Modified Code Tracking Loop Aided by Short Multipath Insensitive Code Loop Discriminator

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BIOGRAPHY

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ABSTRACT

Short delay multipath is common in some challenging environments, such as urban canyons and indoor positioning, where high accuracy requirements are not easy to satisfy due to lack of effective methods of short multipath mitigation.

Short Multipath Insensitive Code Loop Discriminator (SMICLD), first proposed by Jardak & Samama [2007] based on modification of the code loop discriminator, is insensitive to short delay multipath. Its discriminator curve (S-curve), however, is asymmetrical, and it always outputs zero when the code tracking error is negative. As a result, large code tracking bias may be induced by noises or signal code phase jumps. So the stability of SMICLD is a problem.

This paper constructs a modified code tracking loop aided by SMICLD. Although the modified DLL (delay lock loop) has a zero-crossing point bias in multipath environments, it can function well in adjusting the local replica code phase to the correct direction when the code tracking error is negative. The modified DLL aided by SMICLD uses SMICLD when the code tracking error is positive; and switches to the modified DLL when the code tracking error is negative. A zero-crossing point searching strategy is proposed to distinguish the cases of zero tracking error and negative tracking error. The code tracking loop proposed in this paper lets the modified DLL and SMICLD complement each other.

The modified DLL aided by SMICLD has been implemented in the software GPS receiver developed by our group in Beihang University. Its performance against short delay multipath is tested and compared with SMICLD, MEDLL and narrow correlation technique by using a digital IF (intermediate frequency) GPS signal simulator. Test results show that the algorithm proposed in this paper can not only mitigate short delay multipath, but also overcome the instability of SMICLD.

INTRODUCTION

Multipath mitigation has been a hot topic in GPS receiver research. Most multipath mitigation techniques proposed so far, however, are only applicable to medium or long delay multipath situations and have poor performance for short delay multipath, where the delay of the multipath signal with respect to the direct signal is less than 0.5 or even 0.1 PRN (pseudo-random noise) code chips (for GPS L1 C/A signal). Short delay multipath is usually seen in urban canyons, indoor positioning, ranging communication between spacecraft, and so on. It is of great significance but yet very challenging to suppress short delay multipath and improve the ranging accuracy in these occasions.

Three kinds of multipath mitigation techniques can be employed in GPS receivers: antenna-based, correlator/discriminator-based, and parameter estimation-based techniques. As the most popular multipath rejection antenna, the choke ring antenna is effective against the multipath signals with low elevation angles. Since the antenna is the front part of receiver signal processing, a good multipath rejection performance of the antenna can greatly reduce the burdens of the follow-up units in the receiver. Nevertheless, the antenna-based multipath mitigation technique is demanding on hardware. On the other hand, most parametric multipath mitigation techniques perform maximum likelihood estimation of the parameters of the direct signal and multipath signals. Among which the classical and popular algorithm, the multipath estimating delay lock loop (MEDLL), can eliminate not only the code tracking bias but also the carrier tracking bias caused by multipath. MEDLL does well with the suppression of medium or long delay multipath. It becomes powerless, however, on multipath with a delay less than 0.1 chips. This paper focuses on correlator/discriminator-based non-parametric multipath suppression techniques. When multipath exists, the autocorrelation function between the incoming signal and the local replica is distorted, leading to the zero-crossing point bias of the S-curve of the traditional DLL (delay lock loop). This code loop lock point bias will manifest itself in the code phase tracking bias and the resultant pseudorange bias. Therefore, it is possible to suppress the multipath error by properly reconstructing the code loop discriminator or the correlator of the receiver. From this point some classical algorithms have been developed including Narrow correlator (NC), Strobe correlator, Pulse aperture correlator (PAC), and so forth. These techniques show good effects on medium and long delay multipath, and yet little effects on short delay multipath.

Short delay multipath mitigation has not been paid as much attention by researchers so far. Zhang [2005] proposed a short delay multipath mitigation technique based on virtual multipath. This technique performs well when there is a multipath signal stronger than the direct signal and other multipath signals, which greatly restricts its applications in spite of its low computational complexity. Zhou & Huang [2007] improved the short delay multipath mitigation performance of the traditional narrow correlator technique by using Teager-Kaiser operator. Bhuiyan [2010] proposed a Slope-Based Multipath Estimation algorithm based on high correlations between multipath error and multipath amplitude. This algorithm is effective on short delay multipath mitigation with an ideally infinite frontend bandwidth of the receiver. Based on the analysis of the influence of short delay multipath on the receiver code and carrier loops, Gao [2014] modified the narrow correlator technique to eliminate the in-phase short delay multipath. However, the out-of-phase short delay multipath remains a problem. Wang [2012] proposed a multipath model with the multipath ray number, and combined it with the adaptive genetic algorithm to suppress short delay multipath.

Short multipath insensitive code loop discriminator (SMICLD) is a correlator/discriminator-based short delay multipath mitigation algorithm introduced by Jardak & Samama [2007]. SMICLD modifies prompt correlation values and the code discriminator algorithm so that the zero-crossing point of its S-curve has no bias in the presence of short delay multipath. However, the S-curve of SMICLD is asymmetrical. When the tracking error is negative, the output of the discriminator is always zero, which limits the applicability of SMICLD. SMICLD doesn't work when the code tracking error is negative. As a result, large tracking error of SMICL (short multipath insensitive code loop) may be caused by noises and signal phase jumps. The code loop using SMICLD is called SMICL.

We design a simple but effective algorithm, named modified DLL aided by SMICLD, to improve the code tracking performance by modifying the S-curve shape of SMICLD. The algorithm will use SMICLD for the code tracking loop when the code tracking error is positive, and use the modified early minus later discriminator (EMLD) when the code tracking error is negative. A zero-crossing point searching strategy is proposed to distinguish zero tracking error from negative tracking error. This modified code tracking loop aided by SMICLD integrates the advantages of SMICLD and modified EMLD, which can not only suppress short delay multipath but also work properly in the region where the code tracking error is negative. Experimental results show that modified DLL aided by SMICLD can work stably in the presence of noises or even abrupt code phase changes. In the meantime, it holds the capability of short delay multipath mitigation of SMICLD.

The paper is organized as follows. The second section analyses the multipath mitigation performance of SMICLD in terms of S-curve symmetry, multipath ray number, and acceptable multipath delay range. The third section proposes the modified DLL aided by SMICLD and analyzes its feasibility. In the fourth section, the digital GPS signal simulator and software receiver developed by our group in Beihang University are utilized to test the performances of the novel code tracking loop as well as SMICL, traditional DLL and MEDLL in the presence of single short delay multipath, noises and code phase jumps. The fifth section summarizes the study and gives the conclusions.

SHORT MULTIPATH INSENSITIVE CODE LOOP DISCRIMINATOR

SMICLD was proposed by Jardak & Samama [2007]. By modifying the prompt correlation values and the discriminator expression, SMICLD eliminates the zero-crossing point bias of the S-curve in the presence of short delay multipath with its relative delay less than min(Δ/2, 1-Δ/2), where Δ denotes the correlator spacing.

