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Receiver-channel based adaptive blind equalization approach for GPS dynamic multipath mitigation

Zhao Yun *, Xue Xiaonan, Zhang Tingfei

School of Electronics and Information Engineering, Beihang University, Beijing 100191, China

Abstract Aiming at mitigating multipath effect in dynamic global positioning system (GPS) satellite navigation applications, an approach based on channel blind equalization and real-time recursive least square (RLS) algorithm is proposed, which is an application of the wireless communication channel equalization theory to GPS receiver tracking loops. The blind equalization mechanism builds upon the detection of the correlation distortion due to multipath channels; therefore an increase in the number of correlator channels is required compared with conventional GPS receivers. An adaptive estimator based on the real-time RLS algorithm is designed for dynamic estimation of multipath channel response. Then, the code and carrier phase receiver tracking errors are compensated by removing the estimated multipath components from the correlators' outputs. To demonstrate the capabilities of the proposed approach, this technique is integrated into a GPS software receiver connected to a navigation satellite signal simulator, thus simulations under controlled dynamic multipath scenarios can be carried out. Simulation results show that in a dynamic and fairly severe multipath environment, the proposed approach achieves simultaneously instantaneous accurate multipath channel estimation and significant multipath tracking errors reduction in both code delay and carrier phase.

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1. Introduction

Despite continuing improvements in global positioning system (GPS) receivers, multipath signal propagation has re-
mained an unsolved problem.[1] Since a conventional receiver provides no inherent discrimination against multipath signals, the reception of additional signal replica due to reflections causes a bias error in the code delay tracking loop, and also affects the carrier phase tracking loop. When employing 1-chip (early-late correlator spacing) wide standard delay lock loop to track the delay, multipath can introduce a ranging error up to a hundred of meters into a GPS L1 receiver.[2] Meanwhile, the resulting differential carrier phase estimation error can be orders of magnitude higher compared to the case of no multipath propagation in GPS precision applications.[3]

* Corresponding author. Tel.: +86 10 82339721.
  E-mail address: yunzhao@buaa.edu.cn (Y. Zhao).

So far receiver-based approaches to GPS multipath mitigation have obtained significant progress, notable among them are modified tracking channel and multipath estimation techniques. Modified tracking channel methods, such as strobe correlator[4] or pulse aperture correlator,[5] achieve the modified delay-lock discriminator function shape through combination of two correlation discriminators for multipath error reduction. The advantages of this family of methods are that they are relatively simple and able to work in real time. Nevertheless, these methods can only reduce code multipath error to a limited extent, and are not effective in eliminating carrier multipath error. Multipath estimation methods, such as multipath estimation delay lock loop (MEDLL)[6] or multipath mitigation technique (MMT),[7] estimate the unknown parameters of the multipath signal model for multipath error compensation. MEDLL applies the maximum-likelihood estimation theory and can mitigate code and carrier multipath errors, while MMT improves the real-time performance of MEDLL. However, they are only suitable for quasi-static multipath scenarios. Multipath estimators based on the sequential Bayesian estimation are designed for dynamic multipath scenarios,[8,9] i.e., particle filters (from navigation signals' point of view, multipath belongs to multiplicative noises, and standard Kalman filters are not suitable), which require state transition models as a first step towards dynamic estimation, e.g., the multipath delay sequence is usually assumed to be a first-order Markov process.[10] However, for complex and time-variant multipath environments, it is usually difficult to build prior models for actual multipath processes.

From the perspective of navigation satellite channels, and without making an assumption of channel statistical models, channel equalization techniques based on adaptive algorithms are capable of tracking the dynamics of channels and achieving simultaneous multipath estimation and mitigation of multipath tracking errors. The channel equalization methods for global navigation satellite system (GNSS) multipath estimation and mitigation have been addressed in a few literatures. For example, in Ref.[11], a least square algorithm was used and simulation results for multipath scenarios with up to six multipaths were illustrated. In Ref.[12], a modified back-propagation (BP) algorithm (a stochastic gradient least mean square algorithm) was presented to mitigate multipath tracking errors. However, neither the least square algorithm nor the BP algorithm can provide the capability of processing real dynamic multipath.

