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GNSS Signal Design Trade-off Between Data Bit Duration and Spreading Code Period for High Sensitivity in Signal Detection

Kahee Han, Jong-Hoon Won†

World Class Smart Lab of AutoNavLab., Department of Electrical Engineering, Inha University, Incheon 22212, Korea

ABSTRACT

GNSS modernization and development is in progress throughout the globe, and it is focused on the addition of a new navigation signal. Accordingly, for the next-generation GNSS signals that have been developed or are under development, various combinations that are different from the existing GNSS signal structures can be introduced. In this regard, to design an advanced signal, it is essential to clearly understand the effects of the signal structure and design variables. In the present study, the effects of the GNSS spreading code period and GNSS data bit duration (i.e., signal design variables) on the signal processing performance were analyzed when the data bit transition was considered, based on selected GNSS signal design scenarios. In addition, a method of utilizing the obtained result for the design of a new GNSS signal was investigated.

Keywords: correlation, modulation, PRN code, navigation bit

1. INTRODUCTION

Recently, the Global Navigation Satellite System (GNSS) has entered a changing phase throughout the globe. Modernization is in progress for the existing systems, such as the Global Positioning System (GPS) from the United States and the GLObal Navigation Satellite System (GLONASS) from Russia, and new GNSSs have been developed, such as Beidou from China and Galileo from Europe. According to Van Dierendonck (2014), it is notable that these modernization plans are focused on the implementation of new satellite signal design.

In other words, as in the United States where the addition of a new navigation signal is the major element of the GPS modernization plan (The National Coordination Office 2016), the design of a new signal is an important procedure for the modernization of the existing system and the development of a new system. In particular, the spreading code, which is one of the components of a GNSS signal, needs to be designed so that identifiability and orthogonality can be satisfied. Such property of the spreading code is called correlation property, and it can be expressed by auto-correlation and cross-correlation functions. In the acquisition and tracking process, the correlation refines the phase of the receiver code replica so that it can match the incoming signal. The trend of the value can be used as a major index for measuring the acquisition and tracking performance of the receiver. That is, the correlator output used for the signal processing in the receiver is obtained through the correlation between the receiver code replica and the data component or pilot component of the incoming signal, and the property can be used as the Figure of Merit (FoM) for the system depending on the signal design. Based on the use of auto-correlation and cross-correlation functions, Soualle et al. (2005) suggested selection criteria of the spreading code for Galileo. On the other hand, the selection of the data bit duration and carrier frequency, which are related with the remaining components of a GNSS signal, directly affects the process of modulation from the baseband to the passband GNSS signal for transmission/reception. In particular, the data transfer rate and the presence of pilot component are

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†**Corresponding Author**
E-mail: jh.won@inha.ac.kr
Tel: +82-32-860-7406 Fax: +82-32-863-5822

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closely related with the processing of an incoming signal in the receiver, as mentioned in Won et al. (2012) and Hein et al. (2006).

On the other hand, as for the pilot component, additional modulation by secondary code is applied in many cases, and thus it could induce an effect similar to the occurrence of data bit transition. In this regard, Han & Won (2016) examined the effect of data bit transition in relation to correlation, using a correlation percentile function.

The present study aimed to examine the property of desirable GNSS spreading code period and GNSS data bit duration combination during signal design, by clearly explaining the relationship between GNSS code correlation and GNSS data bit, and by analyzing the effect of data bit transition on the signal processing performance based on various signal design scenarios.

2. RELATIONSHIP BETWEEN GNSS CODE CORRELATION AND GNSS DATA BIT

Most newly designed signals include the pilot component to increase the acquisition performance. In the case of next-generation signals excluding GPS L1C (e.g., GPS L5, Galileo E1 OS, Galileo E5a, and Galileo E5b), the same power is distributed to the data component and the pilot component. Accordingly, for the signals having this structure, a technique that uses both components in the acquisition process is preferred in order to increase the acquisition performance (Foucras et al. 2014). In addition, when the acquisition is performed using only the pilot component, the secondary code of the pilot component has an effect similar to that of the data sequence during the acquisition stage. That is, despite the recent GNSS signal design trend where the pilot component is added, the effect of the combination between spreading code and data sequence on the signal needs to be clearly examined in the signal design process for the improvement of the acquisition performance.