A. Definition of SMICLD

The GPS L1 C/A IF signal can be expressed as

$$r(t)=a_0 p(t-\tau_0)\cos(wt+\theta_0)+\sum_{i=1}^{M} a_i p(t-\tau_0-\tau_i)\cos(wt+\theta_i) \tag{1}$$

where $p(t)$ denotes the C/A code sequence of the transmitted signal, and w is the carrier frequency; a_i and θ_i are the amplitude and carrier phase of path i, respectively. τ_0 represents the propagation time of the direct signal; τ_i is the multipath delay relative to the direct signal; M indicates the number of multipath signals. It is assumed that the navigation message does not jump during the observation time for the convenience of analysis. The local C/A code replica is $p(t-\tau)$, which is delayed by τ relative to the transmitted signal. The code tracking error ε is the code phase difference between the direct signal and the local replica ($\varepsilon=\tau-\tau_0$). Fig. 1(a) illustrates the code phase relationship between the received signal and the local replica. After carrier wipe-off, the signal is correlated with the local replica code to obtain the correlation values. Fig. 1(b) shows the ideal autocorrelation function $R(\varepsilon)$.

$$R(\varepsilon)=\begin{cases}1-|\varepsilon| \ , & |\varepsilon|\le 1\\ 0 & , \ others\end{cases} \tag{2}$$

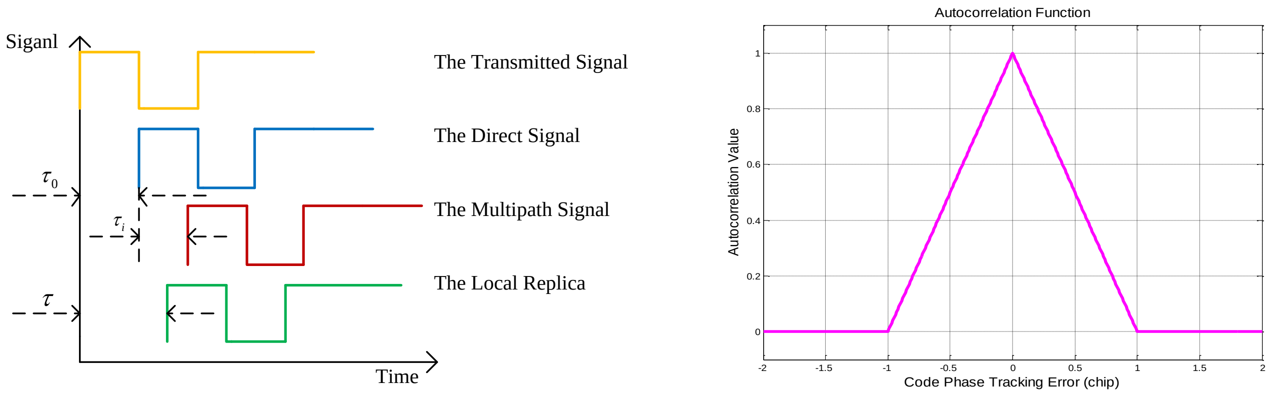


Fig. 1 (a) C/A code sequences of direct path, multipath and local signal; (b) Ideal autocorrelation function

Let's denote the in-phase prompt, quadrature prompt, in-phase early, quadrature early, in-phase late, quadrature late correlation values as IP, QP, IE, QE, IL, QL, respectively. The SMICLD firstly modifies the prompt correlation values:

$$IP^{'}=IP-\frac{\Delta}{2}\frac{IE+IL}{2-\Delta} \tag{3a}$$

$$QP^{'}=QP-\frac{\Delta}{2}\frac{QE+QL}{2-\Delta} \tag{3b}$$

where Δ denotes the correlator spacing, which is generally no more than 1 chip. Then the adjusted prompt correlation values, IP' and QP', are substituted into a novel expression of the discriminator:

$$D=(IE^2+QE^2)-((IP^{'})^2+(QP^{'})^2) \tag{4}$$

According to Jardak & Samama [2007], the discriminator function can be written as

$$D=\begin{cases}2(2-\Delta)\left[a_0^2\varepsilon+\sum_{i=1}^{M}a_i^2(\varepsilon-\tau_i)+\sum_{i=0}^{M-1}\sum_{j=i+1}^{M}a_ia_j\cos(\theta_i-\theta_j)(2\varepsilon-\tau_i-\tau_j)\right] & 0<\tau_{i,j}<\varepsilon\le\min(\frac{\Delta}{2},1-\frac{\Delta}{2})\\ 2a_0^2(2-\Delta)\varepsilon+4\sum_{i=1}^{M}a_0a_i\cos(\theta_0-\theta_i)\varepsilon(1+\varepsilon-\tau_i-\frac{\Delta}{2}) & 0<\varepsilon<\tau_i\le\min(\frac{\Delta}{2},1-\frac{\Delta}{2})\\ 0 & \tau_i-\min(\frac{\Delta}{2},1-\frac{\Delta}{2})<\varepsilon<0<\tau_i\le\min(\frac{\Delta}{2},1-\frac{\Delta}{2})\end{cases} \tag{5}$$

In order to study the characteristics of the discriminator function, the following three cases are discussed.

(1) $0<\tau_i<\varepsilon\le\min(\frac{\Delta}{2},1-\frac{\Delta}{2})$

In this case, the following expression can be derived:

$$\frac{D}{2(2-\Delta)}=a_0^2\varepsilon+\sum_{i=1}^{M}a_i^2(\varepsilon-\tau_i)+\sum_{i=0}^{M-1}\sum_{j=i+1}^{M}a_ia_j\cos(\theta_i-\theta_j)(2\varepsilon-\tau_i-\tau_j) \tag{6}$$

a. Without multipath

$$\frac{D}{2(2-\Delta)} = a_0^2\varepsilon \tag{7}$$

$$0 < \tau_i < \varepsilon \le \min(\frac{\Delta}{2}, 1-\frac{\Delta}{2}) \Rightarrow \varepsilon > 0, 2-\Delta > 0 \Rightarrow D > 0$$

b. Only one multipath ray

$$\begin{aligned}\frac{D}{2(2-\Delta)} &= a_0^2\varepsilon + a_1^2\left(\varepsilon - \tau_1\right) + a_0 a_1 \cos(\theta_0 - \theta_1)(2\varepsilon - \tau_1) \\ &\ge \left(a_0 - a_1\right)\left[a_0\varepsilon - a_1\left(\varepsilon - \tau_1\right)\right]\end{aligned} \tag{8}$$

The multipath delay relative to the direct signal is always positive. Assuming that the direct signal is stronger than multipath signal,

$$a_0 > a_1, \quad \varepsilon > \varepsilon - \tau_1 \tag{9}$$

it is easy to deduce that

$$D > 0 \tag{10}$$

c. Two or more multipath rays

At first, let us assume that the direct signal is interfered by two multipath rays, and the code phase error is larger than the two multipath delays ($0 < \tau_1 < \tau_2 < \varepsilon \le \min(\Delta/2, 1-\Delta/2)$), we have

$$\begin{aligned}\frac{D}{2(2-\Delta)} &= a_0^2\varepsilon + a_1^2\left(\varepsilon - \tau_1\right) + a_2^2\left(\varepsilon - \tau_2\right) \\ &\quad + a_0 a_1 \cos(\theta_0 - \theta_1)(2\varepsilon - \tau_1) + a_0 a_2 \cos(\theta_0 - \theta_2)(2\varepsilon - \tau_2) \\ &\quad + a_1 a_2 \cos(\theta_1 - \theta_2)(2\varepsilon - \tau_1 - \tau_2) \\ &\ge a_0\varepsilon\left(a_0 - a_1 - a_2\right) + a_1\left(\varepsilon - \tau_1\right)\left(a_1 - a_0 - a_2\right) + a_2\left(\varepsilon - \tau_2\right)\left(a_2 - a_0 - a_1\right)\end{aligned} \tag{11}$$

Taking a_0=1, a_1=0.8, a_2=0.5 as an example, the above inequality equation becomes

$$\frac{D}{2(2-\Delta)} \ge -0.3\varepsilon - 0.56\left(\varepsilon - \tau_1\right) - 0.65\left(\varepsilon - \tau_2\right) \tag{12}$$

Obviously,

$$-0.3\varepsilon - 0.56\left(\varepsilon - \tau_1\right) - 0.65\left(\varepsilon - \tau_2\right) \le 0 \tag{13}$$

Since the SMICLD curve is continuous, the discriminator output is not always larger than zero. SMICLD exhibits similar characteristics with more multipath rays.

