Analysis of Multipath Mitigation Techniques with Land Mobile Satellite Channel Model

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Abstract. *Multipath is undesirable for Global Navigation Satellite System (GNSS) receivers, since the reception of multipath can create a significant distortion to the shape of the correlation function leading to an error in the receivers' position estimate. Many multipath mitigation techniques exist in the literature to deal with the multipath propagation problem in the context of GNSS. The multipath studies in the literature are often based on optimistic assumptions, for example, assuming a static two-path channel or a fading channel with a Rayleigh or a Nakagami distribution. But, in reality, there are a lot of channel modeling issues, for example, satellite-to-user geometry, variable number of paths, variable path delays and gains, Non Line-Of-Sight (NLOS) path condition, receiver movements, etc. that are kept out of consideration when analyzing the performance of these techniques. Therefore, this is of utmost importance to analyze the performance of different multipath mitigation techniques in some realistic measurement-based channel models, for example, the Land Mobile Satellite (LMS) channel model [1]-[4], developed at the German Aerospace Center (DLR). The DLR LMS channel model is widely used for simulating the positioning accuracy of mobile satellite navigation receivers in urban outdoor scenarios. The main objective of this paper is to present a comprehensive analysis of some of the most promising techniques with the DLR LMS channel model in varying multipath scenarios. Four multipath mitigation techniques are chosen herein for performance comparison, namely, the narrow Early-Minus-Late (nEML), the High Resolution Correlator, the C/N_0-based two stage delay tracking technique, and the Reduced Search Space Maximum Likelihood (RSSML) delay estimator. The first two techniques are the most popular and traditional ones used in nowadays GNSS receivers, whereas the later two techniques are comparatively new and are advanced techniques, recently proposed by the authors. In addition, the implementation of the RSSML is optimized here for a narrow-bandwidth receiver configuration in the sense that it now requires a significantly less number of correlators and memory than its original implementation. The simulation results show that the reduced-complexity RSSML achieves the best multipath mitigation performance in moderate-to-good carrier-to-noise density ratio with the DLR LMS channel model in varying multipath scenarios.*

Keywords

Multipath mitigation technique, GNSS receiver, channel model, performance analysis.

1. Introduction

Multipath is still considered as a dominant source of ranging errors in Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS) or the developing European satellite navigation system Galileo. Multipath is undesirable in the context of GNSS, since the reception of multipath can create a significant distortion to the shape of the correlation function used in the time delay estimate of a Delay Locked Loop (DLL) of a navigation receiver, leading to an error in the receiver's position estimate. Therefore, in order to mitigate the impact of multipath on a navigation receiver, the multipath problem has been approached from several directions. Among them, the use of special multipath limiting antennas (i.e., choke ring or multi-beam antennas), the post-processing techniques to reduce carrier multipath, the carrier smoothing to reduce code multipath, and the code tracking algorithms based on receiver internal correlation technique are the most prominent approaches [5] - [7]. The use of special multipath limiting antenna may incur extra hardware cost, and the post-processing techniques cannot be utilized in real-time positioning. Hence, the focus in this paper is mainly limited to the correlation-based multipath mitigation techniques as being the most widely used option for multipath mitigation in GNSS receivers.

The most conventional correlation-based code tracking structure is based on a feedback delay estimator known as Early-Minus-Late (EML) technique. In the classical

EML, two correlators are spaced at one chip apart from each other in order to form a discriminator function, whose zero crossings determine the path delays of the received signal [8], [9]. Unfortunately, the classical EML fails to cope with multipath propagation [5], [10]. Therefore, a number of enhanced EML-based techniques have been introduced in the literature for last two decades to mitigate the impact of multipath. One class of these enhanced EML techniques is based on the idea of narrowing the spacing between the early and late correlators, i.e., the narrow EML (nEML) or the narrow correlator [5], [11], [12]. The choice of correlator spacing usually depends on the receiver's available front-end bandwidth along with the associated sampling frequency [13]. A correlator spacing in the range of 0.05 to 0.2 chips is commercially available for the nEML-based GPS receivers [14].

Another class of discriminator-based DLL variants proposed for GNSS receivers is the so-called Double-Delta ($\Delta\Delta$) technique, which uses more than three correlators in the tracking loop (typically, five correlators: two early, one in-prompt and two late) [12]. The $\Delta\Delta$ technique offers better multipath rejection in medium-to-long delay multipath [11], [15] in good Carrier-to-Noise density ratio (C/N_0). Couple of well-known particular cases of $\Delta\Delta$ technique are the High Resolution Correlator (HRC) [12], the Strobe Correlator (SC) [12], [16], the Pulse Aperture Correlator (PAC) [17] and the modified correlator reference waveform [12], [18]. One other similar tracking structure is the Multiple Gate Delay (MGD) correlator [19] – [22], where the number of early and late gates and the weighting factors used to combine them in the discriminator are the parameters of the model, and can be optimized according to the multipath profile as illustrated in [15]. While coping better with the ambiguities of Binary Offset Carrier (BOC) correlation function, the MGD provides slightly better performance than the nEML at the expense of higher complexity and it is sensitive to the parameters chosen in the discriminator function (i.e., weights, number of correlators and correlator spacing) [15], [22].

Another tracking structure closely related to the $\Delta\Delta$ technique is the Early1/Early2 (E1/E2) tracker, initially proposed in [23], and later described in [12]. In E1/E2 tracker, the main purpose is to find a tracking point on the correlation function that is not distorted by multipath. As reported in [12], E1/E2 tracker shows some performance improvement over the $\Delta\Delta$ technique only for very short delay multipath for GPS L1 Coarse/Acquisition (C/A) signal.