2.1 Correlation Property

A receiving antenna receives the carrier that has been modulated using the code generated by the combination of spreading code and data sequence. The received carrier is down-converted to an intermediate frequency (IF) signal through the radio frequency front-end, and this IF signal (receiving code) is used for detecting visible GNSS satellites and extracting navigation data based on the correlation process in the baseband processing procedure. Thus, the spreading code of a GNSS signal should be designed to have outstanding auto-correlation and cross-correlation properties, and the receiving code where spreading code and data sequence have been combined should also be designed to maintain good auto-correlation and cross-correlation properties. The auto-correlation property indicates that when there is a code delay between two sequences, there is almost no correlation though they are the same sequences. It is also called identifiability because the presence of delay can be judged even between the same sequences. The cross-correlation property is also called orthogonality, and indicates that different sequences are orthogonal to each other. For the cross-correlation of an ideal spreading code with an infinite length, the value converges to 0 without the detection of a peak. That is, a code design has good correlation property when a clear peak is detected at the point with a code delay of 0 in the case of auto-correlation and the values at the other points are identical to those of cross-correlation.

However, when the receiving code is a spreading code in a reversed condition by the value of the data bit, expected correlation property may not be observed although the received signal and the code replica match each other having the same spreading code within the coherent integration time. The lack of correlation property would prevent effective signal acquisition. Therefore, during signal design, the results of even correlation and odd correlation, which are two types of correlations considering data bit transition within the correlation time interval, need to be analyzed in terms of the receiver signal processing.

2.2 Even Correlation and Odd Correlation

Even correlation refers to the case in which there is no change in the data bit within the integration time as shown in Fig. 1a, and the auto-correlation and cross-correlation that are generally mentioned in literature assume the even case. When different periodic binary sequences a and b with a length of N have the components of a_i and b_i, respectively, the correlations considering only the sequence (code) at a specific time can be expressed by Eqs. (1) and (2) (Rushanan 2007).

$$\text{auto}(a;\tau) = \sum_{i=0}^{N-1} a_i a_{i+\tau} \tag{1}$$

$$\text{cross}(a,b;\tau) = \sum_{i=0}^{N-1} a_i b_{i+\tau} \tag{2}$$

where τ is the delay, and has a value between 0 and N-1. A correlation function expresses the similarity between signals

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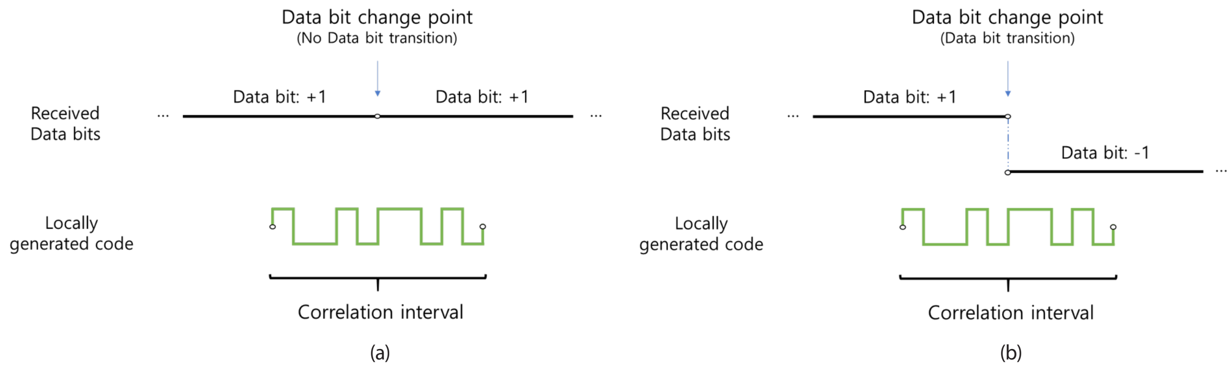

Fig. 1. Even case and odd case.