(2) $0 < \varepsilon < \tau_i \le \min(\frac{\Delta}{2}, 1-\frac{\Delta}{2})$

In this case, the discriminator output can be expressed as

$$D = 2a_0^2(2-\Delta)\varepsilon + 4\sum_{i=1}^{M} a_0 a_i \cos(\theta_0 - \theta_i)\varepsilon(1+\varepsilon-\tau_i-\frac{\Delta}{2}) \tag{14}$$

a. Without multipath:

$$D = 2a_0^2\left(2-\Delta\right)\varepsilon > 0 \tag{15}$$

b. Only one multipath ray:

Assuming that the direct signal is stronger than the multipath signal, the discriminator output can be expressed as:

$$\begin{aligned}D &= 2a_0^2(2-\Delta)\varepsilon + 4a_0 a_1 \cos(\theta_0 - \theta_1)\varepsilon(1+\varepsilon-\tau_1-\frac{\Delta}{2}) \\ &\ge 2a_0\varepsilon\left[(2-\Delta)\left(a_0 - a_1\right) + 2a_1(\tau_1 - \varepsilon)\right] \\ &> 0\end{aligned} \tag{16}$$

c. Two or more multipath rays

At first, let us assume that the direct signal is interfered by two multipath rays, and the code phase error is smaller than the two multipath delays ($0 < \varepsilon < \tau_1 < \tau_2 \le \min(\Delta/2, 1-\Delta/2)$). Then the discriminator expression becomes

$$\begin{aligned}D &= 2a_0^2(2-\Delta)\varepsilon + 4a_0 a_1 \cos(\theta_0 - \theta_1)\varepsilon(1+\varepsilon-\tau_1-\frac{\Delta}{2}) + 4a_0 a_2 \cos(\theta_0 - \theta_2)\varepsilon(1+\varepsilon-\tau_2-\frac{\Delta}{2}) \\ &\ge 2a_0\varepsilon\left[(2-\Delta)\left(a_0 - a_1 - a_2\right) + 2a_1\left(\tau_1 - \varepsilon\right) + 2a_2\left(\tau_2 - \varepsilon\right)\right]\end{aligned} \tag{17}$$

Taking a_0=1, a_1=0.8, a_2=0.6, Δ=1, τ_1-ε=0.1, τ_2-ε=0.15 as an example, the above inequality equation becomes

$$D \geq -0.12 a_0 \varepsilon \tag{18}$$

Therefore, the output of the discriminator is not always larger than zero because the SMICLD curve is continuous. SMICLD exhibits similar characteristics with more multipath rays.

(3) $\tau_i - \min(\frac{\Delta}{2}, 1-\frac{\Delta}{2}) < \varepsilon < 0 < \tau_i \leq \min(\frac{\Delta}{2}, 1-\frac{\Delta}{2})$

The output of SMICLD is always zero and independent to the number of multipath rays

$$D = (IE^2 + QE^2) - ((IP^{'})^2 + (QP^{'})^2) = 0 \tag{19}$$

B. Discussions

In summary, the characteristics of SMICLD can be illustrated by Table 1.

Table 1: SMICLD outputs with different numbers of multipath rays

Code tracking error	Number of multipath rays		
	$M=0$	$M=1$	$M \geq 1$
$\tau_i - \min(\Delta/2, 1-\Delta/2) < \varepsilon < 0 < \tau_i \leq \min(\Delta/2, 1-\Delta/2)$	$D=0$	$D=0$	$D=0$
$0 < \varepsilon < \tau_i \leq \min(\Delta/2, 1-\Delta/2)$	$D>0$	$D>0$	D is not always larger than zero
$0 < \tau_i < \varepsilon \leq \min(\Delta/2, 1-\Delta/2)$	$D>0$	$D>0$	D is not always larger than zero

In the case of only one short delay multipath, when the code tracking error is positive, the output of SMICLD is positive. When the code tracking error is zero or negative (no less than τ_1-min(Δ/2, 1-Δ/2)), the output of SMICLD is always zero. As shown in Fig. 2, the zero-crossing point of the traditional EMLD curve has a bias caused by short delay multipath, whereas SMICLD has no zero-crossing point bias, which means that SMICLD can eliminate short delay multipath error. However, when the code tracking error is negative, the SMICLD output is always zero, which may result in a false lock in the case of strong noises or abrupt phase jumps.

(5) doesn't apply to medium and long delay multipath with delays larger than $\min(\Delta/2, 1-\Delta/2)$. What's more, when the code tracking error is positive, the output of SMICLD may be negative in the presence of two or more multipath rays. In this case, the S-curve of SMICLD will have two or more zero-crossing points in the positive region, which may result in a large code tracking bias.

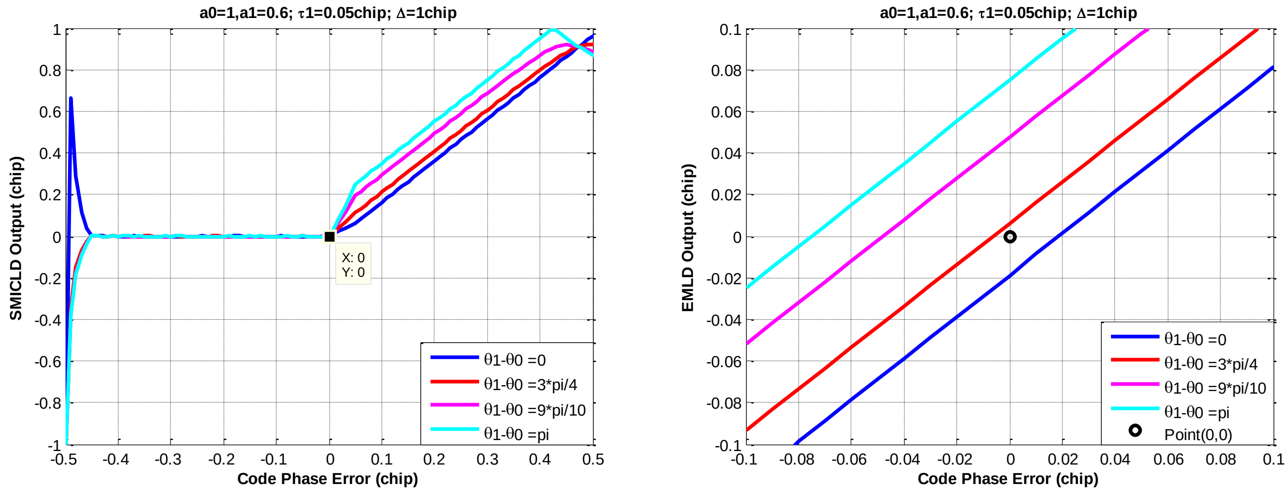


Fig. 2 SMICLD and EMLD output with single short delay multipath

Fig. 3 shows the multipath error envelope of SMICL and early minus late delay lock loop (EML-DLL) in the presence of single multipath with $\alpha = 0.6$ and $\Delta = 1$. When the multipath delay is less than 0.5chip, the code tracking error of SMICL is zero and its multipath mitigation performance is much better than EML-DLL. Even when the correlator spacing of EML-DLL decreases to 0.2 chips (Narrow Correlator), its code tracking error is still larger than SMICL. So SMICLD has excellent performance in mitigating single short delay multipath. However, with the multipath delay exceeding 0.5chips ($\min(\Delta/2, 1\text{-}\Delta/2)$), the code tracking error of SMICL increases dramatically. Note that when the carrier phase of long delay multipath is in phase with the direct signal, the tracking error envelope is negative due to the special discriminator expression of SMICLD.

