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MAI-Mitigation and Near-Far-Resistance Architectures for GNSS Receivers

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Abstract. Multipath, MAI (Multiple Access Interference) and near-far effects are the three main influences on the performance of CDMA-based communication and navigation systems. A great deal of research has been conducted to develop advanced signal processing algorithms and novel receiver structures useful for mitigation of these effects in mobile land wireless communication systems, such as UMTS. Although the multipath effects on PRN code ranging in GNSS have been investigated for about two decades, the MAI and near-far effects have only been discussed in pseudolite applications.

In this paper, the impairments of the satellite-mobile receiver channel with multipath-selective fading, and shadowing/attenuation effects by objects such as trees/forests and buildings, are theoretically analysed, under a more general and practical definition of the "near-far" effect. The MAI-mitigation and near-far resistant receiver structures for Galileo/GNSS applications are presented. The principles of such receiver structures and their applications in GNSS are discussed. Both theoretical analyses and computer simulations are presented and show the applicability of the proposed receiver structures.

Key words: Multipath, Mitigation, Sequential/Parallel Interference Cancellation.

1 Introduction

Since the invention of the Direct Sequence Spread Spectrum (DS/SS) technology, the traditional correlation/matched filter receiver structure has been used for the detection/tracking of DS/SS signals. Despite extensive developments in DS-CDMA (Direct Sequence Code Division Multiple Access)-based communications (e.g. UMTS), the classical receiver structure is still used in current DS-CDMA-based global navigation satellite system (GNSS) receivers (e.g., Kaplan, 1996, Parkinson & Spilker, 1996), and seems to be continuously used in the future Galileo/GNSS receivers. While the traditional receiver structures perform optimally in additional white Gaussian noise (AWGN) environments (e.g., Proakis, 1996), when used for GNSS signal tracking/detection for mobile land applications, MAI and near-far problems may arise. Therefore, the condition of the conventional correlator/matched filter is sub-optimal.

MAI refers to the interference between DS-CDMA satellite signals, which is inherent to CDMA systems. This interference is the result of the random time transmission delays between signals, which make it impossible to design the PRN codes assigned to each satellite to be completely orthogonal. While the MAI caused by any satellite signal is generally small, as the number of satellites increases, the MAI level increases, thus degrading the reception quality of all the GNSS signals. The MAI is conventionally treated as white Gaussian noise.

The near-far problem occurs when the power of the signal received from one transmitter is so strong that the signal received from other transmitter is completely jammed. This is the case when the signals from the different satellites arrive at the receiver with widely varying power level disparities. It is commonly thought that the disparities of the power levels of the received signals are caused by the large differences in distance between the transmitter and receiver. For GNSS, such as GPS, there is no serious near-far problem since the satellites are all roughly at the same range, and the received signal levels are assumed to be nearly equal (e.g., Parkinson & Spilker, 1996).

Multipath effects in satellite-based PRN ranging systems have been investigated for about two decades, and many methods to mitigate multipath effect exist today (e.g., Van Nee, 1997). However, little attention has been paid to MAI and near-far effects, and they are commonly neglected in the design of conventional GNSS receivers. Verdu (1986) has touched briefly upon this subject and concluded that the near-far effect could be a big problem with "pseudolite" applications, though this can be solved by the use of TDMA signal transmission, for example. But the near-far effect is not a big problem for GNSS receivers, because satellite signals with large received power level differences generally also have large Doppler shift differences, which exceed the tracking loop bandwidth.

However, the near-far issue needs further investigation. First, a GNSS receiver always works in the modes of acquisition → tracking → loss-of-lock → reacquisition → tracking. While the near-far effects can be compensated by the great Doppler differences in the receiver tracking mode, they cannot be avoided or compensated at all in the receiver acquisition mode. This is because in general the acquisition bandwidth of a tracking loop working in an acquisition mode is much larger than any Doppler shift, which is intentionally designed for the purpose of fast acquisition. Second, the so-called "general" case assumed previously is actually not general, according to our analysis in urban and suburban mobile GNSS application environments.

The mass market demands the production of low-cost receivers with optimal performance that they are able to operate in environments where most consumers live, travel and work, such as in a moving car, urban, suburban or even indoor areas. It is therefore necessary to develop new technologies for advanced GNSS receivers, offering the capabilities for the MAI-mitigation, near-far and multipath-resistance.

