Transmission power control of terrestrial pseudolite signal for global navigation satellite systems

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Abstract: In global navigation satellite systems (GNSS), we need signals from more than four satellites to find out the location at the receiver. However, the satellite visibility is occasionally blocked especially in city areas. For augmenting the availability, placing the pseudo satellite, or pseudolite, has been proposed. A pseudolite broadcasts the signal in the same format as the satellites broadcast and acts as an additional satellite to the receiver. However, the satellite signals are often blocked by a pseudolite signal at the receiver in the close proximity to the pseudolite, and the phenomenon is referred to as the near-far problem. In this letter, a pseudolite with burst pulse transmission that the power varies pulse-to-pulse is proposed to mitigate the near-far problem.

Keywords: global navigation satellite system, pseudo satellite, burst pulse, transmission power control, near-far problem

Classification: Navigation, Guidance and Control Systems

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1 Introduction

With a car navigation showing the current location, we would arrive at destination without losing our way. It finds out the location receiving the radiowaves from satellites of Global Satellite Navigation System (GNSS) such as Global Positioning System (GPS) of the United States, GLONASS of the Russian Federation, Galileo of the European Union, BeiDou of China, and Quasi Zenith Satellite System (QZSS) in Japan. Finding out the current location needs simultaneous reception of the signals from more than four GNSS satellites.

However, high-rise buildings and elevated roads especially in city areas often block the visibility of the satellite signals, and it results in failure of finding out the location of the receiver. For enabling the receiver in such areas to find out a location, placing a pseudolite (PL) that broadcasts the signal in the same format as the satellites broadcast has been proposed. The origin of PL may be in a navigation experiment using terrestrial transmitters conducted at the United States Army’s Yuma Providing Ground in 1973, the confirmation phase of satellite navigation of GPS [1].

Though various types of PL were proposed in 1980’s, setting the PL transmission power to cover the desired service area also interferes and blocks the satellite signals. The block of the satellite signals comes from the excessive power faced the receiver in the close proximity to the PL, and the phenomenon is referred to as the near-far problem. The Radio Technical Committee for Marine Service (RTCM) proposed the burst pulse transmission for PL in 1986 [2]. In the report, the duty ratio should be less than 10%, and RTCM recommended to set the duty ratio as 1/11. A receiver with the array antenna and the signal processing was also proposed to weaken unnecessary PL signals [3]. However, the shadowing facing the receiver in a terrestrial PL environment magnifies the effect of the near-far problem. Alleviating the near-far problem in PL is a subject to be solved in PL.

In this letter, a method of alleviating the near-far problem in PL operating in city areas is proposed.

2 Analysis of near-far problem deletion of duplicate words and burst transmission in pseudolite

2.1 Dynamic range of GNSS signal reception power

Because the near-far problem due to a PL is source of the excess reception power at the receiver, considering the dynamic range of the receiver is essential to know the availability. GNSS satellites are constellated in the azimuth and elevation angles at the receiver, and it results in the received power variation. The dynamic range for receiving the satellite signals can be used as the margin of the near-far problem in PL signal reception. The reception power variation due to the antenna directivity for different elevation angles reaches 8 dB [4, chap. 8]. Therefore, we assume that power difference of less than 8 dB among satellite signals and a PL signal acceptable for receiving both of the signals.
2.2 Near-far problem analysis in cellular communications

A radiowave transmitted at the antenna is weaken as an increase in the distance between the transmission and reception antennas. On the other hand, buildings, cars, and human bodies would shadow the radiowave path and the shadowing also attenuates the signal. The shadowing randomly attenuates the reception power whose statistic is the log-normal distribution [5]. Even in a shadowing environment, a receiver needs signal whose power is above the minimum reception power. The method of finding out the reception power under such environment is exemplified in reference [6]. The reception power in decibels at the distance \(d\) [m] can be express as

\[
P_r(d) = P_t - 10 \log_{10} K - 10 \gamma \log_{10} \frac{d}{d_0} - \Phi_{\text{dB}} \text{ [dBm]},
\]

