splitter. The splitter (GPSNETWORKING 2015b) divides one signal into four outputs. Two outputs are entered to the D-board corresponding to front-end 0 and the D-board corresponding to front-end 1, respectively. In this regard, the same signal is entered to the two front-ends, respectively. One of the two remaining splitter signal

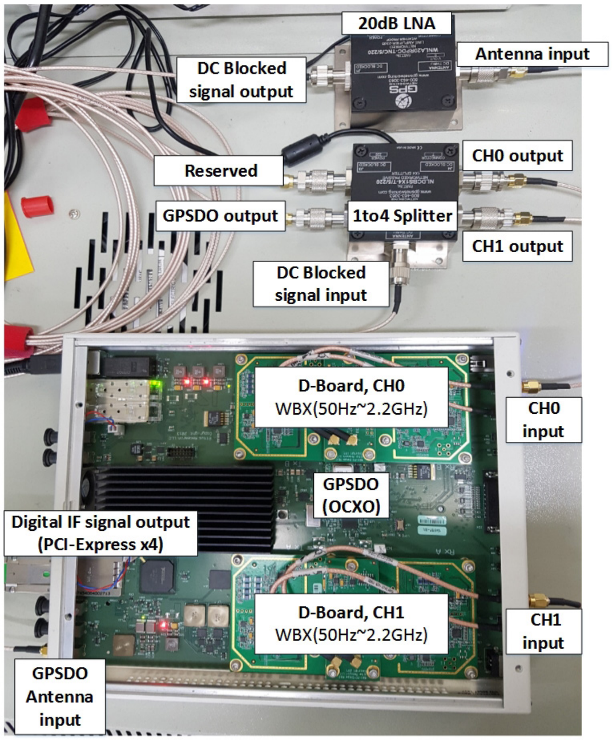

Fig. 4. A hardware configuration of signal RF front-end using USRP X310.

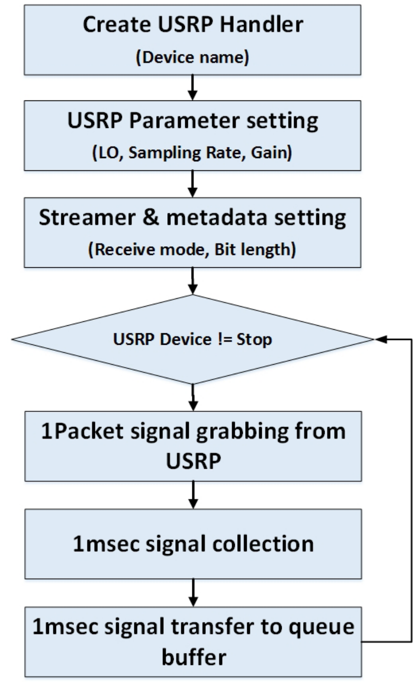

Fig. 5. A flow chart of USRP control software.

outputs is connected to the antenna input of GPSDO. Another output is not used. The IF signals that have been down-converted on the two D-boards are entered to the FPGA of the mother board. In FPGA, they are converted to digital signals through ADC, and are transmitted to PC through the PCI-Express. In PC, this data is received in real time, and the three GNSS IF signals are converted to a baseband by process of signal acquisition and tracking. Then, the signal processing for navigation message extraction and pseudorange estimation is performed.

3.2 Implementation of software

The functions that establish the operating environment of USRP and receive digital IF signals in real time are operated in PC. To control USRP and receive data in PC, Labview, MATLAB, USRP Hardware Driver (UHD), and GNU Radio can be used (Ettus research 2017). Among them, UHD is based on C++ and C, and provides various functions for controlling USRP. In this study, USRP control software was configured using UHD and the flow chart is shown in Fig. 5. First, in “Create USRP Handler”, the USRP device connected to PC is searched, and a handler is created. When a USRP device is found and the frequency/clock source of the mother board are checked, the LO frequency, gain, and sampling rate of each front-end are established in “USRP Parameter setting”. The master clock of the USRP X310 mother board basically operates at 200 MHz, and the sampling rate can be selected (10 Msps, 20 Msps, 25 Msps, 40 Msps, 50 Msps, 66.667 Msps, and 100 Msps) (Park et al. 2016a). For the frequency of LO, a value above 5 MHz can be freely selected, and for the gain, a normalized value can be selected between 0.0 ~ 1.0.

When USRP is properly established based on appropriate parameters, signal data can be received from USRP. The data receiving part can be implemented using the streamer and metadata class of UHD, and the receiving mode and the data size per one sample can be selected. The receiving modes include the mode that repeats until a certain number of samples are received, and the mode that repeats until a separate stop command is applied. In this study, the mode that repeats until a stop command is applied was used. When the setting of USRP is completed, data can be received through PCI-Express. In this regard, the data are transmitted in packets. The size of one packet can vary depending on the hardware performance. The data received in packets are bound by the length of 1 msec, and are stored in a buffer with a queue form.