Another feedback tracking structure is the Early-Late-Slope (ELS) technique [12], which is also known as Multipath Elimination Technique (MET) [24]. The simulation results performed in [12] showed that the ELS is outperformed by the HRC with respect to Multipath Error Envelopes (MEEs), for both Binary Phase Shift Keying (BPSK) and Sine Binary Offset Carrier (SinBOC) modulated signals.

A new multipath estimation technique, named as A-Posteriori Multipath Estimation (APME), is proposed in [25], which relies on a-posteriori estimation of the multipath error tracking. Multipath error is estimated independently in a multipath estimator module on the basis of the correlation values from the prompt and very late correlators. According to [25], the multipath performance of GPS L1 C/A signal is comparable with that of the Strobe Correlator: slight improvement for very short delays (i.e., delays less than 20 meters), but rather significant deterioration for medium delays. A similar slope-based multipath mitigation strategy, named as Slope-based Multipath Estimator (SBME), was proposed in [26]. SBME first derives a multipath estimation equation by utilizing the correlation shape of the ideal normalized correlation function, which is then used to compensate for the multipath bias of a nEML tracking loop. SBME requires an additional correlator at the late side of the correlation function, which is then used in conjunction with a nEML tracking loop. It is reported in [26] that SBME has superior multipath mitigation performance than the nEML, and has slightly worse performance than the HRC in closely spaced two-path channel model.

In [27], a fundamentally different approach is adopted to solve the multipath problem for GNSS receivers. The proposed technique, named as Tracking Error Compensator (TrEC), utilizes the multipath invariant properties of the received correlation function in order to provide significant performance benefits over the nEML for narrow-band GPS receivers [27], [28]. However, the performance of the TrEC has not yet been tested for BOC or Composite BOC (CBOC) signals.

One of the most promising advanced multipath mitigation techniques is the Multipath Estimating Delay Lock Loop (MEDLL) [29] - [31], implemented by NovAtel for GPS receivers. MEDLL is considered as a significant evolutionary step in the receiver-based attempt to mitigate multipath. It uses many correlators in order to determine accurately the shape of the multipath corrupted correlation function. According to [31], MEDLL provides superior medium to long delay multipath mitigation performance than nEML at the cost of multi-correlator based tracking structure.

A completely different approach to mitigate multipath error is used in NovAtel's recently developed Vision Correlator [32]. The Vision Correlator (VC) is based on the concept of Multipath Mitigation Technique (MMT) developed in [33]. It can provide a significant improvement in detecting and removing multipath signals as compared to other standard multipath resistant code tracking algorithms (for example, the PAC of NovAtel). However, the only shortcoming of the VC is that it requires a reference function shape to be used to fit the incoming data with the direct path and the secondary path reference signals. The reference function generation has to be accomplished a-priori, and it must incorporate the issues related to Radio Frequency (RF) distortions introduced by the front-end.

Several advanced multipath mitigation techniques were also proposed in [34]-[36]. While improving the delay estimation accuracy, these techniques require a higher number of correlators than the traditional DLL, and they are also sensitive to the noise-dependent threshold choice [35].

The multipath studies presented in the literature are often based on optimistic assumptions, for example, assuming a static two-path channel [12], [37] or a fading channel with a Rayleigh or a Nakagami distribution [36], [38]. But, in reality, there are a lot of channel modeling issues, for example, satellite-to-user geometry, variable number of paths, variable path delays and gains, Non Line-Of-Sight (NLOS) path condition, receiver movements, etc. that are kept out of consideration when analyzing the performance of these techniques. Therefore, this is of utmost importance to analyze the performance of different multipath mitigation techniques in some realistic measurement-based channel models, for example, the Land Mobile Satellite (LMS) channel model [1]-[4], developed at the German Aerospace Center (DLR). The main motive of this research is to present a comprehensive analysis of some of the most promising techniques in the DLR LMS channel model in varying multipath scenarios. Four multipath mitigation techniques are chosen herein for performance comparison, namely, the nEML, the HRC, the C/N$_0$-based two stage delay tracking technique, and the Reduced Search Space Maximum Likelihood (RSSML) delay estimator. The first two techniques are the most popular and traditional ones used in nowadays GNSS receivers, whereas the later two techniques are comparatively new and modified techniques, recently proposed by the authors in [39] and [34], respectively. These two new techniques are considered here, since they offer better multipath mitigation performance than some other techniques, as mentioned in [35]. A brief description of these techniques is presented in Section 4. A Simulink-based open source software simulator, developed at the Tampere University of Technology (TUT) for Galileo E1 signal [40], is used here to carry out the simulations.

The rest of the paper is organized as follows. Section 2 provides a brief description on the land mobile satellite channel model developed by German Aerospace Center (DLR). Section 3 describes the Simulink-based simulation model for Galileo E1 signal developed in Tampere University of Technology (TUT), Finland. A brief overview of the analyzed multipath mitigation techniques is presented in Section 4. The simulation results in DLR channel model are presented in Section 5 with an illustrative comparison of the analyzed techniques. At the end, some general remarks are drawn in Section 6 based on findings of this research. In brief, the novelty of this work lies in algorithm testing with a realistic DLR LMS channel model, in complexity-reduced RSSML proposal, and in the discussion of the design issues on the multipath mitigation unit of a Galileo receiver. Some part of this work is also available to the research community via an open-access simulator [40] and an open-access DLR LMS channel model [41].