In this paper, the wireless communication channel equalization theory is applied to the tracking channel processing of GPS receivers, and a dynamic multipath mitigation method based on channel blind equalization and the real-time recursive least square (RLS) adaptive algorithm is proposed. Aiming at effectively mitigating the multipath effect in dynamic and accurate GPS navigation applications, a multipath equalizer at the receiver tracking channel level is especially designed for dynamic navigation satellite channels, which can compensate time-variant multipath tracking errors in both code delay and carrier phase, and differs from the techniques for measurement or positioning domain of the receiver. By employing a navigation satellite signal simulator and a GPS software receiver, simulations and the corresponding results for a dynamic and fairly severe multipath environment are given.

2. Blind channel equalization for dynamic multipath mitigation

Telecommunication applications of channel equalization are techniques for dealing with channel distortion problems to improve communication performance. For conventional channel equalization approaches, training sequences periodically transmitted through the channel are needed in order to obtain optimal or near optimal coefficients of the equalizer by training. However, for satellite navigation systems, no training sequence is available, so that a blind equalization approach is employed.

From a single receiver channel's point of view, according to the telecommunication channel equalization theory,[13] the multipath propagation channel corresponding to a navigation satellite can be modeled as

$$y(t) = s(t) \otimes h_c(t) \tag{1}$$

where $s(t)$ represents the transmitted satellite signal, "$\otimes$" is the convolution operator, and $h_c(t)$ represents the impulse response of the multipath channel that is time-variant and unknown to the receiver.

After the receiver correlation processing equivalent to the impulse response function $s(-t)$, the correlator output becomes

$$h_e(t) = y(t) \otimes s(-t) = R_s(t) \otimes h_c(t) \tag{2}$$

where $R_s(t)$ is the auto-correlation function of $s(t)$ and $h_e(t)$ is the equivalent signal channel response, i.e., $h_e(t) \approx h_c(t)$; therefore, the multipath channel output can be approximated by the correlation outputs.

In the presence of multipath, as an important effect in the receiver tracking channel, the ideal triangular correlation function would lose its symmetry. This distortion of the correlation function is illustrated in Fig. 1, where only one-path multipath arrives in the receiver tracking channel, which is just in-phase (see Fig. 1(a)) or out-of-phase (see Fig. 1(b)) with the direct signal. Note that the circle-marker dotted line represents the original triangular correlation function, the cross-marker dotted line the multipath correlation function, and the solid line is the composite of the two. Whereas for multiple-path multipath scenarios, the correlation function distortion could be very complex.

For conventional receiver tracking loops, the operation of code delay tracking loop is based on the measurement of the early and late correlation outputs. According to the early and late correlation values Y_e and Y_l, the prompt correlation value Y_p can then be computed.[14] In the case of no multipath, one in-phase multipath, and one out-of-phase multipath, the early, prompt, and late correlation outputs are illustrated respectively in Fig. 2 (the correlator spacing of 0.5 chip is assumed). It indicates that the prompt correlation value would coincide with the ideal correlation peak only if $Y_e = Y_l$; the correlation function distorted by multipath, i.e., $Y_e \neq Y_l$, results in an additional code tracking error. Since the carrier phase estimation depends on the in-phase and quadrature-phase components of the prompt correlation, an additional carrier phase tracking error is also introduced.