The digital signal data generated from the two front-ends have a size of about 3.0 Gbit/sec when sampled at 50 Msps and 16 bit. This size is similar to the size of the maximum bandwidth when PCI-Express uses four lanes. When an operation other than signal transfer is performed during data reception, a USRP overflow problem could occur as

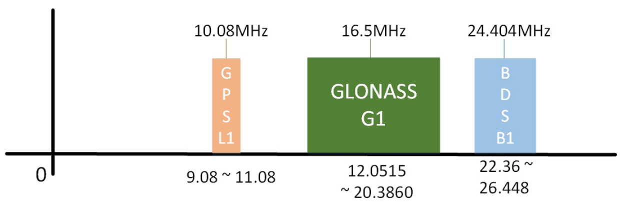

Fig. 6. A spectrum of 1st frequency plan (LO frequency = 1585.5 MHz).

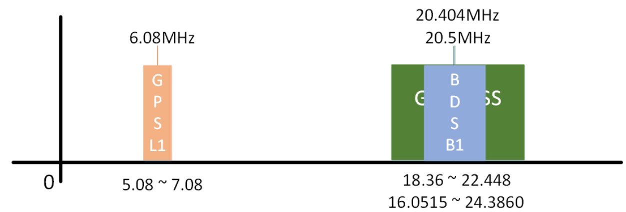

Fig. 7. A spectrum of 2nd frequency plan (LO frequency = 1581.5 MHz).

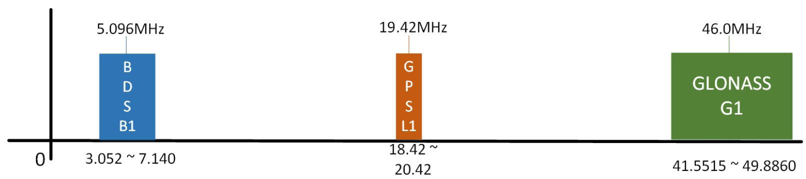

Fig. 8. A spectrum of 3rd frequency plan (LO frequency = 1556 MHz).

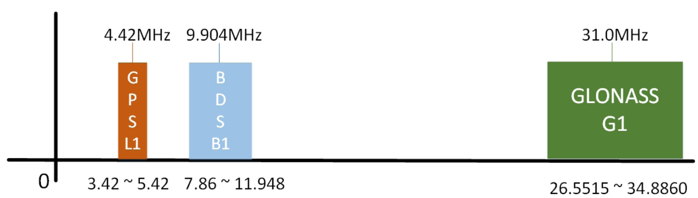

Fig. 9. A spectrum of 4th frequency plan (LO frequency = 1571 MHz).

the data transfer speed decreases due to the limitation of the bandwidth. Thus, the data receiving part of USRP and the signal processing function for the GNSS signal (e.g., signal acquisition, signal tracking, and bit extraction) should be operated using different threads. The software receiver operation based on multi-threads and each signal processing algorithm are described in detail in Park et al. (2016c), and the buffer management algorithm for securing the safety between threads is described in detail in Park et al. (2016b).

4. VARIOUS FREQUENCY PLANS

In Chapter 4, various frequency plans designed considering diverse conditions are introduced. In Plan 1, the LO frequency was set to 1585.5 MHz, and the spectra of the three GNSS signals are shown in Fig. 6. In Plan1, the BDS signal is lost by a bandwidth of about 1.5 MHz, but the three systems are not overlapped. The used LO frequency is higher than the RF center frequencies of GPS and BDS, and thus the two signals become imaginary signals. In Plan 2, the LO frequency was set to 1581.5 MHz so that the BDS and GLONASS signals would be overlapped, unlike Plan 1. Although the GLONASS and BDS signals overlap, there is no signal that is limited when a sampling rate of 50 Msps is used, and thus the three signals can be received without a loss. Fig. 7 shows the spectra of the three signals.

When Plans 1 and 2 are compared, the performances of the case where part of the signal is lost and the case where different signals are overlapped can be compared. The result of the comparison can be reference data for distinguishing the optimum design method when signals are lost or overlapped at a fixed sampling rate.

In Plan 3, the LO frequency was set to 1556 MHz. By using the LO frequency that is lower than that of BDS, it was designed so that the imaginary signal would not be located in the real region. In Plan 4, it was designed so that the imaginary BDS signal would be located in the real region, unlike Plan 3. The LO frequency was set to 1571 MHz. The spectra of Plans 3 and 4 are shown in Figs. 8 and 9, respectively.