2. Land Mobile Satellite Channel Model

The DLR Land Mobile Satellite (LMS) channel model is an open access model, and it can be freely downloaded from the DLR website [41]. The channel model used in this study is the GNSS channel part in a joint channel model for joint GNSS and mobile radio based positioning [4]. This joint model, as shown in Fig. 1, coherently combines the DLR LMS [1]-[3] channel model and an extended WINNER model, which is used for positioning in mobile radio communications. In the GNSS channel model, a combination of a deterministic and statistic modeling approach is considered. The direct path component is determined by physical deterministic effects within a parameterized artificial urban canyon scenario with house fronts, lamppost and trees, which are stochastically generated. These are diffractions caused by house front or a lamp-post which is calculated using Knife Edge. Shadowing effect caused by trees is incorporated by a tree top model having attenuation proportional to the path length through the canopy accomplished by a stochastic fading process. The multipath components are generated with the DLR LMS channel model, which is widely used for the

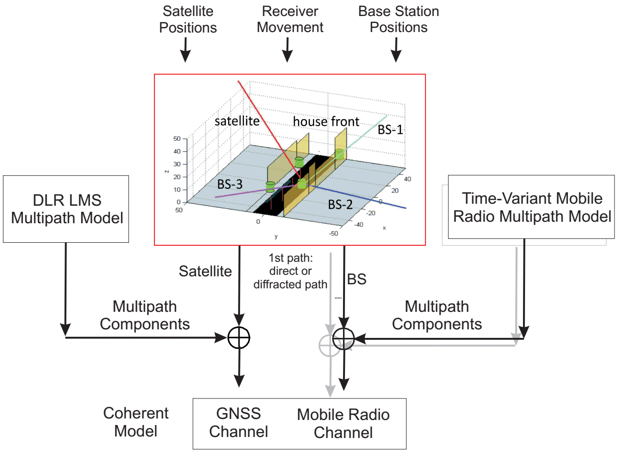


Fig. 1. Flow chart of the combined model for joint GNSS and mobile radio based positioning.

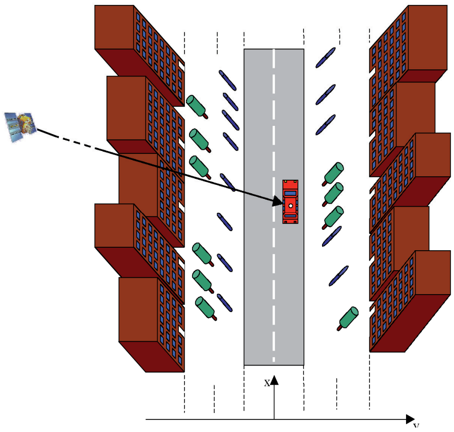


Fig. 2. Satellite model of the artificial scenery with moving receiver.

simulations of the positioning accuracy of mobile satellite navigation receivers in urban outdoor scenarios. Within the DLR LMS channel model, the multipath components are generated by statistical process. For a moving receiver, the delay variance of each path is geometrically determined and the complex amplitude is generated by a stochastic fading process. A typical LMS channel emerges from a constellation depicted in Fig. 2, where the moving receiver is driving through an urban canyon. The obstacles like trees and houses can clearly be seen, and the coordinate system to describe the azimuth and elevation is introduced as explained in [3].

3. Simulation Model

All the simulations have been carried out in an open source Galileo E1 signal simulator [40], which is developed in a Simulink-based platform at Tampere University of Technology (TUT), Finland. The Simulink model used to generate the simulation results is shown in Fig. 3. The Simulink model, as presented here, consists of four parts: i) a transmitter block, ii) a DLR channel block, iii) a Front-end filter block, and iv) a tracking unit (which incorporates a Frequency Locked Loop (FLL), a Phase Locked Loop (PLL) and a Delay Locked Loop).

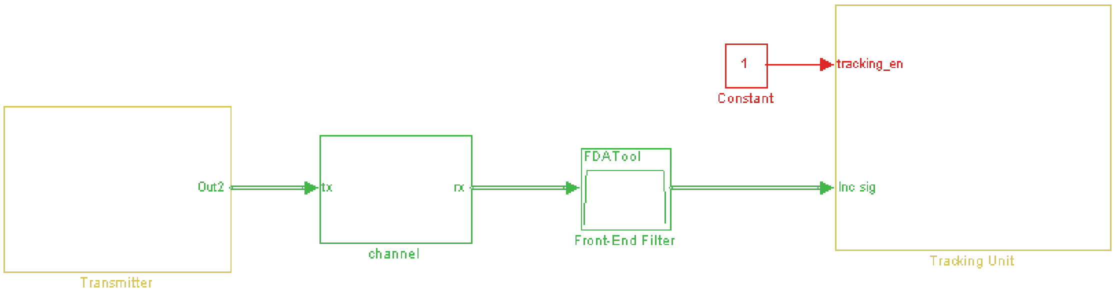


Fig. 3. TUT Galileo E1 signal simulator (upper level block diagram).

3.1 Transmitter Block

The Galileo E1 transmitter block is implemented according to the latest Galileo Open Service (OS) Interface Control Document (ICD) [42]. E1B and E1C channels are modeled according to the following equation [42]:

$$s_{E1}(t)=\frac{1}{\sqrt{2}}(e_{E1B}(t)(\alpha sc_{E1B,a}(t)+\beta sc_{E1B,b}(t)) - e_{E1C}(t)(\alpha sc_{E1C,a}(t)-\beta sc_{E1C,b}(t))) \quad (1)$$

where $sc_X(t)=\mathrm{sgn}(\sin(2\pi R_{s,X}t))$, $e_{E1B(t)}$ and $e_{E1C(t)}$ are binary signal components and α and β represent weighting factors. Above, $R_{s,X}$ is the sub-carrier rate corresponding to channel X (i.e., either E1B or E1C). As explained in [42], $\alpha=\sqrt{10/11}$ and $\beta=\sqrt{1/11}$.