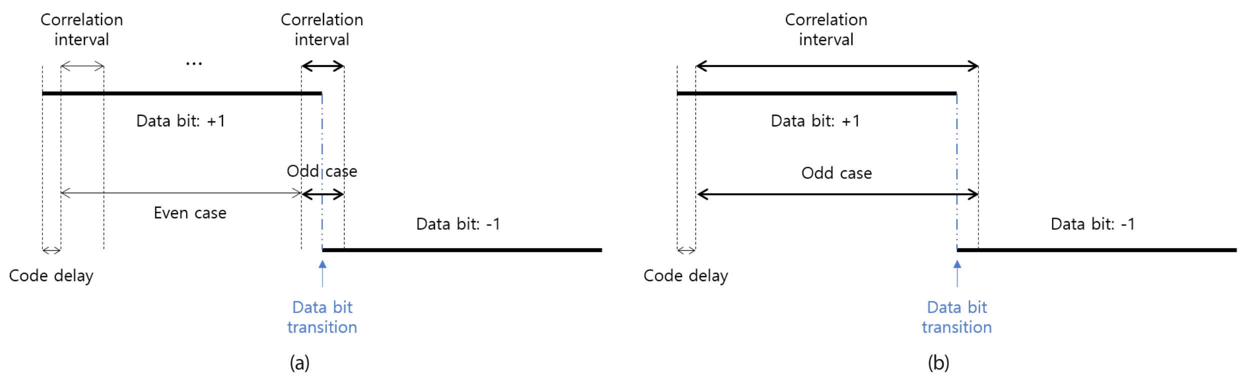

Fig. 2. Even and odd case in GPS L1 C/A and Galileo E1 OS.

considering the delay (τ) of the signal, and it is calculated with respect to τ.

Odd correlation refers to the case in which data bit transition occurs within the integration time as shown in Fig. 1b. Thus, unlike the even case, the reversal of the sequence within the integration time needs to be considered in the equation to obtain a proper correlation value, and it can be expressed by Eqs. (3) and (4).

$$\mathrm{Oddauto}(a;\tau) = \sum_{i=0}^{N-\tau-1} a_i a_{i+\tau} - \sum_{i=N-\tau}^{N-1} a_i a_{i+\tau} \tag{3}$$

$$\mathrm{Oddcross}(a,b;\tau) = \sum_{i=0}^{N-\tau-1} a_i b_{i+\tau} - \sum_{i=N-\tau}^{N-1} a_i b_{i+\tau} \tag{4}$$

However, in practice, the spreading code used for GNSS is mostly designed assuming the even case, rather than the odd case (Rushanan 2007). In the case of the GPS L1 C/A code shown in Fig. 2, 20 spreading code periods exist per 1 data bit (i.e., 20 ms data bit duration, 1 ms code period), and thus it is assumed that the odd case within the same data bit is easily filtered out in the signal acquisition stage. However, when 1 spreading code period exists per 1 data bit as in the Galileo E1 OS code (i.e., 4 ms data bit duration, 4 ms code period), the effect of the odd case needs to be sufficiently considered in the signal design stage. Furthermore, in terms of the performance, the advantages and disadvantages of the signal design need to be numerically analyzed for the case in which multiple spreading code periods exist per 1 data bit as in GPS L1 C/A and the case in which only 1 spreading code period exists per 1 data bit as in Galileo E1 OS.

On the other hand, for the GPS L1 C/A code, the effect of data bit transition can be avoided by limiting the coherent integration time to 1 ms and by additionally performing non-coherent integration (Van Diggelen 2009), and this was demonstrated through the simulation by Foucras et al. (2014). However, there are cases in which a long coherent integration time is required, such as the processing of a weak signal for high sensitivity. Fig. 3 shows the results of even correlation and odd correlation when the GPS L1 C/A code has a coherent integration time of 2 ms. Fig. 3a shows the even correlation, and Figs. 3b and c show the examples of odd correlations where data bit transition has occurred at the 1/4 point (0.5 ms) and the middle point (1 ms) of the coherent integration time, respectively. For the even correlation, a correlation peak was detected; while for the odd correlation, a correlation peak was not detected. In particular, in the case of the odd correlation, the receiving code within the coherent integration time was no longer periodic due to the data bit