The purpose of the comparison between Plans 3 and 4 is to examine the difference in the receiving performances of the imaginary and real signals. In the case of sampling at 50 Msps, the GLONASS signal is mostly lost, and thus is ignored. For GPS, two real signals are used. On the other hand, for BDS, the real signal is used in Plan 3, but the imaginary signal is used in Plan 4. By analyzing the C/N0 and number of visible satellites for the BDS signals received based on the two plans, the difference between the imaginary and real signals can be examined.

Table 1. Parameters of software receiver to measure C/N0.

Parameter	value	Parameter	value
Integration time of Acquisition [msec]	5	Integration time of tracking [msec]	1
Doppler range/bin [Hz]	5000/200	PLL noise band width [Hz]	30
Acquisition threshold	1^{st} peak/2^{nd} peak > 5.0	DLL noise band width [Hz]	2
Max. *k* of NWPR	50	Chip spacing [Chip]	0.5
Max. *m* of NWPR	20	Number of correlator (Complex correlator)	3

Table 2. Performance comparison of front-end 0 and 1 (LO = 1584 MHz, Sampling rate = 50 Msps).

	GPS	GLONASS	BDS	Total
Difference of C/N0 (front-end 0 – front-end 1) [dB-Hz]	0.005	0.213	0.148	0.122
Number of visible satellites (front-end 0/ front-end 1)	9/9	8/8	7/7	24/24

Table 3. Performance comparison of plan 1 and 2 (Sampling rate = 50 Msps).

	GPS	GLONASS	BDS
Difference of C/N0 (plan 1 – plan 2) [dB-Hz]	0.011	1.364	-0.985
Number of visible satellites (plan 1/ plan 2)	9/9	6/6	5/6

5. PERFORAMNCE ANALYSIS WITH VARIOUS IF PLANS

5.1 Introduction to Evaluation Method

To examine and compare the receiving performances of the front-ends designed based on different frequency plans, the C/N0 of satellite signals and the number of visible satellites were measured using the algorithm of a software receiver. The digital IF signals of the two front-ends inputted from USRP are entered to PC, and are stored in the memory. By acquiring this signal, signal acquisition is performed first. The purpose of signal acquisition is to search the satellite signal that exists in the digital IF signal, and correlation calculation is performed for all the possible Doppler and code phase. In this study, the signal acquisition was implemented using the parallel code space search method that can reduce the computational load by searching the code phase in the frequency domain.

The initial Doppler, PRN No., and code phase of a satellite obtained through signal acquisition can be used for tracking the satellite signal. For signal tracking, the changing Doppler and code phase are tracked based on the feedback loop that consists of PLL and DLL. In this regard, the in-phase correlation value can be converted to data bit. Also, the C/N0 of the signal can be estimated using the in-phase correlation value and the quadrature-phase correlation value. In this study, the narrow wide power ratio (NWPR) technique was used as the method for estimating C/N0 (Falletti et al. 2010). Table 1 summarizes the detailed signal processing algorithm and parameter information.

In the experiment, the frequency plans for comparison were applied to front-end 0 and front-end 1, respectively, and signals were received for about 10 minutes. While receiving the signals, the C/N0 and the number of satellites were recorded every second. In this regard, the satellite signal without continuous sig nal tracking was not considered, and only the C/N0 of the satellite signal that had been tracked without code and carrier locking failure for 10 minutes was compared.

5.2 Experiments and Analysis

In the first experiment, to examine the performance difference of each front-end, the same frequency plan was applied, and the C/N0 and the number of visible satellites were compared. Table 2 summarizes the results of the comparison. The C/N0 difference was obtained by the difference in the C/N0 of the front-ends 0 and 1. As the value was a positive number, the C/N0 of front-end 0 was 0.2 dB higher on average than that of front-end 1. Based on the above result, an error of less than 0.2 dB was regarded as the difference induced by the reception of signals at different front-ends, and this was taken into account during the analysis of the results.