It is also important to investigate new GNSS/Galileo receiver structures with the better performance at a low cost, since the new satellite navigation system Galileo and the GPS modernisation program will use new signal structures or parameters (e.g., *EIRP*, PRN chip rate etc.) for the satellite ranging signals (e.g., Spilker, 1999, Hein et al., 2001). One of the special attributes of the proposed new signal structures in the GPS modernisation and new system Galileo, is the use of pilot signals. This provision may allow for the implementation of advanced receiver structures, with simple or moderate computational complexity.

In the following section, the impairments of the satellite-mobile receiver channel with multipath-selective fading, and shadowing/attenuation effects by trees/forests, buildings etc., are theoretically analysed. The problems with the conventional correlation receivers are discussed in Section 3. The principles of the proposed receiver structures, which have capabilities of MAI-mitigation and near-far resistance, are given in Section 4; Finally, the computer simulation results, and discussions on the possible enhanced applications are presented.

2 GNSS CDMA-Channel Model

GNSS, for example, GPS and Galileo, is an asynchronous CDMA system, i.e., the ranging signals are randomly delayed from one another because of different transmitter positions and different propagation paths (channels). The GNSS CDMA channel model is illustrated in Fig. 1.

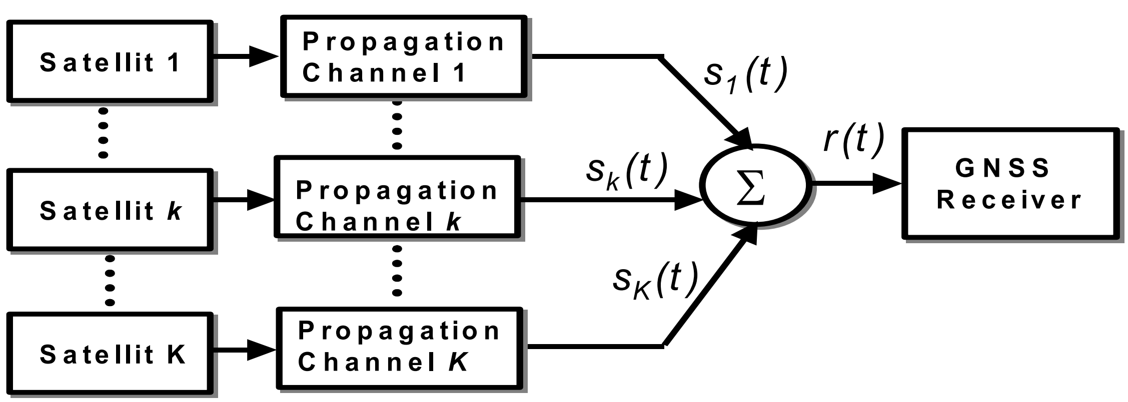

Fig. 1 GNSS CDMA channel model

Each satellite signal passes through a different path to arrive at a receiver. A transmitter onboard each GNSS satellite transmits a binary baseband DS-CDMA signal, derived by multiplying a binary level (±1) information signal with a satellite-specific binary level spreading sequence $c_k(t)$. The spreading sequence $c_k(t)$ exhibits the constant modulus property:

$$|c_k(t)| = 1 \tag{1}$$

where $|\cdot|$ denotes the absolute value. The k-th transmitted signal from k-th satellite $s_k(t)$ is given by:

$$s_k(t) = d_k(t)c_k(t)\cos(\omega_{ck}(t-\tau_k)+\phi_k) \tag{2}$$

where $d_k(t)$ is the information bearing the data signal with the symbol duration T_b.

A simple conventional receiver structure, as stated above, currently used for tracking the PRN codes of satellite 1, satellite 2,..., satellite K (K is 12 in a modern GPS receiver) is illustrated in Fig. 2 (e.g., Kaplan, 1996). The figure shows a bank of K correlators. Here each PRN code waveform is regenerated locally, and correlated with the received, summed, and IF-downconverted K signals $r_{RF}(t)$ in each separated correlator branch. A conventional receiver follows the detection/tracking strategy, that each branch seeks only a certain desired satellite signal and processes other satellite signal interference (termed as MAI), as the unstructured channel noise (termed as AWGN).