3.2 DLR Channel Block

In the channel block, the multipath signals and the complex AWGN are generated. The basic function of the channel block can be modeled according to the following equation:

$$r_{E1}(t)=\sum_{i=1}^{l}a_i(t)s_{E1}(t-\tau_i)+\eta(t) \quad (2)$$

Here $r_{E1}(t)$ is the received E1 signal at the output of the channel block; a_i and τ_i are the path gain and path delay for the i-th path, respectively, and $\eta(t)$ is the complex AWGN. In the simulations reported later in Section 5, the number of channel paths was fixed to 5 ($l = 5$), but this is simply a parameter of the model that can be varied accordingly. The complex path gains a_i and the corresponding path delays τ_i are taken from a five-path DLR LMS channel model, as mentioned in Section 2.

3.3 Front-end Filter Block

In the simulations, a 6th order Chebyshev type I filter is used with a 3-dB double-sided bandwidth of 3 MHz. Simulink's 'Digital Filter Design' toolbox is used to design the filter with the specified parameters.

3.4 Tracking Unit

The tracking Unit consists of three major blocks: 'Carrier Wipe-Off' block, 'Code NCO' block, and 'Dual Channel Correlation and Discriminators' block, as shown in Fig. 4.

The incoming signal is down converted to the baseband in the 'Carrier Wipe-Off' block. The carrier wipe-off is performed according to the following equation:

$$r_{E1\_BB}(t)=r_{E1}(t)e^{-j(2\pi\hat{f}t+\hat{\varphi})} \quad (3)$$

where $\hat{f}$ is the frequency with some initial frequency error ($\hat{f}=f_{IF}+\Delta f$, where $\Delta f <= 125$ Hz, and f_{IF} is the final Intermediate Frequency (IF)); $\hat{\varphi}$ is the estimated phase from the FLL-assisted-PLL. After the carrier wipe-off, the real part and the imaginary part of the complex signal are separated as the in-phase channel and the quadrature channel (i.e., I and Q channels, respectively as shown in Fig. 4) in baseband. The 'Code NCO' block shifts the code phase based on the estimated delay error coming out from the DLL filter. This block generates four signals as output: the adjusted E1B and E1C replicas, the trigger enabling signal and the shifted NCO phase. The trigger enabling signal is used in conjunction with 'tracking_en' which eventually enables both FLL-assisted-PLL and DLL blocks of E1B and E1C channels (when both the variables are set to 1). Both the code and carrier NCOs are implemented using C-language based S-function, the details of which are not addressed here for the sake of compactness.

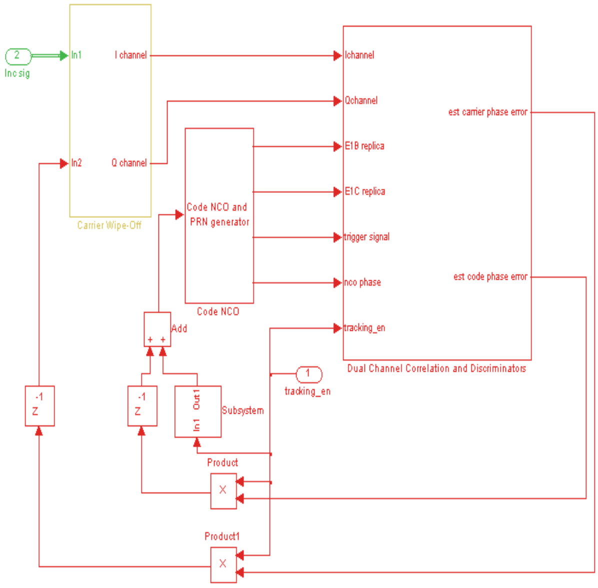


Fig. 4. Tracking unit.

In the 'Dual Channel Correlation and Discriminators' block, E1B and E1C are implemented as two separate channels, as shown in Fig. 5. However, these two channels are approximately the same, except the replicas used for integration and dump, which are either CBOC(+)/CBOC(-) modulated or SinBOC(1,1)-modulated, according to the type of receiver. In the reported simulation, SinBOC(1,1) modulated reference codes are considered for both the channels. It is already shown in [43] that the performance deterioration caused by implementing a SinBOC(1,1) reference receiver is negligible as compared to implementing a CBOC reference receiver.

The C/N$_0$ estimation is performed based on the ratio of the signal's wideband power to its narrowband power as mentioned in [44]. In this method, the power of the signal is computed over a wide bandwidth with a relatively short coherent integration time and over a narrow bandwidth with a longer coherent integration time. The wideband power is computed after 4 milliseconds (ms) of coherent integration (after each code epoch length), and the narrowband power is computed after 16 ms of coherent integration in order to estimate the carrier-to-noise density ratio for each particular channel.