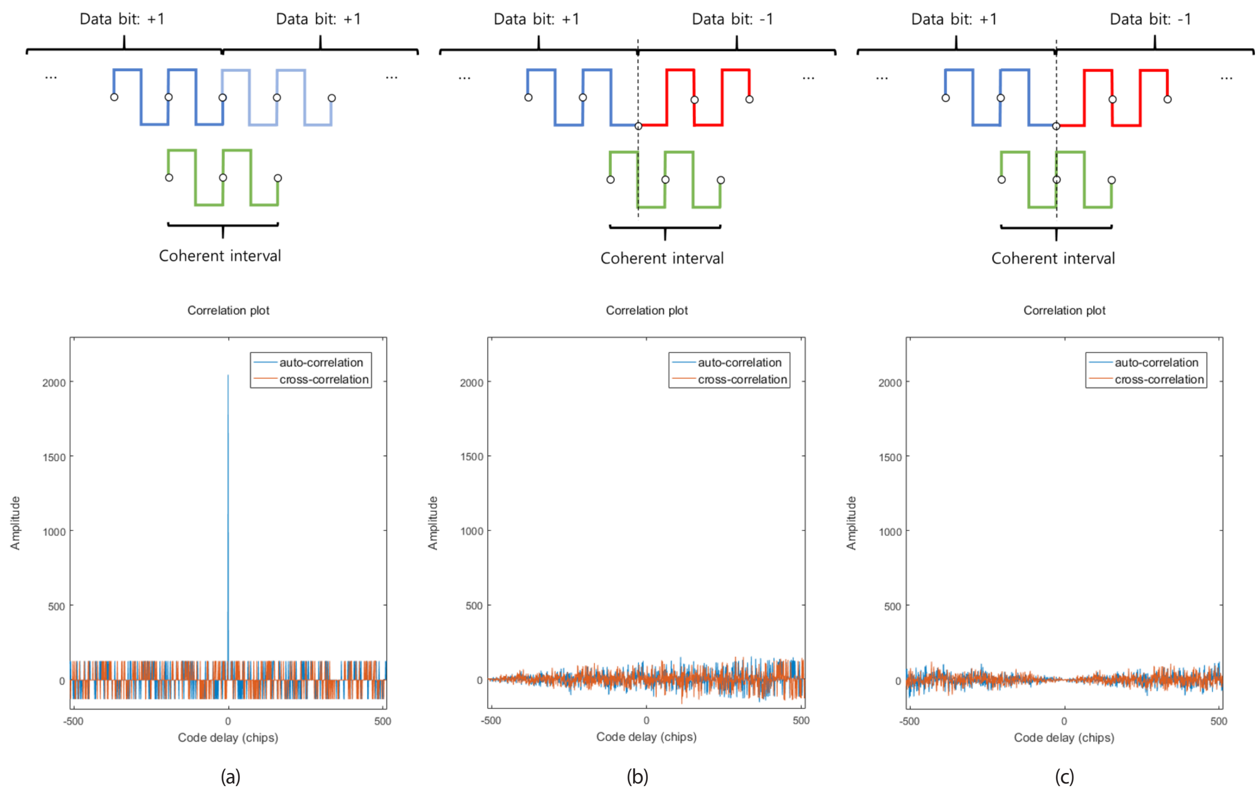

Fig. 3. Even and odd correlation plots. (a) is an even correlation, (b) and (c) are odd correlation, and each data bit transition occurs at 1/4 (0.5 ms) and 1/2 (1 ms) point of the coherent interval (2 ms).

transition, and thus the cross-correlation value was very irregular unlike the even correlation.

3. EFFECT OF DATA BIT TRANSITION ON THE SIGNAL PROCESSING PERFORMANCE

To examine the effect of the presence of data bit transition on the signal processing performance, two analyses were conducted. The correlation properties of the signal for the even case and the odd case were compared and analyzed using the correlation percentile; and by selecting the scenarios that have various combinations of GNSS spreading code period and GNSS data bit duration, the signal detection probability for each scenario was analyzed considering the data bit transition.

3.1 Analysis of the Correlation Property Using the Correlation Percentile

A correlation plot can visually express the correlation property of a signal, but it is not appropriate for the numerical expression for the purpose of analysis. As an alternative, the degree of correlation property can be expressed using correlation percentile. The correlation percentile is the inverse function of the cumulative distribution function that uses the correlation value corresponding to the code delay within the integration time as the variable. That is, the correlation percentile function returns the value corresponding to the percentile p among the correlation values within the integration time.

$$F^{-1}(p) = \inf\{ x \in \mathbb{R} : F(x) \geq p\} \quad (5)$$

where F is the cumulative distribution function that uses the correlation value as the variable, x is the correlation value, p is the percentile, and F^{-1} is the correlation percentile function.