In this paper, the above characteristic of the multipath channel outputs is utilized in the multipath equalizer. In order to obtain the details of the correlation function, a conventional tracking channel is expanded to consist of a set of correlators that cover the code delay from -1.5 chips to $+1.5$ chips (the multipath effects corresponding to the code delay out of this
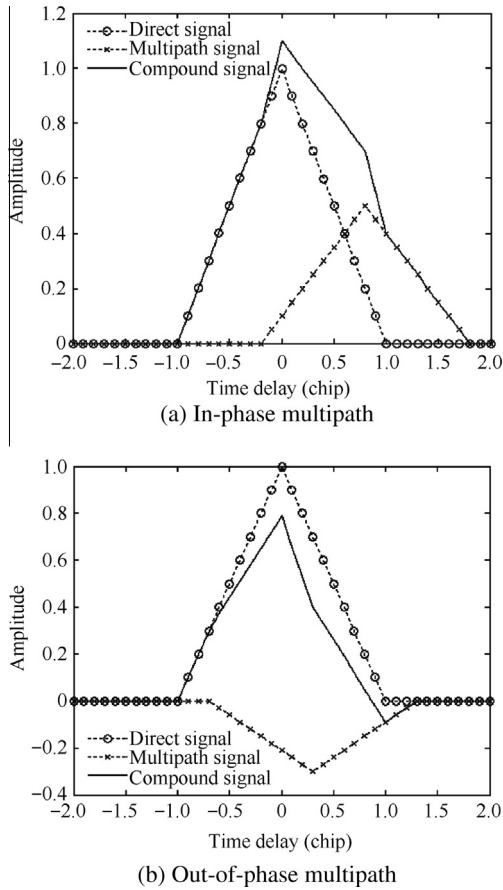
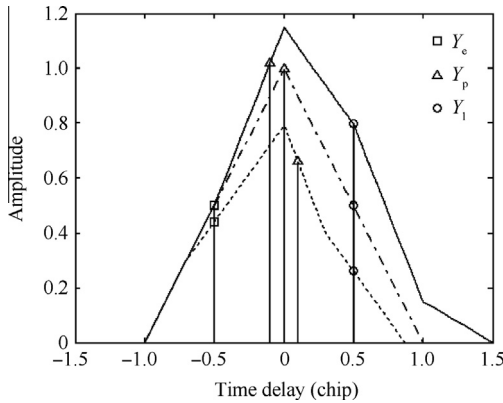**Fig. 1** Correlation function distortion due to multipath.

Fig. 2 Correlation distortion resulting code tracking error.

scope are assumed to be suppressed by the correlator itself) and have a resolution of 0.01 chip (i.e., the minimum correlator spacing). In contrast, only a pair of the early and late correlators is employed for a conventional receiver channel. The above design is equivalent to over-sampling of the complete correlation function, which would result in the innovation acquirement and transformation of a non-stationary process for multipath channels into a cyclostationary process, and thus the two-order statistics can be applied.[15]

Fig. 2 depicts the ideal correlation function shape, but in an actual receiver, only its approximator can be got, and there is a

loss of the correlation peak. In order to combat this effect, a considerably wider pre-correlation bandwidth (e.g., 20 MHz or above) compared to conventional receivers is required, which would result in higher sampling frequency. Despite the challenges, a software receiver (as used in this paper) can fulfill the above requirements much more easily than inflexible hardware receivers.

In telecommunication applications, a channel equalizer has two modes: a direct channel filter; an estimator for channel impulse response estimation plus an inverse-filter for channel response equalization. The latter one is more suitable for time-variant channels and has the advantage of robustness.[16] In this paper the latter equalizer mode is chosen.

The proposed approach consists of first adaptively estimating the impulse response of the time-variant multipath channel, which is based on the channel observations from the expanded correlators (each correlation arm corresponds to a specific code delay) with the digital intermediate frequency (IF) signal as input. This step is followed by achieving an inverse-filter that equalizes the multipath channel response to the desired channel response of multipath free to the maximum extent possible. This multipath channel blind equalizer integrated into a receiver tracking channel is illustrated in Fig. 3. If no multipath occurs, i.e., no correlation distortion is detected, the equalization would not take effect.

3. Adaptive estimation of dynamic multipath channel

Assuming an ideal channel with no multipath, the incoming line-of-sight (LOS) navigation signal to a GPS receiver channel can be expressed as

$$s(t) = A_c c(t - \tau_0) \cos(\omega_c(t - \tau_0)) + n(t) \qquad (3)$$

where A_c is the received signal amplitude, $c(t)$ the spread-spectrum code (i.e., C/A code), ω_c the angular frequency of the received signal, τ_0 the time delay of the LOS signal, $n(t)$ the additive white Gaussian noise, and the navigation data are not taken into account here. Whereas in the presence of multipath, N-path multipath components are assumed, then the input signal is now given by