where \(P_t\) [dBm] is the transmission power, \(K\) is the propagation loss coefficient, \(d_0\) [m] is the reference distance. For free space propagation within the reference distance of \(d_0 = 1\) [m] from the transmitter, we can use \(K = \left(\frac{\lambda}{4\pi}\right)^2\) (\(\lambda\) is the wavelength). \(\gamma\) is the attenuation coefficient, and \(\Phi_{\text{dB}}\) is a zero-mean Gaussian random variable with the variance of \(\sigma_{\text{dB}}^2\) that characterize the shadowing. The outage probability is the probability the reception signal power \(P_r(d)\) [dBm] is below the minimum reception power of \(P_{\text{rmin}}\) [dBm],

\[
P_{\text{out}}(P_{\text{rmin}}, d) = \text{Prob}(P_r(d) < P_{\text{rmin}}) = 1 - Q\left(\frac{P_{\text{rmin}} - P_r(d)}{\sigma_{\text{dB}}}\right),
\]

where

\[
P_r(d) = P_t - 10 \log_{10} K - 10 \gamma \log_{10} \left(\frac{d}{d_0}\right) \text{ [dBm]}
\]

is the mean reception power at \(d\), and

\[
Q(z) = \int_z^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{z^2}{2}\right) \, dz = \frac{1}{2} \text{erfc}\left(\frac{z}{\sqrt{2}}\right)
\]

is the \(Q\)-function representing the probability that a zero-mean Gaussian random variable with the variance of 1 exceeds \(z\) and is also expressed using the complementary error function, \(\text{erfc}(\cdot)\).

For the serving radius of \(R\) from the transmitter, the coverage probability that one can use the system within the region is derived as [6]

\[
P_{\text{cov}}(P_{\text{rmin}}, R) = \frac{1}{\pi R^2} \int_0^{2\pi} \int_0^R \left\{1 - P_{\text{out}}(P_{\text{rmin}}, r)\right\} \cdot r \, dr \, d\theta
\]

\[
= \frac{2}{R^2} \int_0^R r \, Q\left(a + b \log \frac{r}{R}\right) \, dr
\]

\[
= Q(a) + \exp\left(\frac{2 - 2ab}{b^2}\right) Q\left(\frac{2 - ab}{b}\right),
\]

where

\[
a = \frac{P_{\text{rmin}} - P_r(R)}{\sigma_{\text{dB}}}, \quad \text{and} \quad b = \frac{10 \gamma \log_{10} e}{\sigma_{\text{dB}}}.
\]
2.3 Burst pulse transmission of pseudolite
A GPS L1C/A signal conveys navigation messages at a rate of 50 bit/s and the chip rate is 1.023 Mchip/s. The impact on a receiver in the close proximity to a PL would be low if the PL transmits only a small fraction of the 50-bit/s duty cycle. The PL signal blocks the satellite signals for the duration the PL transmits. If the duration of the 11 PL burst pulse is 90.91 µs out of a half duration of the navigation message bit (10 ms). Then, the duty ratio is 1/11, and each of the burst pulse has 93 chips. The all of the 1023 chips of the PL are transmitted in 10 ms. The burst pulse transmission alleviates the near-far problem but interferes the satellite signal reception. Identification, navigation message transfer, and ranging of the PL can be accomplished by the PL signal.