Fig. 4 shows the result in Fig. 3 with respect to the relative frequency and cumulative frequency of the correlation value. In the abscissa, the correlation value is expressed as dB based on 2046 chips that correspond to the length of the Gold code within the coherent integration time. In the case of the even correlation shown in Fig. 4a, a very small correlation value had high relative frequency, and a correlation peak corresponding to singularity was detected for the auto-correlation. This indicates good correlation property where the signal satisfies identifiability and

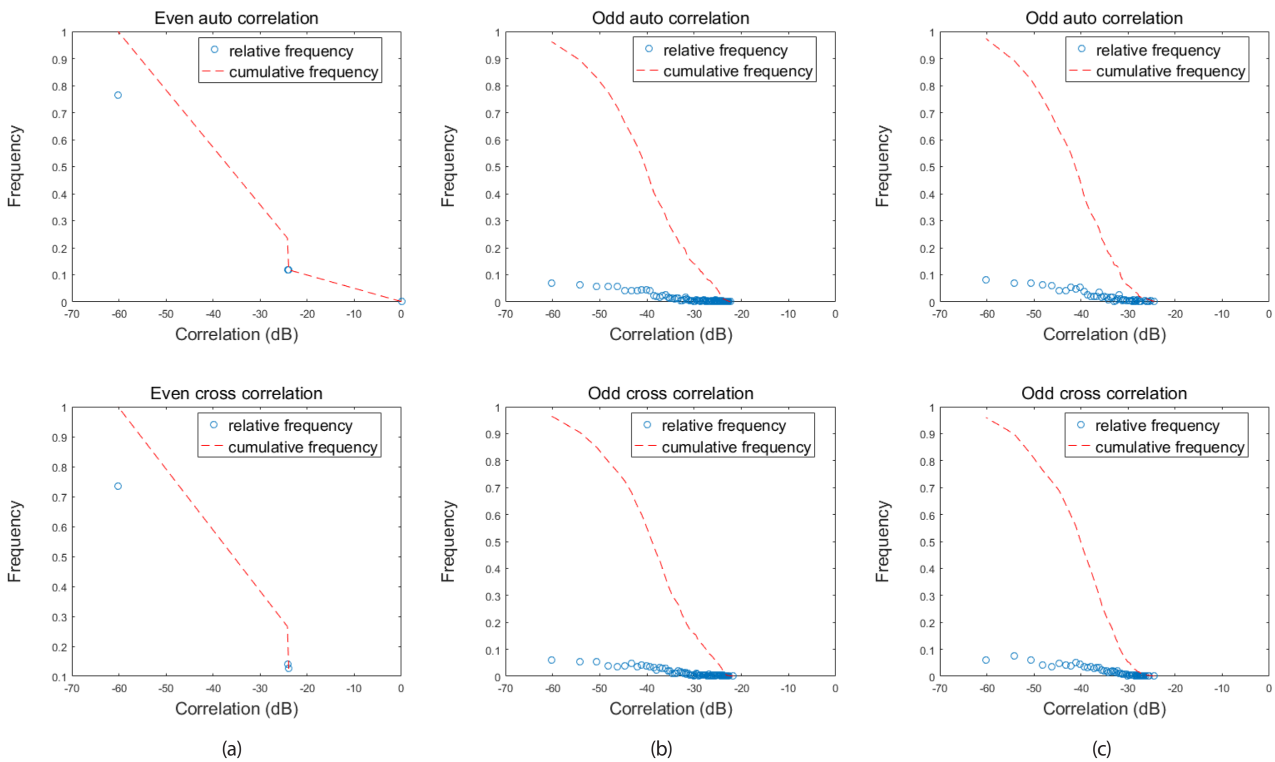

Fig. 4. Correlation percentile plots of Gold code. (a) is an even correlation, (b) and (c) are odd correlation, and each data bit transition occurs at 1/4 (0.5 ms) and 1/2 (1 ms) point of the coherent interval (2 ms).

orthogonality. Figs. 4b and c show the odd correlations when data bit transition is located at the 1/4 point and the middle point of the integration time, respectively. In this case, distinct singularity was not detected, and most correlation values were larger than the correlation value that corresponds to the sidelobe of the even correlation. The effects of the data bit transition examined through the comparison in Fig. 4 are as follows.