$$s_m(t) = A_c c(t - \tau_0) \cos(\omega_c(t - \tau_0)) + n(t) + \alpha_1 A_c c(t - \tau_1)$$
$$\times \cos(\omega_c(t - \tau_1) + \theta_{m1}) + \alpha_2 A_c c(t$$
$$- \tau_2) + \theta_{m2}) + \cdots + \alpha_N A_c c(t - \tau_N)$$
$$+ \theta_{mN}) \qquad (4)$$

where the vector $\begin{bmatrix} \alpha_1 & \alpha_2 & \cdots & \alpha_N \end{bmatrix}$ represents the multipath amplitude ratio with respect to the LOS signal, $\begin{bmatrix} \tau_1 & \tau_2 & \cdots & \tau_N \end{bmatrix}$ is the multipath delay vector and $\begin{bmatrix} \theta_{m1} & \theta_{m2} & \cdots & \theta_{mN} \end{bmatrix}$ the multipath phase vector.

After the correlation with the receiver's locally generated signal, the resulting in-phase (i) components of a pair of early and late correlator outputs can be described as

$$R_{Ei}(\tau) = h_{0i} R_c(\tau - \tau_d) + h_{1i} R_c(\tau - \tau_d - \tau_1) + h_{2i} R_c(\tau - \tau_d$$
$$- \tau_2) + \cdots + h_{Ni} R_c(\tau - \tau_d - \tau_N) \qquad (5)$$

$$R_{Li}(\tau) = h_{0i} R_c(\tau + \tau_d) + h_{1i} R_c(\tau + \tau_d - \tau_1) + h_{2i} R_c(\tau + \tau_d$$
$$- \tau_2) + \cdots + h_{Ni} R_c(\tau + \tau_d - \tau_N) \qquad (6)$$
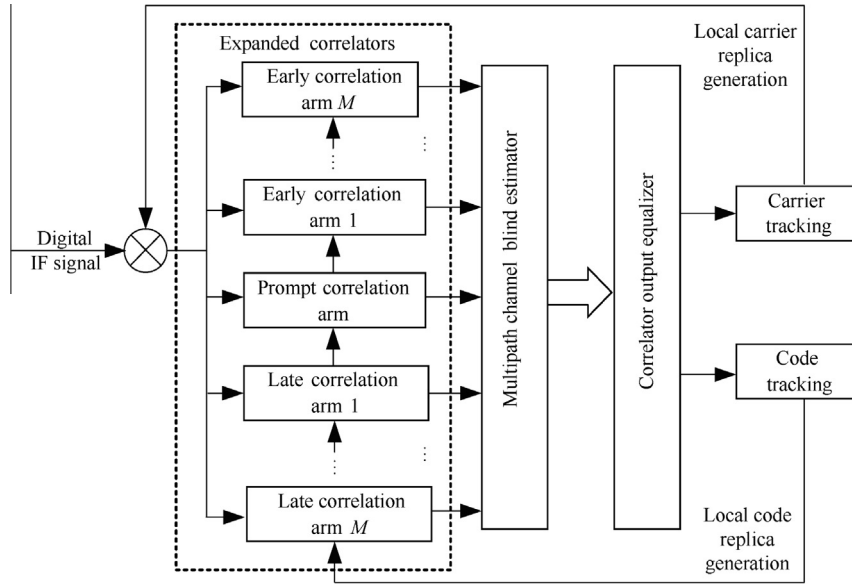
while the corresponding reference signals are