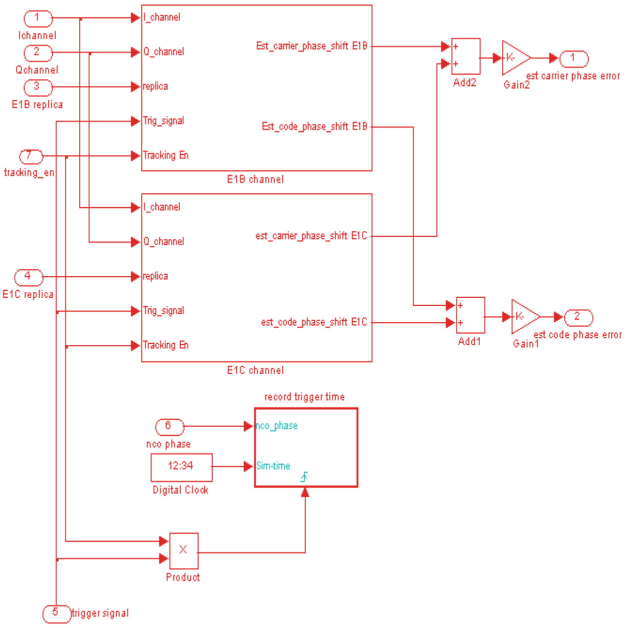


Fig. 5. Dual Channel Correlation and Discriminators block.

4. Multipath Mitigation Techniques

4.1 Conventional Techniques (nEML and HRC)

Several multipath mitigation techniques exist nowadays that reduce the multipath error significantly. Among them, the narrow Early-Minus-Late (nEML) is the most popular technique due to its simpler implementation and robust tracking performance against false locks. The nEML uses a narrower correlator spacing (i.e., usually within 0.05 to 0.2 chips) than the conventional early-minus-late technique which uses 1 chip spacing between early and late correlators. This eventually reduces the tracking error in the presence of noise and multipath [5]. The other conventional technique considered here is the High Resolution Correlator, a variant of the ΔΔ technique. The HRC consists of two correlator pairs, where the spacing between the very early and very late correlators is twice the spacing between the early and late correlators. It was shown in [11] that the HRC has better performance than the nEML in case of medium to long delay multipath. However, the HRC cannot reject the short delay multipath effects and it suffers from false lock problem. Additionally, it has severe performance degradation in noisy environment [34].

4.2 C/N$_0$-based Two Stage Delay Tracking Technique

The C/N$_0$-based two stage delay tracking technique, which is first proposed in [39], is a combination of two individual tracking techniques, namely the nEML and the HRC), the two stage delay tracker always starts with a nEML tracking loop, since it begins to track the signal with a coarsely estimated code delay as obtained from the acquisition stage. At the second or final stage of tracking (i.e., when the DLL tracking error is around zero), the two stage delay tracking technique switches its DLL discriminator from the nEML to the HRC, since the HRC offers better multipath mitigation capability than the nEML. While doing so, it also has to ensure that the estimated C/N_0 level meets a certain threshold set by the two stage tracking technique. This is mainly because of the fact that the HRC cannot perform as well as nEML in weak signal condition due to its smaller uncertainty region around the actual zero crossing. It has been empirically found that a C/N_0 threshold of 33 dB-Hz can be a good choice to switch between the techniques. Therefore, at the fine tracking stage, the two stage delay tracking technique switches from nEML to HRC only when the estimated C/N_0 meets the above criteria (i.e., C/N_0 greater than 33 dB-Hz).

4.3 Reduced Search Space Maximum Likelihood Delay Estimator

A Reduced Search Space Maximum Likelihood (RSSML) delay estimator is a maximum likelihood based approach, which mitigates the multipath effects reasonably well at the expense of increased complexity. The RSSML, as proposed in [34], attempts to compensate the multipath error contribution by performing a nonlinear curve fit on the input correlation function which finds a perfect match from a set of ideal reference correlation functions with certain amplitude(s), phase(s) and delay(s) of the multipath signal. With the presence of multipath signal, the RSSML tries to separate the LOS component from the combined signal by estimating all the signal parameters in a maximum likelihood sense, which consequently achieves the best curve fit on the received input correlation function. As mentioned in [34], the classical RSSML incorporates a threshold-based peak detection method, which reduces the code delay search space significantly.

In the reduced-complexity RSSML implementation, a slightly different approach has been adopted for the selection of competitive delays. Instead of computing the peak detection thresholds based on the estimated noise variance [34], it considers all those code delays as the competitive delays that are within ±0.2 chips away from the prompt correlator, as shown in Fig. 6. This is meaningful in the sense that it is quite likely to have a delay error near the previous delay estimate. By doing so, the reduced-complexity RSSML avoids computing the peak detection thresholds, the estimation of which is often inaccurate in time-varying urban/suburban multipath channel model. In this implementation, a total of 41 correlators have been used with a correlator spacing of 0.05 chips resulting in a code delay window range of ±1 chip with respect to the prompt correlator. This new approach reduces the correlator requirement by around 78.76% in contrast to the classical RSSML that requires 193 correlators to cover a code delay window range of ±2 chips with respect to the prompt correlator.

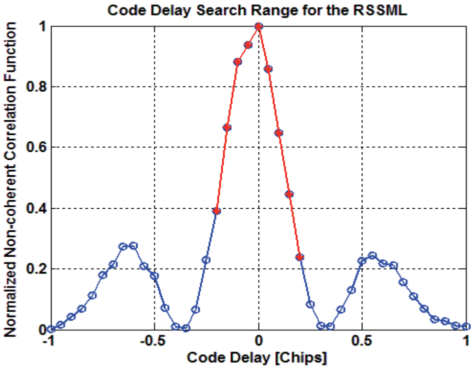


Fig. 6. Competitive code delays (around ±0.2 chips within the prompt correlator) for the RSSML.