- For the auto-correlation, when the data bit transition occurred at the 1/4 point of the integration time (Fig. 4b), a rather high correlation value was obtained compared to when it occurred at the middle point (Fig. 4c). However, for both cases, it is difficult to detect the correlation peak as singularity unlike the even correlation shown in Fig. 4a. Thus, the auto-correlation property of the spreading code was weakened by the data bit transition.
- In the case of the cross-correlation, a low correlation value was obtained both when data bit transition occurred and when it did not occur. However, a rather high correlation value was obtained when the data bit transition occurred at the 1/4 point of the integration time. A large correlation value indicates weak cross-correlation property. Thus, for the odd correlation, the cross-correlation property was weakened depending on the data bit transition occurrence point.

Table 1. Correlation sidelobe for each percentile for PRN1 and PRN2 code.

Percentiles (%)	EAC [dB]	ECC [dB]	OAC		OCC	
			at quarter, 0.5 ms [dB]	at middle, 1 ms [dB]	at quarter, 0.5 ms [dB]	at middle, 1 ms [dB]
99	-23.9	-23.9	-23.9	-26.0	-23.5	-27.1
99.9	-23.9	-23.9	-22.6	-24.5	-22.7	-25.5
99.99	0	-23.9	-22.4	-24.5	-21.7	-24.5

EAC: Even auto correlation, EAC: Even auto correlation, ECC: Even cross correlation, OAC: Odd auto correlation, OCC: Odd cross correlation

That is, the results of the even and odd correlations shown in Fig. 4 indicated that the correlation property varied depending on the presence and occurrence point of the data bit transition despite the use of the same code.

Table 1 summarizes the results shown in Fig. 4. The odd correlation generally had a large cross-correlation value than the even correlation, at the same percentile. For the Gold code, the correlation value corresponding to the percentile of below 99.9% is the case in which the outlier corresponding to the correlation peak has been excluded. Thus, through the values summarized in Table 1, the characteristics of the sidelobe size for the correlation function of the signal can be examined depending on the presence and occurrence point of the data bit transition. According to Soualle et al. (2005), the deviation from the correlation property of an ideal

Table 2. Simulation scenarios.

Scenario No.	Code length [chips] T_c [ms]	Data bit T_d [ms]	Nb of code periods (T_d / T_c)	Coherent integration time (T_{coh}) [ms]	Nb of noncoherent summation (K)	dwell time KT_{coh} [ms]	Remarks
1	1023 T_c = 1	10	10	10	2	20	
2	2046 T_c = 2	10	5	10	2	20	
3	5115 T_c = 5	10	2	10	2	20	
4	10230 T_c = 10	10	1	10	2	20	GPS L1C
5	20460 T_c = 20	20	1	20	5	20	
6	4092 T_c = 4	4	1	4	1	20	Galileo E1 OS

spreading code is proportional to the degree of the effect on the receiver performance. Therefore, it is expected that the adverse effect on the signal processing performance of the receiver would be larger for the odd correlation where the correlation peak was not detected or the difference between the correlation peak and the sidelobe was very small.

3.2 Scenario Selection

To examine the effect of data bit transition depending on the combination of GNSS spreading code period and GNSS data bit duration, the signal detection probability was analyzed for each scenario. Table 2 summarizes each signal design scenario selected for the analysis. In the selected scenarios, the same dwell time was used for the fair comparison.

The spreading codes of Galileo E1 OS and GPS L1C, which correspond to next-generation signals, have a code period identical to that of the data bit duration, unlike the existing GPS L1 C/A code. On the other hand, in the case of GPS L5, the code rate of the spreading code is 10 times higher than that of GPS L1 C/A, but the code period is identical (1 ms), and thus 10 code periods (epoch) exist in 1 data bit duration. As each signal has different ratios of GNSS spreading code period to data bit duration, the effect of the ratio of spreading code period to data bit duration on the signal performance needs to be analyzed in relation to GNSS signal design. Therefore, Scenarios 1 – 4 were selected so that the effect of the ratio of code period to data bit duration could be examined by using the same coherent integration time and the number of non-coherent summation (K). Scenarios 5 and 6 were selected so that the effect of the same GNSS spreading code period, GNSS data bit duration, and coherent integration time could be examined, along with Scenario 4.