To simplify the analysis, without loss of generality, it is assumed here that there is no multipath effect and that the data modulation is Binary Phase Shift Keying (BPSK). The received and summed K signals $r_{RF}(t)$ is given by equation (3).

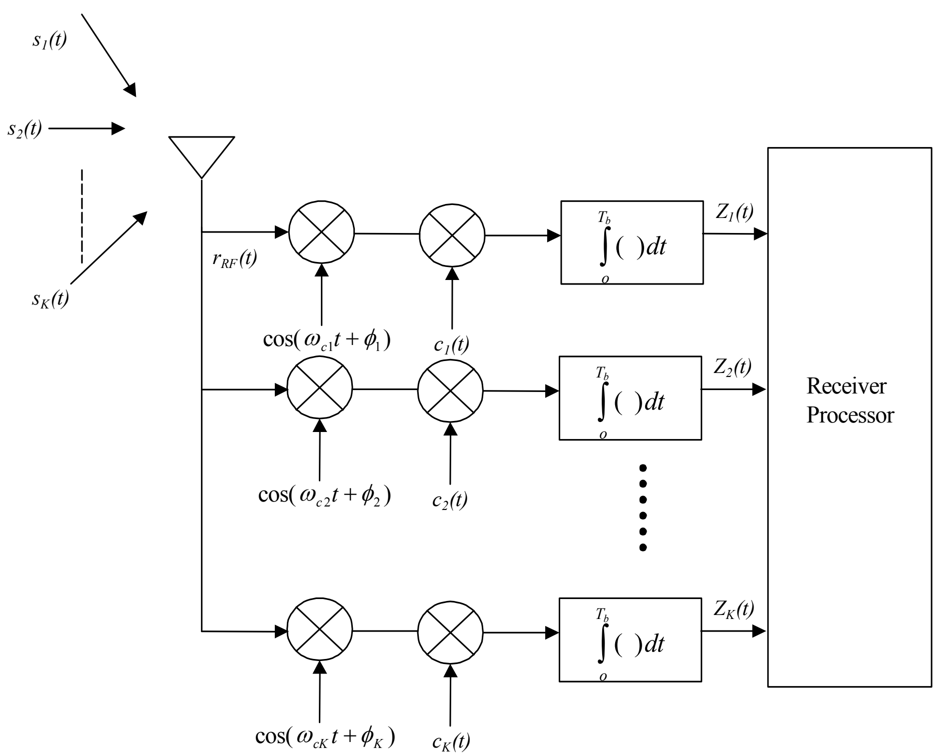

Fig. 2 A simplified bank of a conventional GNSS receiver structure for reception of the signals, $s_1(t), s_2(t), \ldots, s_k(t)$, from satellite 1, satellite 2, ..., satellite k, respectively

$$r_{RF}(t) = \sum_{k=1}^{K} \sqrt{2P_k}\, c_k(t-\tau_k) d(t-\tau_k) \cos(\omega_{ck}(t-\tau_k) + \phi_k) + n_{RF}(t) \tag{3}$$

where

P_k The average received signal power in k^{th} satellite,

K The number of satellites being in view,

τ_k The time delay of the k^{th} satellite through k-th propagation path k = 1,2,..., k,

ω_{ck} The k^{th} satellite's carrier frequency, which is equal to $\omega_{ck}=\omega_c+\Delta\omega_{ck}$, with ω_c being the nominal carrier frequency and $\Delta\omega_{ck}$ the carrier frequency offset,

ϕ_k The phase of the k^{th} satellite's carrier signal,

$n_{RF}(t)$ The AWGN resulting from the RF front end.