The ideal non-coherent correlation functions are generated off-line considering a pre-correlation bandwidth of 3 MHz (double-sided) and those are saved in a look-up table in memory. In real-time, the reduced-complexity RSSML reads the correlation values from the look-up table, translates the ideal reference correlation functions at the middle delay index to the corresponding candidate delay index within the code delay window, and then computes the Minimum Mean Square Error (MMSE) for that specific delay candidate. As mentioned earlier, the search space is reduced to the code delays that are within ±0.2 chips from the prompt correlator. The brief step-by-step procedure for the proposed reduced-complexity RSSML implementation is summarized below:

Step 1: *Generate candidate code delays;*

Step 2: *Read the non-coherent reference correlation functions from the look-up table;*

Step 3: *Translate the non-coherent reference correlation functions which are at the middle delay index to the corresponding candidate delay index for each candidate code delay;*

Step 4: *Compute the MMSE for each candidate code delay;*

Step 5: *Select the candidate code delay with the lowest MMSE value as the LOS code delay.*

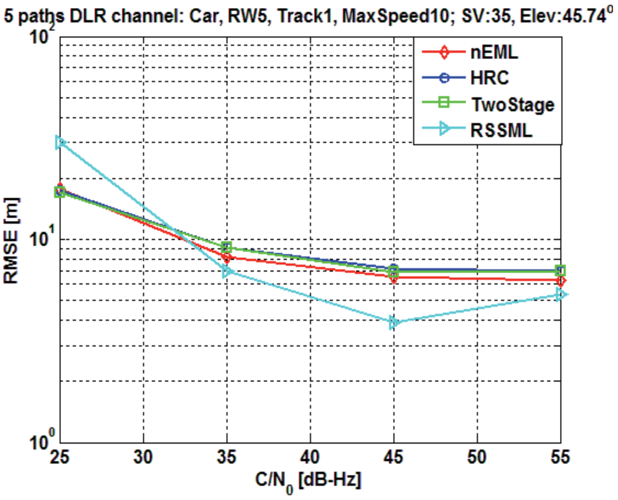
5. Simulation Results

Simulations have been carried out in a five-path DLR LMS channel model in varying scenarios (i.e., pedestrian/car navigation, different road widths, different satellite elevations, etc.). Tab. 1 summarizes the key simulation parameters for Fig. 7. The simulations have been carried out for 10 seconds (s) for each particular C/N_0 level, generating 10000/4=2500 observations per C/N_0. The tracking errors are computed after each coherent integration period (i.e., 4 ms for Galileo E1 signal). In the final statistics, the tracking errors for the first two seconds are ignored in order to remove the initial error bias that may come from the delay difference between the received signal and the locally generated reference code. Therefore, the left-over tracking errors after two seconds are mostly due to the effect of multipath and noise. The Root-Mean-Square-Error (RMSE) are computed for 2000 (i.e., 10 – 2 = 8 s of data generates 2000 measurements) tracking measurements in each particular C/N_0 level. The RMSE of delay estimates are plotted in meters (m), by using the relationship $RMSE_m = RMSE_{chips} * c * T_c$; where c is the speed of light, T_c is the chip duration, and $RMSE_{chips}$ is the RMSE in chips. RMSE vs. C/N_0 plots are shown in Fig. 7 for the simulation profile mentioned in Tab. 1 with two different first-path delays (i.e., ~0.04 chips and ~0.16 chips, respectively).

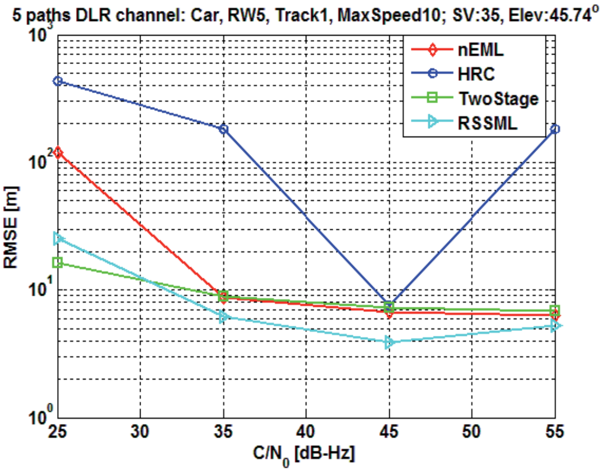
Parameters	Values
Band	E1
fs (MSps)	26
IF (MHz)	3.42
Receiver filter (-3dB filter boundaries) (MHz)	3.42±1.5
C/N_0 (dB-Hz)	[25; 35; 45; 55]
Track number	01
Track type	Car
Road width (m)	5
Maximum speed	10 m/s
Satellite Vehicle (SV) number	35
Satellite Vehicle (SV) elevation (deg.)	45.74
Number of channel paths	5
Data duration (s)	10
Correlator spacing (chips)	0.17 chips for all techniques, except RSSML which has 0.05 chips spacing
First path delay (samples)	1 or 4

Tab. 1. Simulation parameters.

The impact of the first-path delay on the nEML and the HRC techniques is evident from the figure (i.e., high RMSE values for certain C/N_0 levels). It can also be seen that the reduced-complexity RSSML and the two stage delay tracking technique exhibit similar tracking performance no matter what the first path delays are (at least for the first-path delays in the range of ±0.16 chips). There is quite likely to have a delay mismatch between the received signal and the locally generated reference code in the range of ±0.16 chips, which actually depends on the time-bin resolution of the code search space at the acquisition stage. Therefore, it is very important to verify the robustness of a delay tracking technique in terms of first-path delay tolerance, especially in harsh multipath channel conditions where the threat of false locking to any of the close-in paths is quite significant. However, the reduced-complexity RSSML offers the best tracking performance in both the scenarios for moderate-to-good C/N_0 (i.e., C/N_0 higher than 33 dB-Hz), followed by the two stage delay tracking technique being the second best option. The tracking error plots for two different path delays are also shown in Fig. 8. As seen in Fig. 8(b), the HRC locks to a neighboring peak even in a good signal condition in case of ~0.16 chips first-path delay.