3 Proposed pseudolite whose transmission power varies
3.1 Coverage and outage probabilities in conventional pseudolite
For a PL, we assume $P_t$ so that $P_r(d)$ at the fringe reaches $P_{\text{min}}$. Then, $P_t$ can be calculated by $P_{\text{min}} - 10 \log_{10}(K) + 10\gamma \log_{10}(R/d_0)$. A decrease in the distance between the PL and the receiver tends to interfere the reception of the satellite signals, and an increase in the distance weaken the PL signal. Therefore, the serving region of a PL is an elliptical shape as illustrated in Fig. 1(a). The region becomes complex shapes in shadowing environments. The PL signal is available at the receiver when $P_r(d)$ is between $P_{\text{min}}$ and $P_{\text{max}}$.
The outage probability of PL can be derived by modifying Eq. (2) as
\[
P_{\text{out}}(P_{\min}, P_{\max}, d) = \text{Prob}(P_r(d) < P_{\min} \mid P_r(d) < P_{\max})
\]
\[
= 1 - Q\left(\frac{P_{\min} - P_r(d)}{\sigma_{\text{dB}}}\right) + Q\left(\frac{P_{\max} - P_r(d)}{\sigma_{\text{dB}}}\right).
\]
(7)
The coverage probability is also calculated using Eq. (5) as
\[
P_{\text{cov}}(P_{\min}, P_{\max}, R)
\]
\[
= \frac{1}{\pi R^2} \int_0^{2\pi} \int_0^R \left[1 - P_{\text{out}}(P_{\min}, P_{\max}, r)\right] \cdot r \, dr \, d\theta
\]
\[
= Q(a) + \exp\left(\frac{2 - 2a_{\min} b}{b^2}\right) Q\left(\frac{2 - a_{\min} b}{b}\right)
\]
\[
- \exp\left(\frac{2 - 2a_{\max} b}{b^2}\right) Q\left(\frac{2 - a_{\max} b}{b}\right),
\]
(8)
where
\[
a_{\min} = \frac{P_{\min} - P_r(R)}{\sigma_{\text{dB}}}, \quad a_{\max} = \frac{P_{\max} - P_r(R)}{\sigma_{\text{dB}}}, \quad \text{and} \quad b = \frac{10\gamma \log_{10} e}{\sigma_{\text{dB}}}.
\]
P_{\text{out}} and P_{\text{cov}} are calculated using Eqs. (7) and (8) and are shown in Fig. 1(b). In the evaluation, R of 500 m, \(\gamma\) of 3.71, and \(\sigma_{\text{dB}}\) of 3.65 dB are assumed [6]. The maximum coverage probability was about 0.4 due to the near-far problem.

### 3.2 Transmission power control of pseudolite

For further mitigating the near-far problem, a method of transmission power control is proposed as illustrated in Fig. 2(a). The duty ratio of the conventional PL is \(\tau_1\) in the figure, and the proposed PL transmits the second pulse after the 1st pulse transmission. The duty ratio is \(\tau_2\) and the power is reduced by \(\alpha\) [dB] than the 1st pulse power. The proposed PL transmits several pulses in a cycle, and the serving region illustrated in Fig. 2(b) is superposition of serving region rings corresponding
to the pulses, and it results in a wider serving region. If we set \( \alpha \) to the power difference between \( P_{\text{max}} \) and \( P_{\text{min}} \), serving areas \( A_1 \), \( A_2 \), and \( A_3 \) corresponding to the pulses are continuous as illustrated in Fig. 3(a). For \( R_1 = 500 \text{ m} \) and \( \gamma = 3.71 \), \( R_2 \), \( R_3 \), \( R_4 \) are 304.3 m, 185.2 m, and 112.7 m. Because the PL signal is available when the receiver can use one of these pulses, the coverage probability of the proposed PL is calculated by

\[
\frac{1}{C_0} \left( 1/C_0 P_{\text{cov1}} \right) \cdot \frac{1}{C_1} \left( 1/C_0 P_{\text{cov2}} \right) \cdot \frac{1}{C_1} \left( 1/C_0 P_{\text{cov3}} \right),
\]

where \( P_{\text{cov1}}, P_{\text{cov2}}, P_{\text{cov3}} \) are the coverage probabilities for 1st, 2nd, and 3rd pulses. The coverage probability is shown in Fig. 3(b). The maximum coverage probability of the proposed PL was about 0.6. The ring radius of the conventional PL was from 378 m to 500 m, whereas that of the proposed PL was from 134 m to 500 m. The serving region of the proposed PL is 2.16 times wider than that of the conventional PL.

4 Conclusion

In this letter, a method of transmitting pseudolite signal was proposed. The outage and coverage probabilities of the conventional burst pulse pseudolite in a shadowing environment were evaluated. Then, the pseudolite whose transmission power varies pulse-to-pulse was proposed for mitigating the effect of the near-far problem. The serving region of the proposed PL is 2.16 times wider than that of the conventional pseudolite.