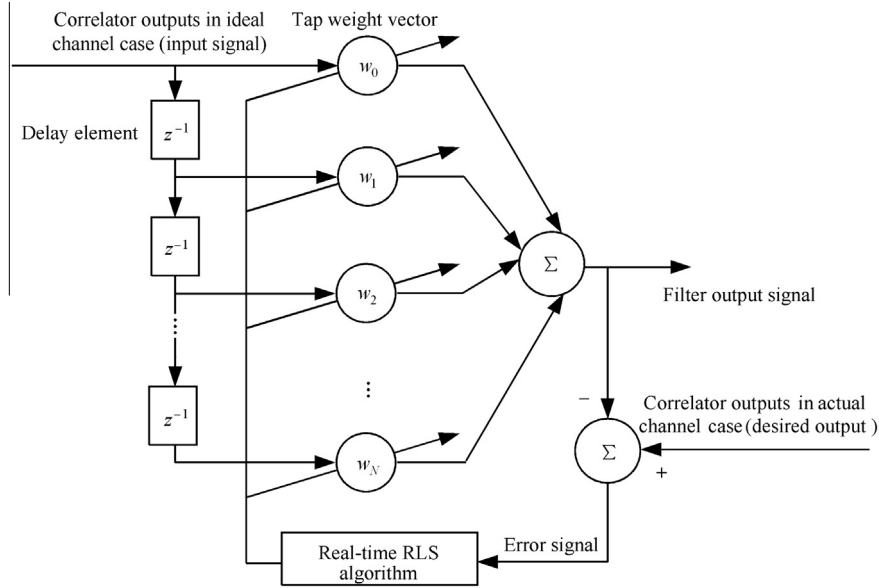**Fig. 3** Multipath channel blind equalizer for a receiver tracking channel.

Fig. 4 Multipath estimator based on an adaptive filter.

$$s_E(t) = 2\cos\left(\omega_0 t + c(t - \tau + \tau_d)\frac{\pi}{2}\right) \tag{7}$$

$$s_L(t) = 2\cos\left(\omega_0 t + c(t - \tau - \tau_d)\frac{\pi}{2}\right) \tag{8}$$

and the local carrier may be written as

$$l_i(t) = 2\cos(\omega_1 t + \theta) \tag{9}$$

where τ represents the code delay estimated by the receiver, which consists of the LOS signal propagation delay estimation and the code tracking error caused by multipath; τ_d is the offset delay for the early or late correlator, i.e., the correlator spacing; θ represents the estimated carrier phase, which consists of the LOS signal carrier phase estimation and the carrier phase tracking error caused by multipath; ω_0 is the reference angular frequency, $\omega_1 = \omega_c - \omega_0$; $R_c(\cdot)$ the correlation function; $[h_{0i} \quad h_{1i} \quad \cdots \quad h_{Ni}]$ represents the discrete channel impulse response coefficients for the in-phase components, and the kth vector element can be expressed as

$$h_{ki} = \alpha_k A_c \cos(\theta_{mk} - \theta) \tag{10}$$

The corresponding quadrature-phase (q) components of the correlators' outputs can be obtained by replacing cosine-function in the above equations with sine-function.

The multipath channel blind estimator is achieved by an adaptive filter, in which the correlation function for the ideal multipath-free channel is used as the input signal of the filter, and the correlation output vector corresponding to the actual multipath channel is used as the desired output signal. The order of the adaptive filter (i.e., the number of delay taps plus 1) depends on the time delay resolution for the multipath, and in this paper the delay resolution is 0.01 chip, i.e., the sampling interval of the correlation function (this interval and the signal

sampling interval of the receiver are both independent). The adaptive algorithm is utilized, that is, when the filter approaches convergence, its tap coefficients can represent the channel parameters. This adaptive filter for the multipath channel blind estimation is illustrated in Fig. 4, in which the time delays of the filter taps represent the discriminable multipath relative delay, and the weights of the filter taps represent the multipath amplitudes in complex forms (the absolute value and phase angle for amplitude and carrier phase, respectively). Thus, the multipath components are rebuilt by the adaptive filter based on the measurements of the correlators' outputs.

The adaptive filter approaches the channel impulse response recursively by using the real-time RLS adaptive algorithm[13], which is characterized by the forgetting factor and quite suitable for time-variant channel parameter estimation. In this algorithm the tap weights are updated by minimizing the accumulative square error function as

$$J(n) = \sum_{j=1}^{n} \lambda^{n-j} e^*(j,n) e(j,n) \qquad (11)$$

where λ is the forgetting factor that determines the dependence degree of the algorithm upon the channel's historical sampled data; $e^*(j,n)$ represents the complex conjugate of $e(j,n)$, which is the error computed by using the tap weight vector at time instance n to test the channel's sampled data at time instance j. If the algorithm has converged at time instance n, which indicates that $J(n)$ has reached the minimum value, the channel impulse response coefficients are obtained, i.e., they can be represented by the tap weight vector at that time.