Assuming that the k^{th} satellite is the desired one in the k^{th} branch of the bank of correlators, and assuming perfect carrier recovery (i.e. $\Delta\omega_{ck}$ = 0, ϕ_k = 0), the baseband signal $r(t)$ at the mobile unit is given by:

$$\begin{aligned} r(t) &= \sqrt{2P_k}\, c_k(t-\tau_k) d(t-\tau_k) \\ &+ \sum_{\substack{i=1 \\ i\neq k}}^{K} \sqrt{2P_i} \cos(\Delta\omega_{ik}\tau_i + \phi_i) c_i(t-\tau_i)) d(t-\tau_i) + n(t) \end{aligned} \tag{4}$$

where $n(t)$ is the equivalent AWGN at baseband. Assuming perfect code synchronization of k^{th} correlator ($\tau_k = 0$), the output of the k^{th} correlator is obtained as:

$$\begin{aligned} Z_k &= \frac{1}{T_b}\int_0^{T_b} r(t) c_k(t) dt \\ &= \frac{\sqrt{2P_k}}{T_b} d_k [\int_0^{T_b} c_k(t) c_k(t) dt] \\ &+ \sum_{\substack{i=1 \\ i\neq k}}^{K} \frac{\sqrt{2P_i}\cos(\Delta\omega_{ci}\tau_i + \phi_i)}{T_b} \int_0^{T_b} d_i(t-\tau_i) c_i(t-\tau_i) c_k(t) dt \\ &+ \frac{1}{T_b}\int_0^{T_b} n(t) c_k(t) dt \\ &= \sqrt{2P_k}\, d_k + MAI_k + n_k \end{aligned} \tag{5}$$

with T_b being the duration of the data symbol of the information waveform $d(t)$.

As stated above, because the satellite-receiver is an asynchronous link, the term within the first pair of brackets is unity. As a result, Equation (5) can be written as:

$$\begin{aligned} Z_k &= \sqrt{2P_k}\, d_k + MAI_k + n_k \\ MAI_k &= \sum_{\substack{i=1 \\ i\neq k}}^{K} \frac{\sqrt{2P_i}\cos(\Delta\omega_{ci}\tau_i + \phi_i)}{T_b} \int_0^{T_b} d_i(t-\tau_i) c_i(t-\tau_i) c_k(t) dt \\ n_k &= \frac{1}{T_b}\int_0^{T_b} n(t) c_k(t) dt \end{aligned} \tag{6}$$

where the first term in Equation (6) is the desired signal component, the second term is due to MAI, and the third term is AWGN.

From Equation (6), the MAI and near-far problems can be easily understood.

MAI problem

The conventional correlation seeks only the desired signal for detection and tracking, and the non-zero cross-correlation-caused MAI would be zero if the PRN codes are designed to be perfectly orthogonal for random time delay τ_k. Unfortunately, it is hardly possible to achieve this ideal result for the satellite-receiver asynchronous links and therefore MAI always exists. In practice, PRN codes with near-ideal properties (good auto- and cross-correlation functions) are sought after (e.g., Spilker, 1999).

While the MAI caused by any satellite signal is generally small, as shown in Equation (6), an increase in the number of satellites results in MAI level increases. Thus the degradation in the reception quality of all links in

GNSS requires consideration in the GPS/Galileo "Overlay" scenario (e.g., Hein et al., 2001).

When a large number of MAI signals are received with almost equal power levels, the MAI appears to be Gaussian according to the Central Limit Theorem, and almost white within the band of interest. Thus, the conventional receivers may approach their optimal performance. Unfortunately, for GNSS applications, only a moderate number of satellite signals are received simultaneously and the signal power levels may not be the same. Therefore, the conventional MAI-AWGN assumption is not realistic and the correlation receiver structure is not optimal.

Near-far problem

As shown in Figs. 3, 4 and 5, signal propagation from different satellites is attenuated to different power levels by a variety of objects, such as trees, forest, and buildings. The conventional assumption that all satellite signals have equal power levels is unrealistic in practical GNSS application environments.