3.3 Analysis of the Signal Detection Probability for Each Scenario

The analysis of the signal detection probability was conducted using Monte-Carlo simulation. The FFT-based parallel time search method (so called FFT search) has the advantage of fast search speed; but when the received signal within the integration time is non-periodic due to data bit transition, the obtained result is different from that of the serial search method (Johansson et al. 1998). In the present study, the effect of data bit transition on the signal processing performance was analyzed by comparting the signal detection probability for each scenario when the parallel time search method was used in the acquisition process.

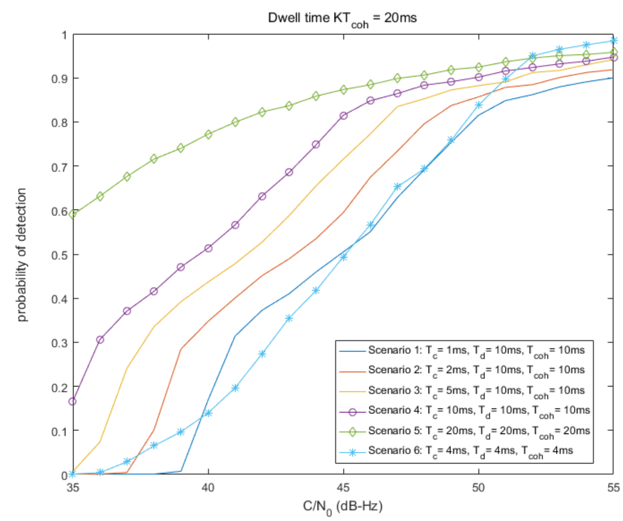

Fig. 5. Detection probability curve of each signal design scenarios.

Fig. 5 shows the signal detection probability curve for each scenario. For the ease of simulation, different threshold values were used for each scenario as follows. According to Misra & Enge (2011), the standard deviation of the cross-correlation value of a random code is inversely proportional to the square root of the code length. Thus, for each scenario, the threshold was established through dividing the value corresponding to the auto-correlation peak when C/N_0 was 55 dB-Hz, by the square root of the selected code length. When the threshold is established as mentioned above, a high threshold value is obtained, and thus false alarm barely occurs. In an environment with high

C/N_0, all the scenarios showed good detection probability; but each scenario showed different results as the C/N_0 decreased. The comparison of Scenarios 1–4 indicated that the signal detection probability was improved as the GNSS spreading code period increased when the same GNSS data bit duration and coherent integration time were used. In addition, the comparison of Scenarios 4–6 indicated that when the GNSS spreading code period, data bit duration, and coherent integration time were identical, more outstanding signal detection probability was obtained as the coherent integration time increased.

However, during the design of a signal, other signal performances need to be considered in addition to the detection probability. According to Won et al. (2012), as the data bit duration decreases (i.e., as the data rate increases), the Time to First Fix (TTFF) performance is improved, but the tracking loop stability or bit error rate (i.e., the data recovery performance) is attenuated by the coherent integration time that is limited by the data bit duration.

Therefore, in the case of the signal scenario having long GNSS code period and data bit duration recommended by the simulation result, the detection probability and the tracking/data recovery performances were improved, but the TTFF performance was not improved. On the other hand, as for Scenario 6 with a data bit duration of 4 ms, when the coherent integration time was designed to be identical to the data bit duration for the sensitivity improvement, the TTFF performance could be improved compared to those of the other scenarios having a relatively long data bit duration, and the detection probability was similar to those of the other scenarios when the C/N_0 was high.

The goal of a GNSS receiver is to obtain accurate ranging information as well as to demodulate the navigation data bit based on the received GNSS signal (Won et al. 2012). Therefore, during the design of a GNSS signal, various figures of merit for navigation (e.g., TTFF and data recovery) and the trade-off between the figures of merit should be analyzed in addition to the signal detection probability analyzed in the present study so that the GNSS receiver can efficiently achieve the goal.