4. Receiver tracking error compensation

The multipath estimator is followed by a compensator, so that the correlation outputs distorted by multipath can be compensated, and thus the multipath tracking errors in both code delay and carrier phase are mitigated. With the estimated multipath channel parameters, the correlation function for each multipath component would be obtained. Since the correlation function for the ideal multipath-free channel is known, it can be used to separate the multipath components from the LOS signal. In addition, the multipath signal is assumed to be delayed and has lower power compared to the LOS signal. Therefore, the correlation function can be decomposed into the LOS signal part and the multipath components part, and then the correlation distortion is compensated as follows:

$$R_{\text{com}}(\tau) = R_{\text{r}}(\tau) - \sum_{p=1}^{N} R_{\text{m}p}(\tau) \qquad (12)$$

where $R_{\text{r}}(\tau)$ represents the correlation value of received signal, $\sum_{p=1}^{N} R_{\text{m}p}(\tau)$ is the sum of the correlation values of multipath components and $R_{\text{com}}(\tau)$ the compensated correlation value.

Since the tracking errors caused by multipath in code delay and carrier phase tracking loops mainly come from the distortion of the correlation function, the correlation compensation enables the tracking loops to track the LOS signal, i.e., it achieves multipath mitigation in the tracking loops.

5. Simulation results

For performance assessment, simulations with the proposed adaptive blind multipath equalizer have been carried out.

The multipath signals are generated by a navigation satellite signal simulator,[17] which provides multipath modeling for urban navigation environments.[18] In the simulations, a typical dynamic multipath scenario is specified in which a vehicle carrying a receiver with an antenna mounted on its roof moves along street surrounded by high buildings and has a straight line trajectory at a speed of 20 m/s. Near echoes that have shorter delays and a lower power (their power decrease exponentially with their delays) play a leading role in the simulated multipath scenarios. Being incorporated with the above multipath channel blind equalizer, a software receiver[19,20] processes the signal simulator's generated signals with the non-coherent early-minus-late delay lock loop (DLL) for code delay tracking and a Costas phase locked loop (PLL) for carrier phase tracking. Only GPS L1 signal is involved in the simulations, and the signal's carrier-to-noise-density ratio (C/N_0) is set to be 45 dB-Hz. Lower C/N_0 is expected, but the C/N_0 that this equalization approach can reach mainly depends on the multipath component of the lowest power.

In this dynamic multipath scenario, a specific satellite (Satellite 22) channel example is given hereafter. Despite multipath occur in multiple satellite channels in this scenario, each satellite channel can be considered independently. The multipath signals and their associated satellite channel signals could enter the same receiver channel, which leads to the multipath effect, but they would not affect other receiver channels owing to cross-correction. At the beginning of the simulation scenario taking effect, there is only a direct path between the satellite and the receiver antenna. After the first 3 s of the scenario, the multipath signal components appear and enter the receiver, which causes the obvious tracking errors. Finally, after 8.3 s of the multipath duration, the normal tracking is recovered. In the above process, the corresponding prompt correlator output ($\sqrt{i^2 + q^2}$) values for this satellite are shown in Fig. 5.

For evaluation of the multipath estimation performance, an example at a specific simulation epoch is given. At this simulation epoch, the signal simulator simulates the received signal for a specific receiver channel composed of one direct-path satellite signal and 12 multipath components. The multipath estimator is based on the adaptive filter with 151 delay taps and the RLS algorithm having a forgetting factor of 0.98 (the expe-
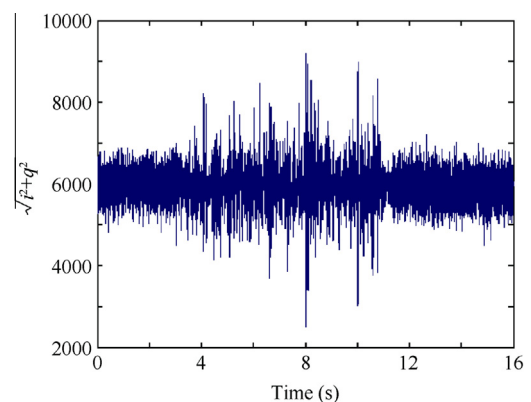