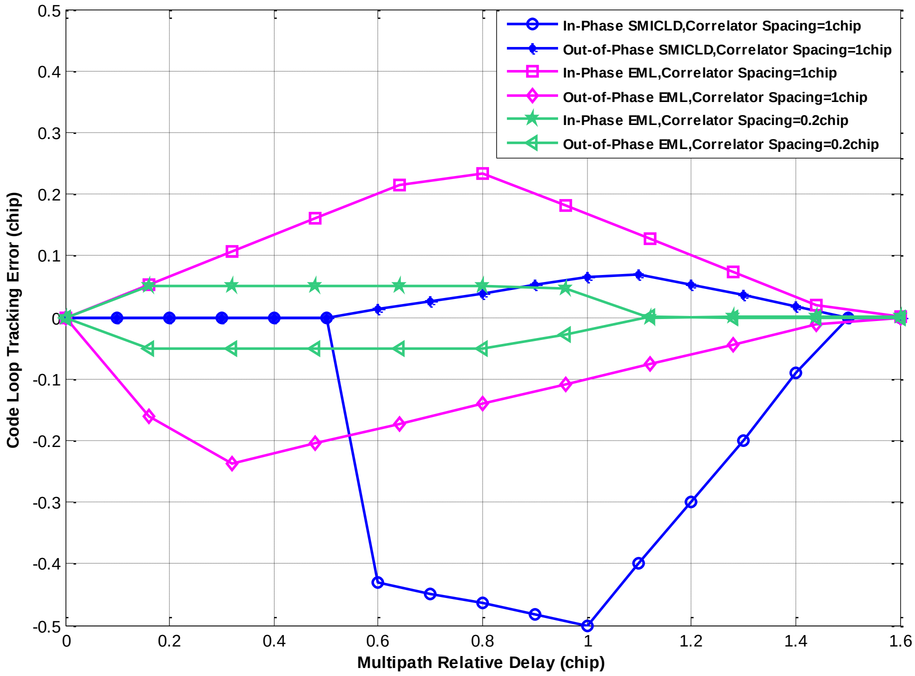


Fig. 3 Multipath error envelopes of SMICL and EML-DLL with single multipath

Therefore, SMICLD has the following disadvantages:

1. The output of SMICLD is zero when the code tracking error is negative, so SMICLD may lead to false lock or poor stability in the presence of strong noises and abrupt code phase changes.
2. SMICLD cannot function well with two or more multipath rays.
3. SMICLD cannot mitigate the medium and long delay multipath with the delay larger than min(Δ/2, 1-Δ/2).

This paper focuses on the problem of zero output of SMICLD on the negative axis, and proposes a simple but effective method to improve the stability of SMICLD.

MODIFIED DLL AIDED BY SMICLD

In the case of single short delay multipath, the output of SMICLD is always zero when the code phase error is negative, which may make the code phase of the local replica lock to the zero-crossing point located in the negative region. Jardak & Samama [2007] suggested to delay the initial phase of the prompt replica code with respect to the phase determined by the acquisition process by 0.5 chip, which made SMICLD work in the positive region ($\varepsilon > 0$) in the beginning of tracking. If the satellite signal suffers from strong noises or abrupt code phase changes caused by ionospheric scintillations, high dynamics or signal blocks during tracking, the code tracking error is likely to become negative.

In order to mitigate the short delay multipath and track the received signal accurately, a simple but effective algorithm is proposed to solve the problem of zero output of SMICLD in the negative region. Conventional DLL uses EMLD to detect code tracking errors. Although EMLD has a certain tracking bias in the presence of short delay multipath, its discriminator curve is still near linear and symmetrical around the zero-crossing point.

From this a modified code tracking loop aided by SMICLD, named modified DLL aided by SMICLD, can be constructed, where EMLD and SMICLD can complement each other. As a result, the receiver can suppress short delay multipath error and keep tracking the direct signal not only in the positive region but also in the negative region ($\varepsilon < 0$). The algorithm of modified DLL aided by SMICLD is illustrated in Figure 4.

When the code tracking error is positive, the code loop uses SMICLD; when the code tracking error is negative, the code loop uses modified EMLD. The key point is how to distinguish a zero code tracking error from a negative code error. A zero-crossing point searching strategy with controllable errors will be proposed in the following. Let CP_0, CE_0 and d represent the local replica code phase, the code tracking error, and the zero-crossing position resolution, respectively. When SMICLD outputs zero, the code phase of the local replica is reduced to CP_0-d, which means that the code tracking error $\varepsilon = CE_0$ is shifted to CE_0+d. The correlation and SMICLD will be computed again. If the new SMICLD output still remains zero, CE_0 will be considered as negative. Then the code loop is switched into the modified EML-DLL mode.

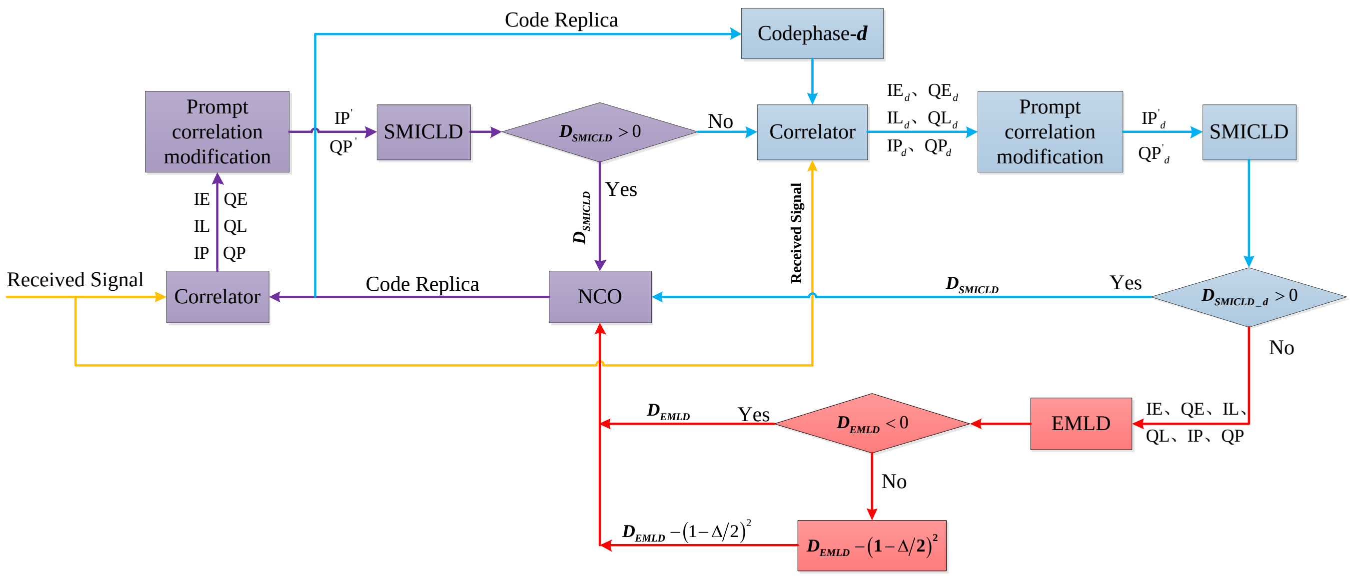


Fig. 4 Algorithm of modified DLL aided by SMICLD

It is noticed that although the slope of EMLD keeps positive near the zero-crossing point for all the single multipath situations, the zero-crossing point of traditional EMLD may be located on the negative axis. For example, when the multipath is out of phase with the direct signal, traditional EMLD will output a positive value for a small negative code error, which makes the code loop lock to the zero-crossing point on the negative axis. A simple solution to this problem is to subtract a certain value from the output of EMLD when CE_0 is negative and EMLD output is positive. Assuming that the DLL employs early-minus-later power discriminator (EMLP), the EMLP output is

$$D_{EMLP} = \left(IE^2 + QE^2\right) - \left(IL^2 + QL^2\right) \tag{20}$$

where

$$\begin{aligned}
IE &= a_0 R(\varepsilon - \Delta/2)\cos\theta_0 + a_1 R(\varepsilon - \tau_1 - \Delta/2)\cos\theta_1 \\
QE &= a_0 R(\varepsilon - \Delta/2)\sin\theta_0 + a_1 R(\varepsilon - \tau_1 - \Delta/2)\sin\theta_1 \\
IL &= a_0 R(\varepsilon + \Delta/2)\cos\theta_0 + a_1 R(\varepsilon - \tau_1 + \Delta/2)\cos\theta_1 \\
QL &= a_0 R(\varepsilon + \Delta/2)\sin\theta_0 + a_1 R(\varepsilon - \tau_1 + \Delta/2)\sin\theta_1
\end{aligned} \tag{21}$$