4. CONCLUSION

In this study, the effect of data bit transition on the signal processing performance was examined through the analysis of correlation property and signal detection probability. An actual GNSS transmission/reception signal consists of the codes where spreading code and data sequence have been combined, and thus, data bit transition needs to be considered when obtaining the correlation property in the performance analysis, which is the FoM for the signal design. In order to design a new signal with good correlation property, it is desirable to select the spreading code optimized for both even correlation and odd correlation, or to make the combination of GNSS spreading code period and GNSS data bit duration that minimizes the effect of data bit transition. In particular, the results of the simulation in Section 3.3 indicated that the effect of data bit transition became larger as the C/N0 decreased. On the other hand, when it is assumed that the spreading code has the same code rate, the length of the GNSS spreading code increases as the period of the GNSS spreading code increases. Therefore, the long GNSS spreading code requires a high-performance receiver during the processing of the signal. Accordingly, for the design of a GNSS signal, appropriate combination of GNSS code period and GNSS data bit duration needs to be selected depending on the purpose and environment of the signal for each service.

The results of the present study and relevant future research can be used to define the FoMs that need to be considered during signal design, and to organize the relationships with the signal design parameters based on equations.

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REFERENCES

Foucras, M., Ekambi, B., Bacard, F., Julien, O., & Macabiau, C. 2014, Optimal GNSS Acquisition Parameters when Considering Bit Transitions, Proceedings of IEEE/ION PLANS 2014, Position Location and Navigation Symposium, May 2014, Monterey, United States, IEEE, pp.804-817. http://dx.doi.org/10.1109/PLANS.2014.6851445

Han, K. & Won, J.-H. 2016, GNSS Signal Design Strategy: Focusing on the Relationship Between GNSS Code Correlation and Navigation Date Bit, Proceeding of Korean GNSS Society Conference, 2-4 Nov 2016, Jeju, Korea

Hein, G. W., Avila-Rodriguez, J.-A., Wallner, S., Pratt, A. R., Owen, J., et al. 2006, MBOC: The New Optimized Spreading Modulation Recommended for Galileo L1 OS and GPS L1C, Inside GNSS, May/June 2006.

Johansson, F., Mollaei, R., Thor, J., & Uusitalo, J. 1998, GPS satellite signal acquisition and tracking, Undergraduate projects, Division of Signal Processing, Lulea University of Technology, S-971 87 Lulea, Sweden, August 21 1998.

Misra, P. & Enge, P. 2001, Global Positioning System: Signals, Measurements, and Performance (Massachusetts: Ganga-Jamuna Press)

Rushanan, J. J. 2007, The Spreading and Overlay Codes for the L1C Signal, NAVIGATION: Journal of The Institute of Navigation, 54, 43-51. https://doi.org/10.1002/j.2161-4296.2007.tb00394.x

Soualle, F., Soellner, M., Wallner, S., Avila-Rodriguez, J.-A., Hein, G. W., et al. 2005, Spreading Code Selection Criteria for the future GNSS Galileo, Proceeding of the European Navigation Conference GNSS 2005, Munich 19-22 July 2005

The National Coordination Office 2016, [Internet], cited 2016 Apr. 26, available from: http://www.gps.gov/systems/gps/modernization/

Van Dierendonck, A. J. 2014, New GNSS Signals: Will Modern Also Be Better?, Inside GNSS, MARCH/APRIL 2014. http://www.insidegnss.com/node/3963

Van Diggelen, F. S. T. 2009, A-GPS: Assisted GPS, GNSS, and SBAS (Boston: Artech House Inc.)

Won, J.-H., Eissfeller, B., Schmitz-Peiffer, A., Floch, J.-J., Zanier, F., et al. 2012, Trade-off Between Data Rate and Signal Power Split in GNSS Signal Design, IEEE Transactions on Aerospace and Electronic System, 48, 2260-2281. https://doi.org/10.1109/TAES.2012.6237591

Kahee Han is a M.S. student in the Department of Electrical Engineering at Inha University, Korea. She received B.S. degree from Inha University in 2017. Her research interests include GNSS signal design and Assisted-GNSS.

Jong-Hoon Won received the Ph.D degree in the Department of Control Engineering from Ajou University, Korea, in 2005. After then, he had worked with the Institute of Space Technology and Space Applications at University Federal Armed Forces (UFAF) Munich, Germany. He was nominated as Head of GNSS Laboratory in 2011 at the same institute, and involved in lectures on advanced receiver technology at Technical University of Munich (TUM) since 2009. He is currently an assistant professor of Electrical Engineering of Inha University since 2015. His research interests include GNSS signal design, receiver, navigation, target tracking systems and self-driving cars.

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