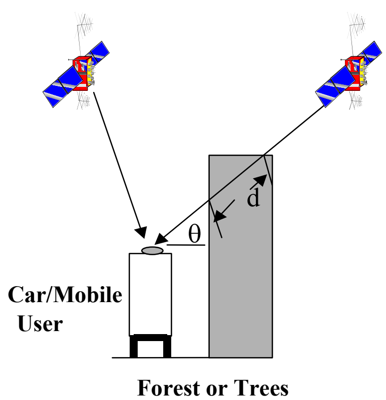

Fig. 3 Power level dispersion caused by tree attenuation

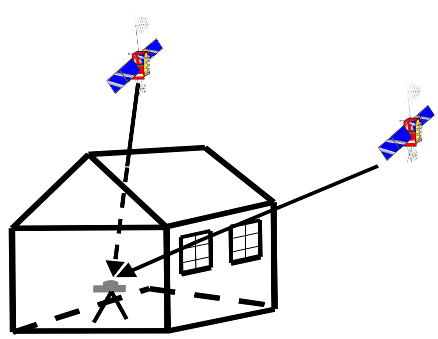

Fig. 4 Power level dispersion caused by different path attenuation

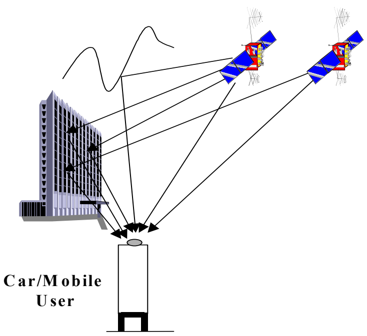

Fig. 5 Power level dispersion caused by multipath fading

3 MAI-Mitigation and Near-Far-Resistance Receiver Architectures

3.1 Sequential Interference Cancellation – SIC Algorithm

The principle of sequential interference cancellation (SIC) is shown in Fig. 6.

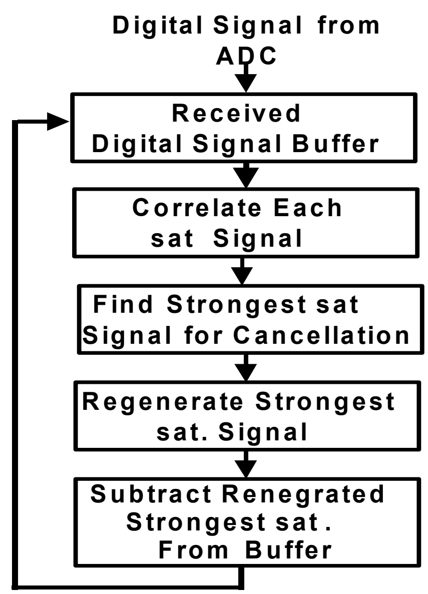

Fig. 6 Block Diagram of the Sequential Interference Cancellation (SIC)

All the signals are estimated at each iteration of the scheme. The signal with the largest power is then regenerated and subtracted from the buffered received signal. The remaining signals are now re-estimated, and the new strongest satellite signal is selected, regenerated, and subtracted. The process continues until all the signals have been recovered or the maximum number of cancellations is reached. After satellites 1 through k-1 have been removed, the decision statistic for the *k*th satellite is:

$$z^{(k)} = \int_0^{T_b} r^{(k)}(t) a_k(t-\tau_k) dt \quad (7)$$

where $r^{(k)}$ is the received signal after satellites 0 through k-1 have been cancelled, which is given by:

$$r^{(k)}(t) = r(t) - \frac{2}{T_b} \sum_{j=0}^{K-1} Z^{(k)} a_k(t-\tau_k) \cos(\omega + \theta_k t) \quad (8)$$

It has been shown that SIC is very robust to diverse power levels (e.g., Patel & Holtman, 1994). This is due to the strongest satellite signals all being cancelled from the received waveform. The SIC is considered as one of the simplest forms of MAI-mitigation and near-far resistance receiver structures. However, the algorithm for the cancellation must perform all the cancellations while maintaining the necessary navigation data rate. Obviously, the larger the number of satellite signals, the longer the processing time.

3.2 Parallel Interference Cancellation - PIC Algorithm

The principle of the Parallel Interference Cancellation (PIC) is shown in Fig. 7. In Stage 1, a bank of correlators correlate all the satellite signals received. Then, each satellite signal is estimated and regenerated. In the next stage, a new estimate for each satellite is formed by taking the received signal and subtracting from it all other estimated signals.