If $\tau_1 - \min(\Delta/2, 1-\Delta/2) < \varepsilon \le \min(\Delta/2, 1-\Delta/2)$, we can get

$$\begin{aligned}
R(\varepsilon - \Delta/2) &= \varepsilon - \Delta/2 + 1 \\
R(\varepsilon + \Delta/2) &= 1 - \left(\varepsilon + \Delta/2\right) \\
R(\varepsilon - \tau_1 - \Delta/2) &= \varepsilon - \tau_1 - \Delta/2 + 1 \\
R(\varepsilon - \tau_1 + \Delta/2) &= 1 - \left(\varepsilon - \tau_1 + \Delta/2\right)
\end{aligned} \tag{22}$$

By substituting (21) and (22) in (20), D_{EMLP} becomes:

$$D_{EMLP} = 4\left(1 - \frac{\Delta}{2}\right)\left[a_0^2 \varepsilon + a_1^2\left(\varepsilon - \tau_1\right) + a_0 a_1\left(2\varepsilon - \tau_1\right)\cos\left(\theta_0 - \theta_1\right)\right] \tag{23}$$

Without losing generality, the amplitude of the direct signal a_0 can be normalized to 1. Assuming that the multipath relative delay τ_1 is smaller than $1-\Delta/2$, the EMLP output with a zero code tracking error satisfies

$$
\begin{aligned}
D_{EMLP\_\varepsilon=0} &= -4\left(1-\frac{\Delta}{2}\right)\left[a_1^2\tau_1 + a_1\tau_1\cos\left(\theta_0-\theta_1\right)\right] \\
&\le -4\left(1-\frac{\Delta}{2}\right)\left[a_1^2\tau_1 - a_1\tau_1\right] < \left(1-\frac{\Delta}{2}\right)^2
\end{aligned}
\tag{24}
$$

Thereby $(1-\Delta/2)^2$ will be subtracted from D_{EMLP} if $D_{EMLP\_\varepsilon\le 0}$ >0, which ensures that

$$
-\left(1-\frac{\Delta}{2}\right)^2 \le D_{EMLP\_\varepsilon=0} - \left(1-\frac{\Delta}{2}\right)^2 < 0 \tag{25}
$$

If $D_{EMLP\_\varepsilon\le 0}$ <0, the expression of EMLP will not be changed. So the zero-crossing point of the modified EMLP-DLL is always located on the positive axis. Fig. 5 illustrates the S-curves of modified DLL aided by SMICLD in different conditions. The right half part is the S-curve of SMICLD, and the left half part belongs to the modified EMLP.

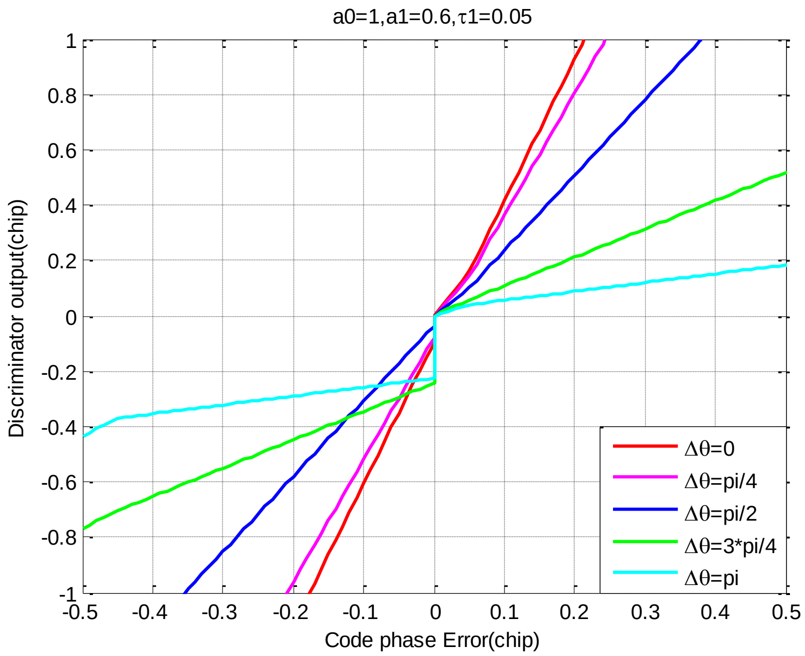


Fig. 5 S-curve of modified DLL aided by SMICLD

A specific example can be given to explain the code tracking process of modified DLL aided by SMICLD. Assuming that the code tracking error is -0.2chip and setting the resolution as *d*= 0.05chip, SMICLD will output zero. As shown in Fig. 6, the current state of the code loop is point A for SMICLD, and SMICLD still outputs zero after the code phase error increases 0.05chip. In this case, modified EMLD is employed at point A, and the current state of code loop is switched to point B. Then the local replica code phase is adjusted according to the output of modified EMLD, which switches the state of code loop to point C according to (25). The output of SMICLD is positive now, and then code tracking error will be pulled to zero by SMICLD.

The tracking process of SMICL, modified DLL aided by SMICLD and EML-DLL will be simulated in the presence of no noise and only one short delay multipath ray with a relative delay of 0.1 chips, relative amplitude of 0.6, a carrier phase difference between the direct and multipath signals of $\pi/6$, and an initial code tracking error of 0.03chip. In addition, the code tracking error jumps to -0.03chip at the time of 5 second.

As shown in Fig. 7, all the three discriminators can work stably in the first five seconds. The code tracking errors of SMICL and modified DLL aided by SMICLD are zero, whereas EML-DLL is affected by short delay multipath and has a certain tracking bias. After the abrupt code phase changes, SMICLD cannot find this negative-going phase error and thus locks to the point with a tracking bias of -0.03chip; EML-DLL recognizes this code phase change and adjust the code phase of local replica timely to track the received signal with the same zero-crossing-point bias; whereas modified DLL aided by SMICLD catches the phase jump, pulls the tracking error to zero.

