Multipath Mitigation Techniques for Satellite- Based Positioning Applications

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1. Introduction

The ever-growing public interest on location and positioning services has originated a demand for a high performance Global Navigation Satellite System (GNSS), such as the Global Positioning System (GPS) or the future European satellite navigation system, Galileo. The performance of GNSS is subject to several errors, such as ionosphere delay, troposphere delay, receiver noise and multipath. Among all these errors, multipath is the main limiting factor in precision-oriented GNSS applications. The reception of multipath creates a bias into the time delay estimate of the Delay Lock Loop (DLL) of a conventional navigation receiver, which eventually leads to an error in the receiver's position estimate. In order to mitigate the multipath influence on navigation receivers, 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 techniques based on receiver internal correlation function are the most prominent approaches.

In this chapter, the discussion is mainly focused on the correlation-based multipath mitigation techniques at the receiver side; since the correlation-based multipath mitigation approach is by far the most convenient and popular way to deal with multipath error for a stand-alone GNSS receiver. The classical correlation-based code tracking structure used in GNSS is based on a feedback delay estimator and is implemented via a feedback loop. The most known feedback delay estimator is the Early-Minus-Late (EML) DLL technique, where two correlators spaced at one chip from each other are used in the receiver in order to form a discriminator function, whose zero crossings determine the path delays of the received signal Baltersee et al. (2001), Bischoff et al. (2002), Chen & Davisson (1994), Fine & Wilson (1999), Fock et al. (2001), Laxton (1996). The classical EML fails to cope with multipath propagation Dierendonck et al. (1992), Simon et al. (1994). Therefore, several enhanced EML-based techniques have been introduced in the literature during the last two decades in order to mitigate the impact of multipath, especially in closely spaced path scenarios. One class of these enhanced EML techniques is based on the idea of narrowing the spacing between the early and late correlators, i.e., narrow EML (nEML) or narrow correlator Dierendonck et al. (1992), Irsigler & Eissfeller (2003), McGraw & Braasch (1999). The choice of correlator spacing depends on the receiver's available front-end bandwidth along with the associated sampling frequency Betz & Kolodziejski (2000). Correlator spacings in the range of 0.05 to 0.2 chips are commercially available for nEML based GPS receivers Braasch (2001).

Another family of discriminator-based DLL variants proposed for GNSS is the so-called Double-Delta ($\Delta\Delta$) technique, which uses more than 3 correlators in the tracking loop (typically, 5 correlators: two early, one in-prompt and two late) Irsigler & Eissfeller (2003). The $\Delta\Delta$ technique offers better multipath rejection in medium-to-long delay multipath Hurskainen et al. (2008), McGraw & Braasch (1999) 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) McGraw & Braasch (1999), the Strobe Correlator (SC) Garin & Rousseau (1997), Irsigler & Eissfeller (2003), the Pulse Aperture Correlator (PAC) Jones et al. (2004) and the modified correlator reference waveform Irsigler & Eissfeller (2003), Weill (2003). One other similar tracking structure is the Multiple Gate Delay (MGD) correlator Bello & Fante (2005), Bhuiyan (2006), Fante (2003), Fante (2004), 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 Hurskainen et al. (2008). 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 is sensitive to the parameters chosen in the discriminator function (i.e., weights, number of correlators and correlator spacing) Bhuiyan (2006), Hurskainen et al. (2008).

Another tracking structure closely related to $\Delta\Delta$ technique is the Early1 / Early2 (E1/E2) tracker, initially proposed in Dierendonck & Braasch (1997), and later described in Irsigler & Eissfeller (2003). 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 Irsigler & Eissfeller (2003), E1/E2 tracker shows some performance improvement over $\Delta\Delta$ 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) Irsigler & Eissfeller (2003), which is also known as Multipath Elimination Technique (MET) Townsend & Fenton (1994). The simulation results performed in Irsigler & Eissfeller (2003) showed that ELS is outperformed by HRC with respect to Multipath Error Envelopes (MEEs), for both Binary Phase Shift Keying (BPSK) and Sine BOC(1,1) (SinBOC(1,1)) modulated signals.

A new multipath estimation technique, named as A-Posteriori Multipath Estimation (APME), is proposed in Sleewaegen & Boon (2001), 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 Sleewaegen & Boon (2001), 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.

In Phelts & Enge (2000a), a fundamentally different approach is adopted to solve the problem of multipath in the context of GNSS. 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 nEML for narrow-band GPS receivers Phelts & Enge (2000a), Phelts & Enge (2000b).

One of the most promising advanced multipath mitigation techniques is the Multipath Estimating Delay Lock Loop (MEDLL) Nee (1992), Nee et al. (1994), Townsend et al. (1995) 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 Townsend et al. (1995), MEDLL provides superior long delay multipath mitigation performance compared to nEML at the cost of multi-correlator based tracking structure.