Fig. 5 Prompt correlator output of a receiver channel under a dynamic multipath scenario.

rience values for the forgetting factor are from 0.95 to 0.99, and this value is obtained by a trial). In the test, this multipath estimator has converged after five iterations. It indicates that this approach is qualified for processing dynamic multipath, in contrast to the conventional adaptive algorithms that require dozens or even hundreds times of iterations. The
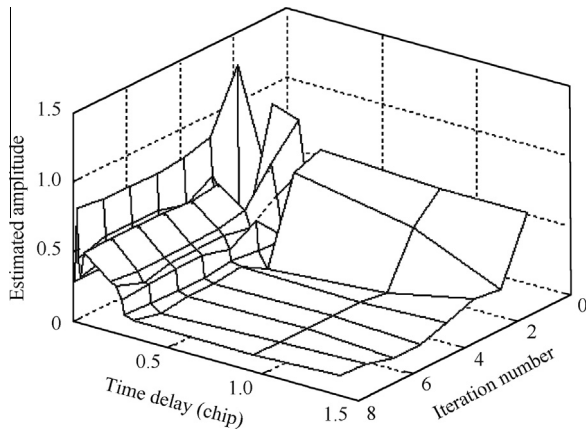

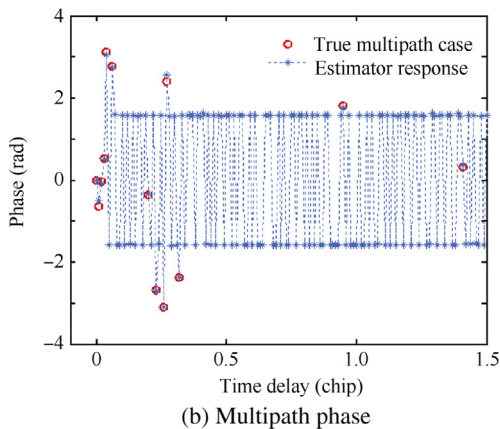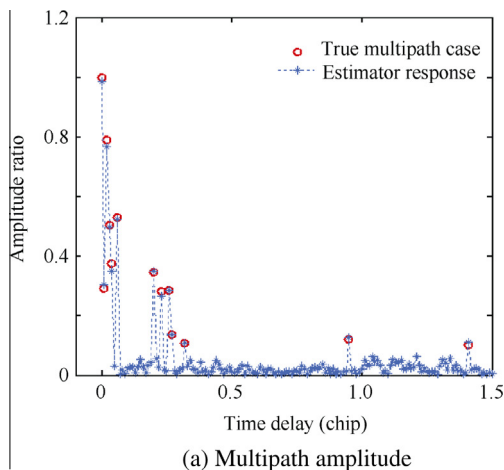**Fig. 6** Estimation improvement over the iteration number.

(a) Multipath amplitude

(b) Multipath phase

Fig. 7 Estimation performance for multipath amplitude and multipath phase.

(a) Before multipath compensation
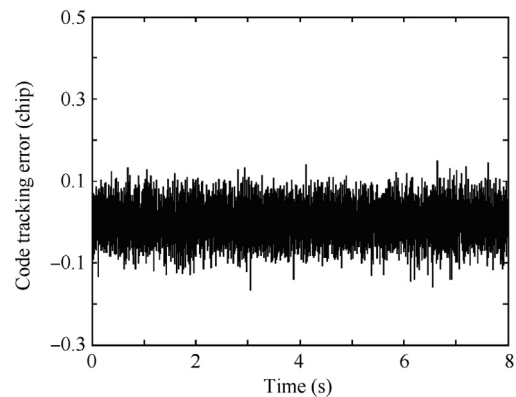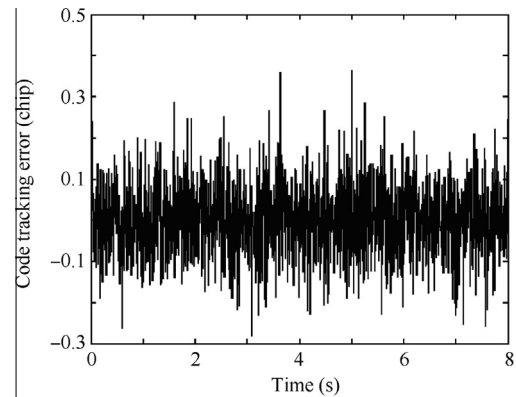

(b) After multipath compensation

Fig. 8 Compensation performance for code tracking error.

improvement in the multipath amplitude estimation over the RLS algorithm iteration number is depicted in Fig. 6.