The first stage of this PIC receiver structure consists of a bank of correlators that are used to generate decision statistics for every bit *i* for the *kth* satellite, $Z_{k,i}$. These decision statistics then generate the estimation of the satellite's signal, $s^{(k)}$. In the next stage, as stated previously, a new estimate for the *kth* satellite is formed by taking the received signal and substrating from it all $s^{(k)}$ such that j=1, …, N; j≠k. This process may be repeated for a number of stages. Consequently, the received signal at stage s for the *kth* satellite's signal path is

$$r_k^{(s)}(t) = r(t) - \sum_{\substack{j=1 \\ j\neq k}}^{K} s_k^{(s)}(t-\tau_k) \quad (9)$$

The decision statistic for the *ith* navigation data bit of satellite *k* after *s* stages of interference cancellation is then given as:

$$Z_{k,i} = \int_{iT+\tau_k}^{(i+1)T+\tau_k} r_k^{(s)}(t) a_k(t-\tau_k) \cos(\omega_c t + \phi_k) dt \quad (10)$$

In comparison with the SIC algorithms, the processing time with the PIC algorithms is greatly reduced for the large number of satellites, but its hardware is considerably more complicated than that of the SIC.

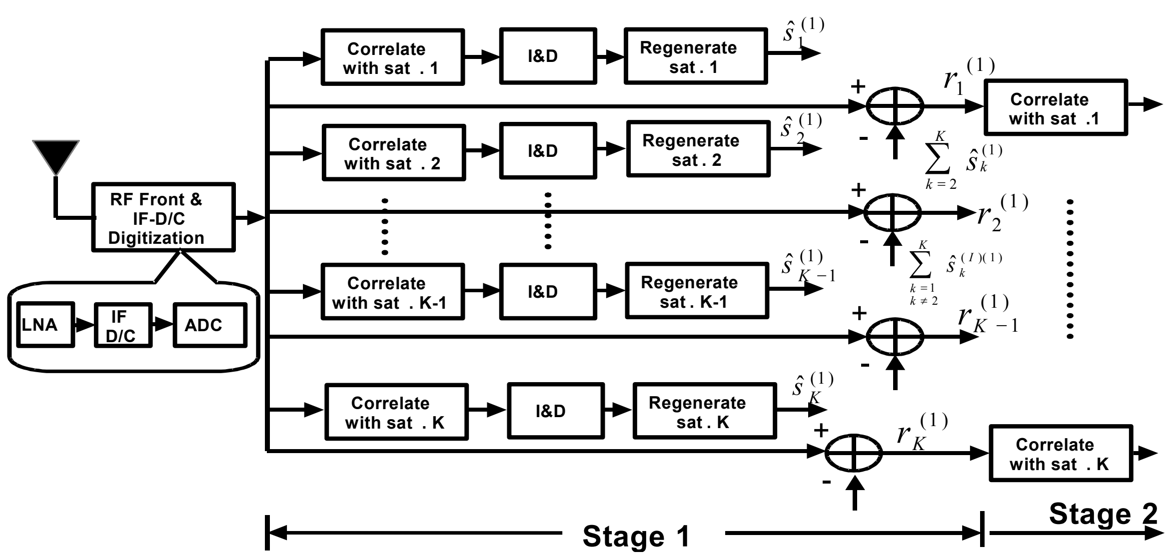

Fig 7. Block Diagram of Parallel Interference Cancellation

4 Simulations

Simulations are made using the MATLAB Simulink package in the baseband, according to the principle stated above. The purpose of this simulation is to verify the applicability of the algorithms and receiver structures discussed. 1023 Gold codes are used, but the practical GPS signal environment and link budget are not applied. The simulation results on the SIC receiver structure are shown in Figs. 8, 9, and 10. The simulation results on the PIC receiver structure are consistent with the results presented here.

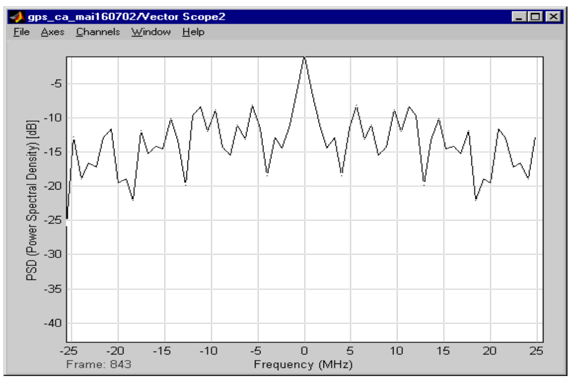

Fig 8. Signal of Interested (SOI) plus background noise only without any other MAI