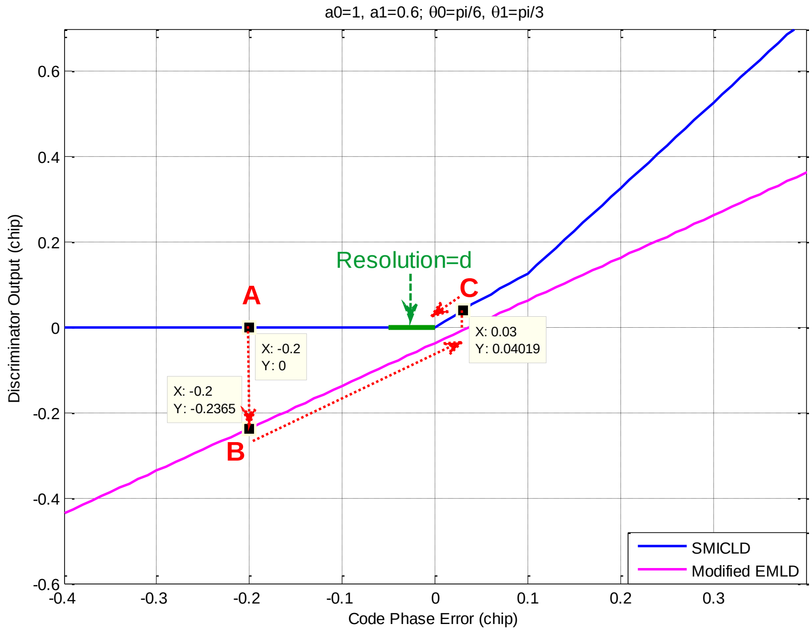


Fig. 6 Code phase tracking process of modified DLL aided by SMICLD

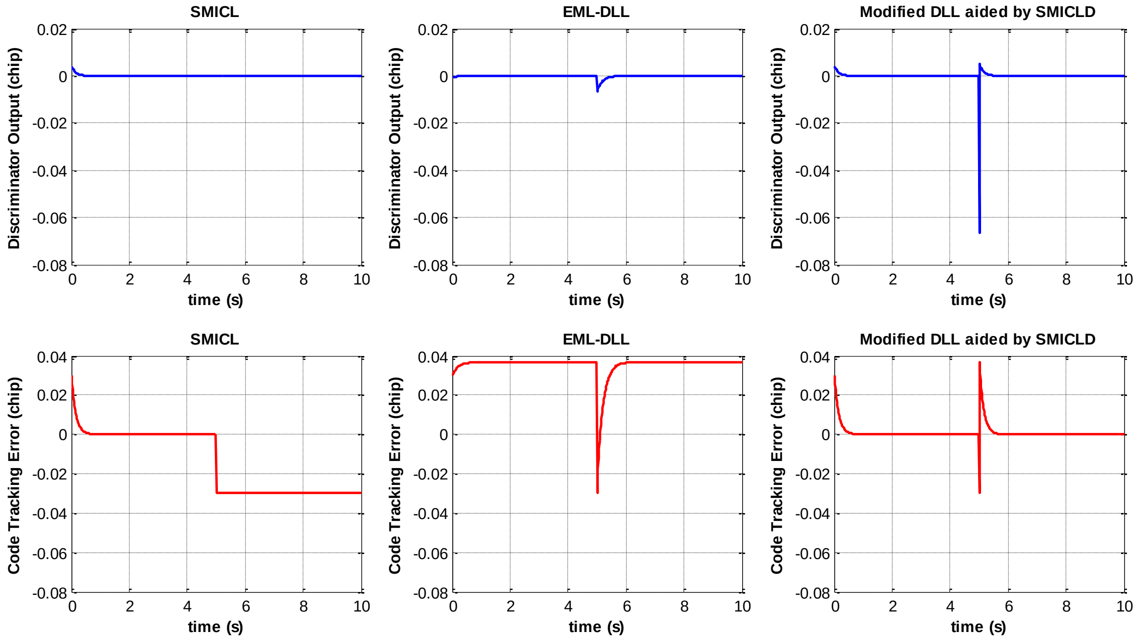


Fig. 7 Discriminator outputs and code tracking errors of SMICL, EML-DLL and modified DLL aided by SMICLD

TEST RESULTS

All the above-mentioned code tracking loops have been implemented in the software GPS L1 C/A receiver developed by our group. And the following four scenarios are simulated using our digital IF GPS signal simulator to test their performance against short delay multipath:

A. single-satellite signal with neither noise nor abrupt code phase jump;
B. single-satellite signal with noises;
C. single-satellite signal with abrupt code phase jumps;
D. single-satellite signal with both noises and abrupt code phase jumps.

And two kinds of multipath signals have been generated. One is in phase and the other is out of phase with the direct signal. The sampling frequency and the carrier frequency are 100MHz and 1.405MHz, respectively.

Firstly, the single-satellite digital IF GPS L1 C/A signal of scenario A is generated accompanied by one short delay in-phase multipath ray with a relative delay of 0.1chip and amplitude of 0.6. The correlator spacing of the software receiver is set to 1chip for SMICL and modified DLL aided by SMICLD, and 0.2chip for EML-DLL and MEDLL. Figure 8 shows the discriminator output, the code NCO output, and the code tracking error of SMICL obtained by the difference between the simulated code phase and the receiver code phase accumulator output.