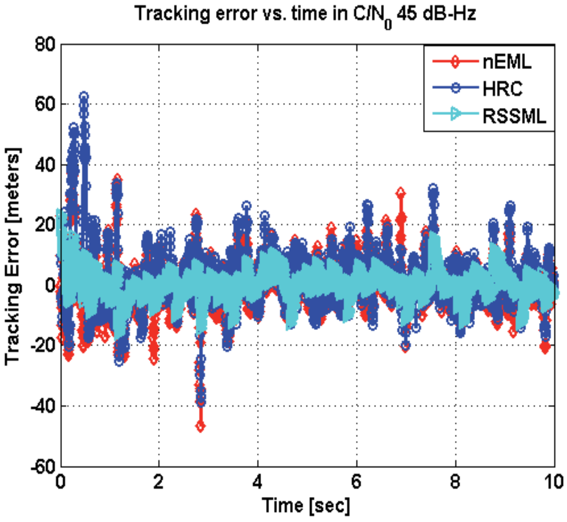


(a) First path delay: ~0.04 chips

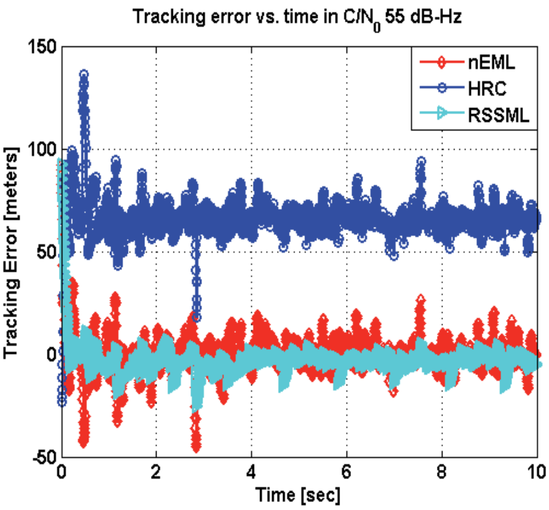


(b) First path delay: ~0.16 chips

Fig. 7. RMSE vs. C/N_0 for SV 35 with different first path delays in an urban environment (maximum speed: 10 m/s) in a five-path DLR channel model.

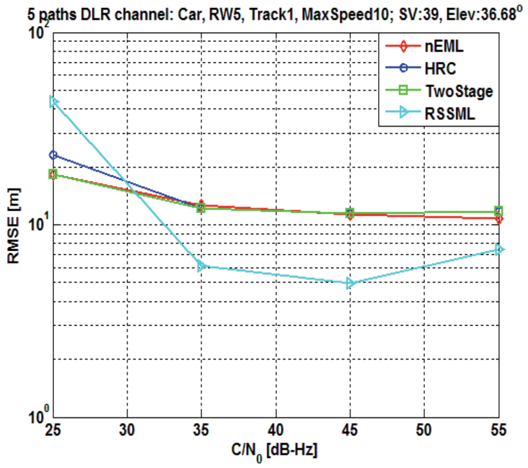


(a) First path delay: ~0.04 chips, C/N_0: 45 dB-Hz

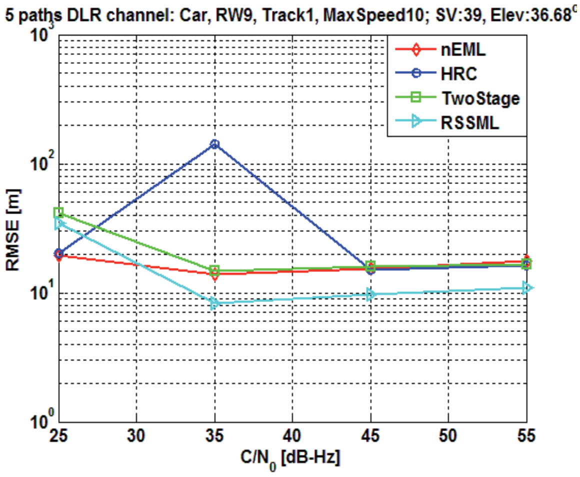


(b) First path delay: ~0.16 chips, C/N$_0$: 55 dB-Hz

Fig. 8. Tracking error vs. time for SV 35 in an urban environment (maximum speed: 10 m/s) in a five-path DLR channel model.



(a) Road width: 5 m



(b) Road width: 9 m

Fig. 9. RMSE vs. C/N$_0$ for SV 39 with different road widths in an urban environment (maximum speed: 10 m/s) in a five-path DLR channel model, first-path delay: 0 chips.

In Fig. 9, RMSE vs. C/N$_0$ plots are shown for Satellite Vehicle (SV) 39 with an elevation angle 36.7^0 for two different road widths (i.e., 5 m and 9 m) in an urban environment. The simulation is set for the car users with a maximum speed of 10 m/s, and the first-path delay in this case is assumed to be 0 chips. All other parameters are unchanged from the previous simulation. It can be seen from Fig. 9(b) that the HRC locks to a false neighboring peak at C/N$_0$ 35 dB-Hz in the case of 9 meters road width, even with 0 chips first-path delay. Here also, the reduced-complexity RSSML shows the best multipath mitigation performance from C/N$_0$ 30 dB-Hz and onwards for both the scenarios, followed by the nEML and the two stage delay tracking technique.