The results in Table 3 compare Plans 1 and 2 introduced in Chapter 4. Plan 1 was applied to front-end 0, and Plan 2 was applied to front-end 1. For Plan 1 and Plan 2, GPS showed no change except for the 4 MHz difference in the center frequency. As expected, the C/N0 estimation results for GPS were similar in the two plans. On the other hand, in Plan 2 that was designed so that GLONASS and BDS would overlap, the receiving performance of GLONASS deteriorated by 1.3 dB on average compared to that in Plan 1. In the case of BDS, the C/N0 was about 1 dB higher in Plan 2 where it overlaps with GLONASS than in Plan 1 where part of the signal is limited due to bandwidth limitation. The 1 dB higher result despite the overlapping of the signal with GLONASS indicates that a loss of more than 2 dB occurred due to the bandwidth

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Table 4. C/N0 comparision of plan 3 and 4 (Sampling rate = 50Msps)

PRN No. 1 ~ 9	1	3	4
Difference of C/N0 (plan3 - plan4)[dB-Hz]	-0.029	-0.040	-0.016
PRN No. 10 ~ 19	**10**	**12**	**17**
Difference of C/N0 (plan3 - plan4)[dB-Hz]	-0.025	-0.062	-0.038

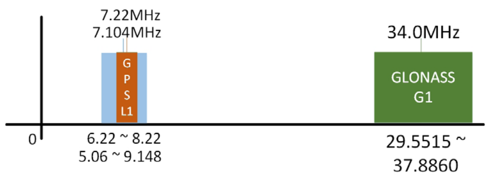

Fig. 10. A spectrum of 5th frequency plan (LO frequency = 1568.2 MHz).

limitation. Also, there was one less BDS satellite compared to that in Plan 2.

The results in Table 4 compare Plan 3 and Plan 4. Plan 3 was applied to front-end 0, and Plan 4 was applied to front-end 1. The purpose of this experiment was to compare the performances of the real and imaginary signals for BDS. Table 4 summarizes the results of the C/N0 comparison for the BDS satellites. The difference between the real and imaginary signals was less than 0.04 dB, indicating that there was almost no error. Based on the experiment, the following two results could be obtained.

1) The overlapping of signals with another system showed better performance than the loss of signals due to bandwidth limitation.
2) There is no performance difference between the real and imaginary signals.

5.3 An Application for Software Receiver

Based on the two conclusions obtained from the experiment, a frequency plan shown in Fig. 10 can be designed. When the LO frequency is set to 1568 MHz, the real signal of GPS and the imaginary signal of BDS overlap as shown in Fig. 10. When GLONASS is ignored, a sampling rate of 19 Msps is needed to receive the BDS and GPS signals. On the other hand, in Plan 4 which is similar to the aforementioned plan, a minimum of 22 Msps sampling rate is needed to receive the GPS and BDS signals. When the sampling rate available in USRP is used, 20 Msps and 25 Msps need to be used, respectively. Although there could be some intra-system noise due to the overlapping of the bands of the different systems, a 5 Msps lower sampling rate can be selected. As the sampling rate is lowered, the bandwidth of the interface necessary for digital signal transmission decreases along with the number of correlation calculations. In particular, for a real-time software receiver that is sensitive to computational load, the hardware cost and computation burden can be reduced. Therefore, in the case of a software receiver, a method using a 1569 MHz LO frequency could be a more efficient frequency plan.

Table 5. C/N0 comparison of plan 5 and 4 (Sampling rate = 20 Msps).

	GPS	BDS
Difference of C/N0 (plan 5 – plan 4) [dB-Hz]	-0.0668	2.929
Number of visible satellites (plan 5/ plan 4)	9/9	7/6

The effect can be examined based on the estimation of C/N0 using a 20 Msps sampling rate for the signal in Plan 4 and the signal in Plan 5 suggested in Section 5.3. Table 5 compares the results of the reception for Plan 5 and Plan 4. In the case of GPS, the effect of intra-system noise due to the overlapping of the band was less than 0.1 dB. For BDS, part of the signal was lost as a 20 Msps sampling rate was used for Plan 4; and due to this problem, Plan 5 had a 2.9 dB higher C/N0 value than Plan 4. Also, one more satellite signal was received for Plan 5. Based on the results of the experiment in this study, a frequency plan that is more appropriate for a software receiver could be designed.

6. CONCLUSIONS

In this study, the receiving performances for various frequency plans that can receive multi-GNSS signals using single RF front-end were measured and evaluated through an experiment. For the fair evaluation of two frequency plans, two synchronized front-ends were configured using USRP X310. To evaluate the quality of the digital IF signal received at each front-end, the USRP control, signal reception, signal acquisition, signal tracking, and C/N0 estimation function were implemented based on software. Using the implemented software and USRP-based hardware, the signal receiving performances for various frequency plans were evaluated based on the C/N0 value.

As a result, it was found that the overlapping of signals with another system showed better performance than the loss of signals due to bandwidth limitation. Based on this, various frequency plans that can receive the GPS/GLONASS/BDS signals and a frequency plan that is appropriate for a software receiver that can efficiently receive the GPS/BDS signals using a low sampling rate were examined. The results of the experiment for the various frequency plans suggested in this study would be useful reference data for the development of a receiver that can receive multi-GNSS signals using single front-end in the future.

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