The resulting estimation performance is shown in Fig. 7, in which the estimated channel parameters for every 0.01 chip step are compared to those the simulator has generated. Fig. 7(a) and (b) represent the estimation performance for the amplitude ratio and carrier phase, respectively. The resulting multipath estimation errors for the amplitude ratio and carrier phase are 0.014 (i.e., 0.3 dB) and 0.086 rad (i.e., 0.01 cycles).

According to the estimated multipath parameters, the correlation function for each multipath component is determined and removed from the actual correlator outputs. The resulting performance for mitigating the tracking errors over 8.3 s of the multipath duration are shown in Figs. 8 and 9, in which the tracking errors after the channel equalization are compared to the original multipath tracking errors. Fig. 8(a) and (b) represents the original tracking error and compensation performance for the code. Meanwhile, Fig. 9(a) and (b) represents the original tracking error and compensation performance for the carrier phase. The original code and carrier phase tracking errors caused by multipath and noise are 0.09 chip (1σ) and 0.21 rad (1σ), respectively, and the corresponding errors after multipath mitigation are reduced to 0.04 chip (1σ) and 0.09 rad (1σ), respectively. Then the normal tracking of the receiver is recovered, although the specific tracking errors relate to the receiver design.

(a) Before multipath compensation
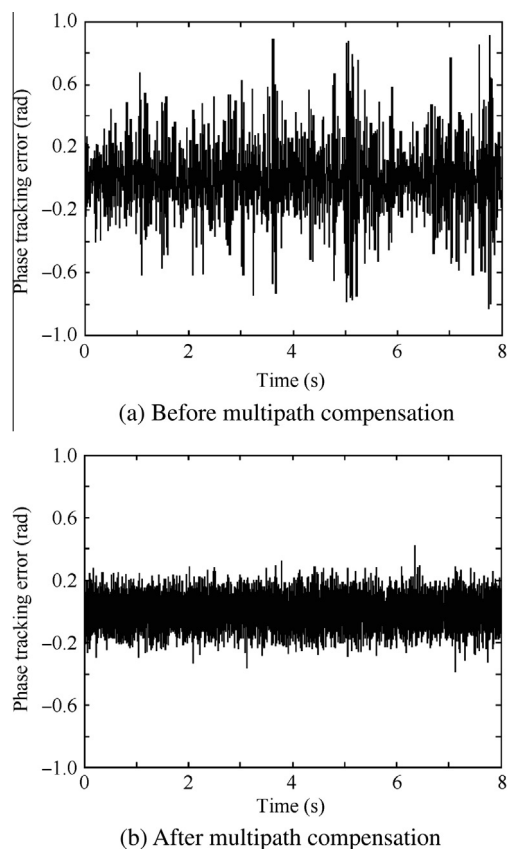

(b) After multipath compensation

Fig. 9 Compensation performance for phase tracking error.

6. Conclusions

A receiver-channel based dynamic multipath mitigation approach for simultaneous estimation of multipath channel response and compensation of multipath tracking errors in both code delay and carrier phase loops is proposed in this paper, which is achieved by the channel blind equalization technique and the real-time RLS adaptive algorithm.

For evaluation of performance, simulations in which a navigation satellite signal simulator and a GPS software receiver are employed are carried out. Under a dynamic and fairly severe multipath scenario involving up to 12 multipath components, the proposed approach achieves accurate multipath channel estimation within a few iterations of the adaptive algorithm, and simultaneously reduction of multipath tracking errors in both code delay and carrier phase to reach the normal tracking level of the receiver.

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Zhao Yun is a lecturer in the School of Electronics and Information Engineering at Beihang University. Her main research interests lie in satellite navigation signals simulator, GNSS multipath environment simulation, and multipath mitigation.