In Fig. 10, a RMSE vs. C/N$_0$ plot is shown for SV 25 having a low elevation angle 5.4^0 for a pedestrian user (maximum speed 1 m/s) in an urban environment. The first-path delay is assumed to be ~0.08 chips, and the road width is 9 m. All other parameters are unchanged from the previous simulation.

As seen from Fig. 10, the nEML and the HRC both suffer from poor tracking robustness. Like the previous simulation results, the reduced-complexity RSSML offers the best tracking performance followed by the two stage delay tracking technique.

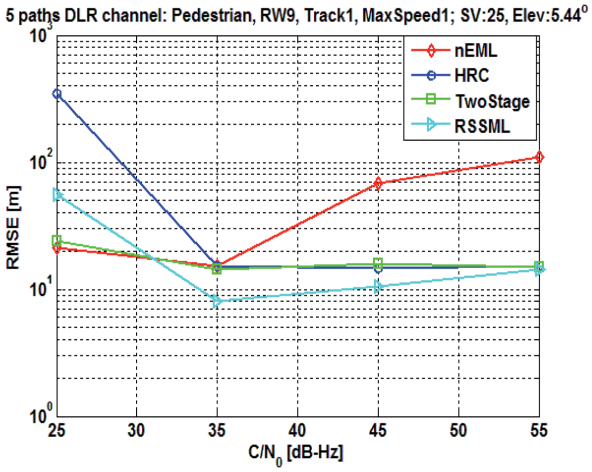


Fig. 10. RMSE vs. C/N$_0$ for the low-elevated SV 25 with first path delay ~0.08 chips in a pedestrian environment (maximum speed: 1 m/s) in a five-path DLR channel model.

A comparative performance analysis is shown in Tab. 2 for the four different techniques analyzed herein. The analysis is mostly based on tracking robustness, multipath mitigation performance, correlator requirement, memory requirement and implementation complexity. In all the simulations, the reduced-complexity RSSML achieved the best multipath mitigation performance from C/N$_0$ 33 dB-Hz and onwards. In addition, it can also be considered as the most robust technique as it offers steady tracking performance in different channel conditions. After the reduced-complexity RSSML, the two stage delay tracking technique can be the second best choice in terms of multipath mitigation performance and tracking robustness. The good thing with the two stage delay tracking technique is that it utilizes the inherent advantages of both the techniques (i.e., the nEML and the HRC) in an intelligent way with the help of a C/N_0 estimator. However, the performance of the two stage technique is somehow dependent on the accuracy of the C/N_0 estimation, and therefore, a good C/N_0 estimator should be used for an optimal performance.

The HRC suffers from false locking, especially in noisy environment, or in harsh multipath environment like dense urban canyon, and hence, it is not recommended to use HRC in those channel conditions. On the contrary, the nEML is still an attractive choice for the mass-market receivers for its relatively better tracking robustness, moderate multipath mitigation performance, and above all, simpler implementation.

Techniques **Criteria**	**nEML**	**HRC**	**Two Stage**	**Reduced – Complexity RSSML**
Multipath mitigation performance	Good	Very Good	Very Good	Best
Tracking robustness	Good	Bad	Very Good	Best
Correlator requirement	Few (3)	Few (5)	Few (5)	Many (41)
Memory requirement	No	No	No	Yes
Implementation complexity	Very Low	Very Low	Low	Moderate

Tab. 2. Performance analysis of multipath mitigation techniques.

The implementation complexity of any multipath mitigation technique mainly depends on the correlation structure and the implementation issues concerning channel estimation, correlator requirement, required number of mathematical operations, memory requirement and so on. Among the analyzed techniques, the reduced-complexity RSSML is the most complex one, since it utilizes a moderate number of correlators for channel estimation. Additionally, it requires a moderate set of reference correlation functions which are generated off-line to be used as a-priori information while estimating the LOS code delay. The memory requirement of the reduced-complexity RSSML eventually depends on few factors including the maximum number of paths to be considered, the correlator spacing, the number of correlators and the resolution of each multipath parameter (i.e., path delays, path phases and path amplitudes). In our MATLAB implementation, the complexity-reduced RSSML requires little less than 1 megabytes of memory with maximum number of paths set to 2, the correlator spacing set to 0.05 chips, and the number of correlators for a two-chip window length set to 41. This new approach reduces the memory requirement by 92.86% in contrast to the classical RSSML that requires 14 megabytes of memory.

6. Conclusions

Multipath is a major limiting factor for high precision-oriented GNSS applications. A variety of multipath mitigation techniques exist in the literature to deal with this particular phenomenon. Most of these techniques offer good multipath mitigation performance for medium-to-long delay multipath. However, the multipath studies presented in the literature are often based on optimistic assumptions, for example, assuming a static two-path channel or a fading channel with a Rayleigh or a Nakagami distribution, and so on. This is always very meaningful to analyze the performance of different techniques in some realistic measurement-based channel models, for example, the DLR LMS channel model. In this study, the authors provided a comprehensive analysis of some of the most promising multipath mitigation techniques in the DLR LMS channel model. It was shown that the reduced-complexity RSSML, in general, achieved the best multipath mitigation performance in a realistic DLR channel model in varying multipath scenarios. The implementation complexity of the proposed reduced-complexity RSSML was also reduced from its original implementation. The correlator requirement and the memore requirement are reduced by 78.76% and 92.86%, respectively in contrast to the classical RSSML. Yet, it requires a moderate amount of correlators and memory as compared to the existing tracking techniques, which makes it suitable for high-end receivers. Among the other analyzed techniques, the C/N_0-based two stage delay tracking technique can be a good DLL choice for mass-market receivers as it offers the best trade off between performance and complexity.

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