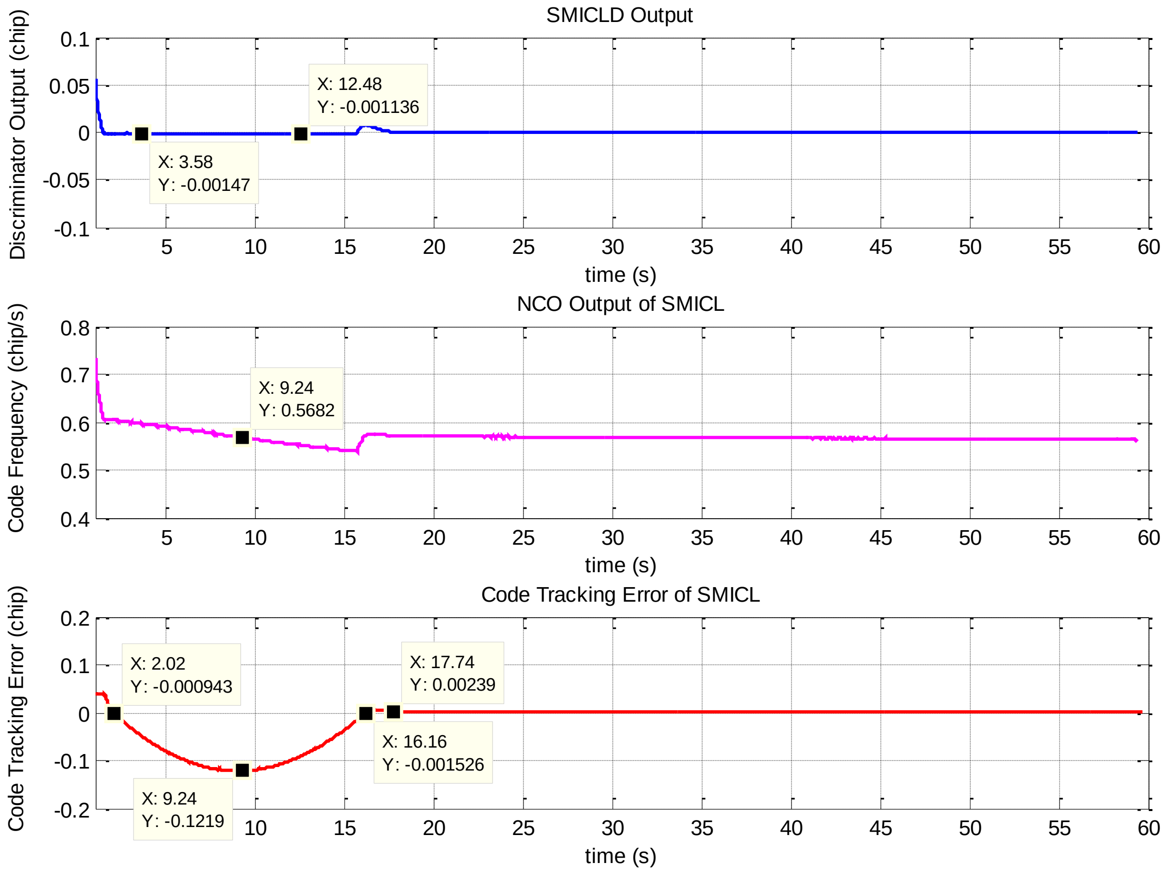


Fig. 8 Discriminator output and code tracking error of SMICL

It can be seen that the code tracking error of SMICL goes from a positive value to lower than -0.1chips and slowly converges to zero after about 17.7s. In steady state tracking, the output frequency of NCO F_{NCO} should be equal to the code frequency of the incoming signal. After the acquisition and pulling in process, both the initial code tracking error and the output of SMICLD are positive, and the NCO output frequency f_{NCO} is higher than F_{NCO}, which draws the tracking error to zero. At about 2.02s, although the code tracking error is zero, f_{NCO} is still higher than F_{NCO}. So the local replica keeps running faster than the received code. As a result, the code phase of the local replica will exceed that of the received signal. After 2.02s, the code tracking error is negative while SMICLD output keeps near zero. Note that when the code tracking error is negative, SMICLD actually outputs -0.001chip rather than zero, which makes the local replica code rate decrease very slowly. This is because the true correlation function is not all the same as the ideal correlation function expressed by (2). At about 9.24s, f_{NCO} is equal to F_{NCO}, so the code tracking error reaches its minimum. After 9.24s, f_{NCO} goes smaller than F_{NCO}, such that the code tracking error begins to decrease. At about 16.16s, the code tracking error is zero, and the received code rate is faster. Therefore, the code tracking error will become positive. SMICLD comes into its linear region and outputs a positive value, which drives f_{NCO} to higher, so the local replica code accelerates to reduce the code tracking error. At about 17.74s, the code tracking error converges to zero, and the code phase of the direct signal is locked.

The code tracking errors of SMICL, modified DLL aided by SMICLD, EML-DLL and MEDLL for Scenario A are compared in Fig. 9(a). It can be seen that EML-DLL and MEDLL exhibit a certain bias caused by short delay multipath. The code tracking error of SMICL fluctuates in the beginning and converges to zero very slowly due to its near zero negative output of discriminator. Modified DLL aided by SMICLD can timely adjust the local replica code phase to be aligned with the received signal and eliminate the bias induced by the short delay multipath, which combines the advantages of modified EMLD and SMICLD.

Fig. 9(b) shows the results of Scenario B with a carrier-to-noise ratio of 55dB-Hz and a frontend bandwidth of 2MHz. When the code tracking error jumps into the negative region caused by noises, SMICLD cannot identify it properly. Consequently the code tracking error of SMICL goes through large fluctuations as explained above. The jitter of EML-DLL is the smallest, but it locks onto a biased code phase. Nor can MEDLL eliminate this bias caused by short delay multipath. In contrast, modified DLL aided by SMICLD can mitigate the short delay multipath with much smaller fluctuations than SMICL.

Fig. 9(c) and Fig. 9(d) show the tracking results of Scenario C and D, where the code phase of the simulated signal is reduced by 0.1 chip at each integer multiple of 10s, and other parameters keep the same as those of Scenario A and B. It can be seen that SMICL cannot detect the code phase jumps and track the signal in time, whereas modified DLL aided by SMICLD overcomes this problem while mitigating the short delay multipath effect. Although the traditional EML-DLL and MEDLL can also detect the changes of the received signal code phase, they cannot eliminate the tracking bias induced by short delay multipath.

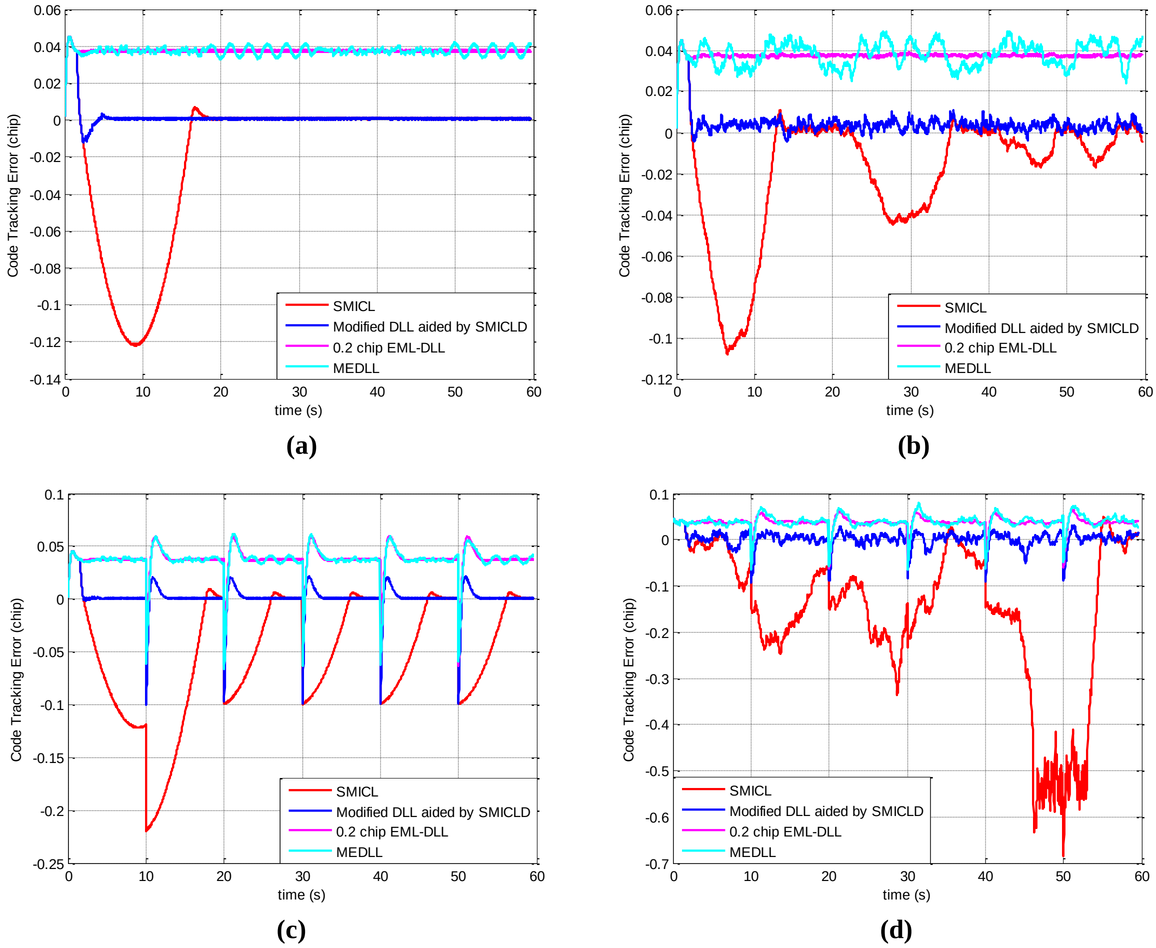
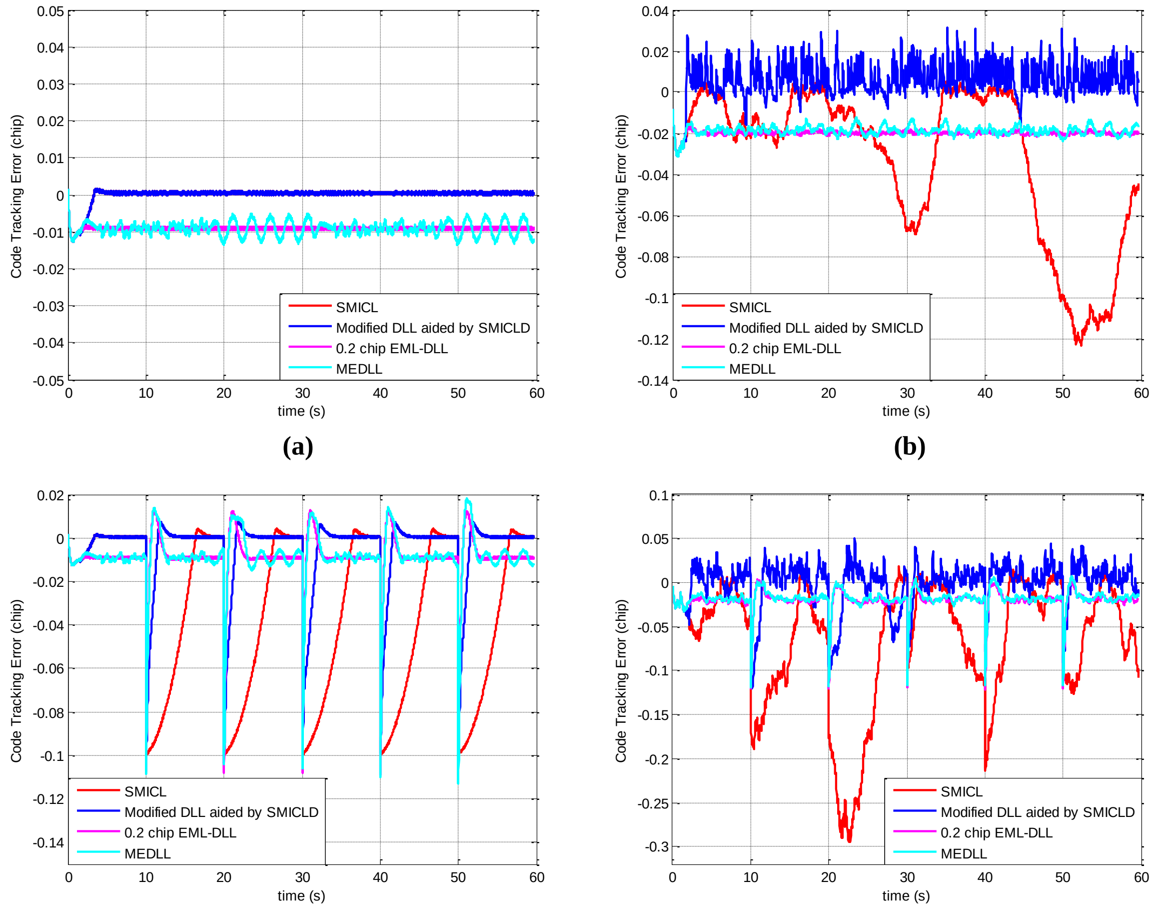