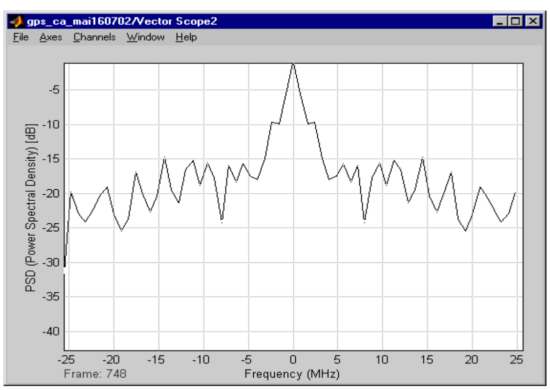

Fig.9 Unwanted signal/MAI signal level is 5dB larger than that of SOI

From the simulation results shown in Figs. 8, 9, and 10, it can be concluded that if the unwanted signal, or MAI is 10dB larger than that of a SOI, the correlation receiver cannot properly track the SOI PRN code. From Fig 11 it can be seen that the SIC algorithm is applicable for MAI mitigation or near-far resistance.

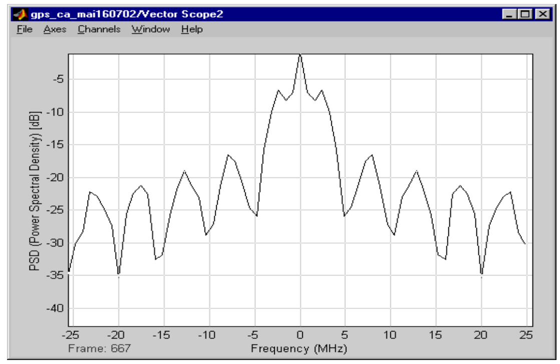

Fig 10 Unwanted signal/MAI signal level is 10dB larger than that of SOI

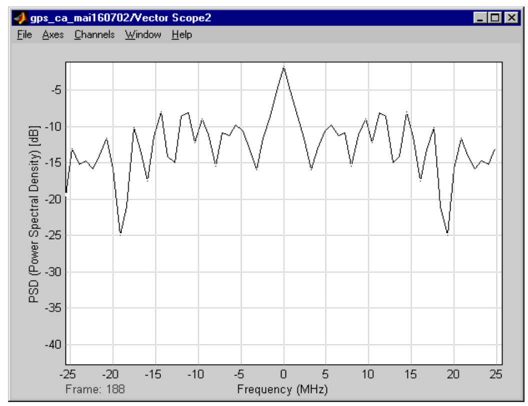

Fig 11 Correlation of SOI after using SIC for the cancellation of the unwanted signal/MAI signal; the unwanted signal/MAI signal level is 10dB larger than that of SOI

5 Possible Enhanced Applications

Compared with conventional GNSS receivers, the satellite signal availability could be improved in urban and indoor environments by using the proposed GNSS receiver architectures. Furthermore, this kind of receiver architecture could be used in pseudolite applications, and the integration of GNSS/INS/Pseudolite, or INS/Pseudolite could improve the system performance under a variety of poor operational environments (Wang, 2002). However, multipath and near-far effects remain major problems in GNSS/INS/Pseudolite, or INS/Pseudolite integration for system performance improvement. Although there have been many techniques proposed to solve the near-far problem, the proposed GNSS receiver architectures are software radio architectures which could be a promising approach in the future.

6 Concluding Remarks

In this paper, the MAI-mitigation and near-far resistant receiver structures for GNSS/Galileo have been presented. The simulation results have shown that the algorithms are applicable.

Some conventional techniques as reported in Sudhir (2001), for example, aim to improve the conventional receiver sensitivity alone, but cannot improve the indoor satellite signal availability, because the conventional structure is sensitive to all the signals, noise, MAI and other interference. The proposed MAI mitigation, near-far resistance receiver structure, together with other high receiver sensitivity techniques, can improve the indoor and urban canyon satellite signal availability.

Although the PIC receiver structure is more complex than that of a conventional receiver structure, the data-flow-oriented nature of the PIC is more suitable for implementation with the DSP/FPGA, which is a cheaper, compact, more flexible software radio approach.

Further investigations are required to verify the potential applications of both SIC and PIC in future GNSS receivers.

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