Fig. 9 Code tracking error of SMICL, modified DLL aided by SMICLD, EML-DLL and MEDLL with in-phase multipath in scenario: (a) A; (b) B; (c) C; (d) D

Since usually the multipath out of phase with the direct signal is more difficult to deal with than the in-phase multipath, this worse case is also tested with the above four scenarios. The out of phase multipath signal has a relative delay of 0.1chip and amplitude of 0.2. Fig.10 shows the code tracking errors of SMICL, modified DLL aided by SMICLD, EML-DLL and MEDLL of four scenarios with out-of-phase multipath.

Fig. 10(a) shows that the code error of SMICL is the same as that of modified DLL aided by SMICLD. This is because the small code error introduced by small multipath is within the error resolution *d*. Only SMICLD is used in modified DLL aided by SMICLD. Fig. 10(c) shows that modified DLL aided by SMICLD mitigates the short delay multipath and adjusts the local code phase timely to track the direct signal suffering from abrupt code phase jumps without noise. Fig. 10(b) and Fig. 10(d) show that modified DLL aided by SMICLD suffers from small fluctuations caused by noises, because that its S-curve goes through a gap from the zero-crossing point to the negative region. Noise has become an important error source in these cases due to the small slope of S-curve and small multipath. However, modified DLL aided by SMICLD still outperforms SMICL in terms of multipath mitigation and loop stability, and outperforms EML-DLL, MEDLL and SMICL in terms of code tracking bias.



(c) **(d)**

Fig. 10 Code tracking error of SMICL, modified DLL aided by SMICLD, EML-DLL and MEDLL with out-of-phase multipath in scenario: (a) A; (b) B; (c) C; (d) D

For a quantitative comparison, means and standard deviations of code tracking errors with two kinds of multipath in four scenarios presented above are summarized in Table 2 and Table 3.

Table 2: Means and standard deviations of code tracking errors with in-phase multipath

Multipath Mitigation Methods	Code tracking errors							
	Mean (chip)				Standard Deviation (chip)			
	Scenario A	Scenario B	Scenario C	Scenario D	Scenario A	Scenario B	Scenario C	Scenario D
EML-DLL	0.0374	0.0376	0.0371	0.0374	0.0022	0.0038	0.0138	0.0138
MEDLL	0.0374	0.0371	0.0369	0.0388	0.0028	0.0061	0.0144	0.0163
SMICL	-0.0360	-0.0181	-0.0523	-0.1581	0.0504	0.0319	0.0573	0.1631
Modified DLL aided by SMICLD	0.0029	0.0076	0.0019	0.0019	0.0087	0.0119	0.0132	0.0174

Table 3: Means and standard deviations of code tracking errors with out-of-phase multipath

Multipath Mitigation Methods	Code tracking errors							
	Mean (chip)				Standard Deviation (chip)			
	Scenario A	Scenario B	Scenario C	Scenario D	Scenario A	Scenario B	Scenario C	Scenario D
EML-DLL	-0.0091	-0.02	-0.0091	-0.0202	0.00058	0.0014	0.0126	0.0125
MEDLL	-0.0091	-0.0188	-0.0087	-0.0186	0.0019	0.0024	0.0131	0.0126
SMICL	$6e^{-6}$	-0.033	-0.0338	-0.0665	0.0021	0.0370	0.0381	0.0726
Modified DLL aided by SMICLD	$6e^{-6}$	0.0053	-0.0052	-0.0020	0.0021	0.0085	0.0177	0.0263

It can be seen that:

(1) The means of tracking errors of modified DLL aided by SMICLD are smaller than those of other code loops in four scenarios, which means that modified DLL aided by SMICLD has the best performance on short delay multipath mitigation among the four code loops.

(2) Although modified DLL aided by SMICLD are more sensitive to noise than MEDLL and EML-DLL, the standard deviations of its code tracking errors are much smaller than those of SMICL, and its noise jitters are partly controllable. In our view, the multipath induced bias is more problematic than the noise jitter which can be further reduced by parameter tuning and appropriate filtering in the future.

CONCLUSIONS

This paper has analyzed the multipath mitigation performance of SMICLD. Although SMICLD can mitigate short delay multipath, the zero output in the negative region of its S-curve leads to large biases under noises and abrupt code phase changes. Additionally, SMICLD does not work well with two or more multipath rays or with medium and long delay multipath.

Aiming at improving the S-curve of SMICLD, this paper proposes a modified DLL aided by SMICLD, as well as a strategy to identify the polarity of the code tracking error. The algorithm uses modified EML discriminator for negative code tracking error and switches to SMICLD for positive code tracking error. Simulation results show that the modified DLL aided by SMICLD keeps the short delay multipath mitigation performance of SMICL while overcoming its disadvantages of instability under severe signal phase fluctuations.

The modified DLL aided by SMICLD, SMICL, EML-DLL and MEDLL have been implemented in our software receiver and their short delay multipath mitigation performances have been compared by using the digital IF GPS signal simulator in different scenarios with in-phase and out-of-phase multipath. Test results show that modified DLL aided by SMICLD can not only mitigate the code tracking biases caused by short delay multipath, but also timely adjust the local replica code phase to track the received signal in the presence of noises and abrupt code phase jumps and thus overcomes the stability problem of SMICLD.

Future work includes fine parameter tuning and effective filtering to reduce the gap in its S-curve and thus reduce the noise jitter. The cases with more than one multipath rays will also be investigated.

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