A new technique to mitigate multipath by means of correlator reference waveform was proposed in Weill (1997). This technique, referred to as Second Derivative correlator, generates a signal correlation function which has a much narrower width than a standard correlation function, and is therefore capable of mitigating multipath errors over a much wider range of secondary path delays. The narrowing of the correlation function is accomplished by using a specially designed code reference waveform (i.e. the negative of the second order derivative of correlation function) instead of the ideal code waveform used in almost all existing receivers. However, this new technique reduces the multipath errors at the expense of a moderate decrease in the effective Signal-to-Noise Ratio (SNR) due to the effect of narrowing the correlation function. A similar strategy, named as Slope Differential (SD), is based on the second order derivative of the correlation function Lee et al. (2006). It is shown in Lee et al. (2006) that this technique has better multipath performance than nEML and Strobe Correlator. However, the performance measure was solely based on the theoretical MEE curves, thus its potential benefit in more realistic multipath environment is still an open issue.

A completely different approach to mitigate multipath error is used in NovAtel's recently developed Vision Correlator Fenton & Jones (2005). The Vision Correlator (VC) is based on the concept of Multipath Mitigation Technique (MMT) developed in Weill (2002). It can provide a significant improvement in detecting and removing multipath signals as compared to other standard multipath resistant code tracking algorithms (for example, PAC of NovAtel). However, VC has the shortcoming 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 Bhuiyan (2011), Granados et al. (2005), Granados & Rubio (2000), Lohan et al. (2006). These techniques, in general, offer better tracking performance than the traditional DLL at a cost of increased complexity. However, the performance of these techniques have not yet been evaluated in more realistic multipath channel model with real GNSS signals.

The rest of this chapter is organized as follows. Multipath propagation phenomena is described first, followed by a description on the influence of signal and receiver parameters on multipath error. The following section provides an elaborate description on different multipath mitigation techniques starting from the conventional state-of-the-art techniques to the relatively complex advanced multipath mitigation techniques. An extensive literature review on the contemporary research on multipath mitigation techniques are also provided. The performance evaluations of some of the multipath mitigation techniques are shown in Section 6 via multipath error envelopes and also via simulations in multipath fading channel model. Finally, some general conclusions are drawn based on the discussions provided in earlier sections.

2. Multipath propagation

Multipath propagation occurs mostly due to reflected GNSS signals from surfaces (such as buildings, metal surfaces etc.) near the receiver, resulting in one or more secondary propagation paths. These secondary path signals, which are superimposed on the desired direct path signal, always have a longer propagation time and can significantly distort the amplitude and phase of the direct path signal. This eventually leads to a deformation in the correlation function as shown in Fig. 1, where a direct LOS signal is added constructively

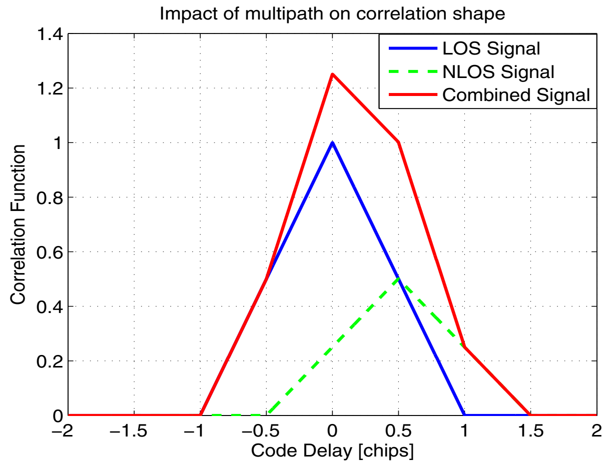

Fig. 1. Received correlation function in two path static channel model, path delays: [0 0.5] chips, path amplitudes: [0 -3] dB, in-phase combination.

with an in-phase (i.e., 0° phase difference), delayed (0.5 chips delayed) and attenuated (-3 dB attenuated) version of it to form a compound signal. The deformed correlation shape introduces an error bias in the pseudorange measurement that resulted in a degraded positioning performance.

In severe multipath environments like those in dense urban areas, it may be possible that the LOS signal is obstructed completely and only the reflected signals are present. These multipath effects on the code phase measurements are most crucial, and the multipath error can reach up to a few tens of meters, or a couple of hundred at most Gleason & Egziabher (2009). Moreover, unlike other error sources, multipath cannot be reduced through differential processing, since it decorrelates spatially very rapidly. All these issues are the main driving factors for the research conducted in the context of this thesis striving for an optimum correlation-based multipath mitigation technique in terms of mitigation performance as well as implementation complexity.

3. Influence of signal and receiver parameters on multipath error

The way multipath affects the tracking and navigation performance of a receiver depends on a number of signal and receiver parameters. Among them, the most influential parameters are:

- Type of signal modulation,

- Front-end filter bandwidth (i.e., precorrelation bandwidth),
- Correlator spacing used in the code tracking,
- Type of discriminator used to run the DLL (i.e., nEML, HRC, etc.),
- Code chipping rate,
- Number of multipath signals,
- Amplitudes, delays and phases of multipath signals with respect to the LOS signal, etc.

The type of signal modulation basically determines the shape of the correlation function. For example, BPSK is used to modulate GPS L1 C/A signal, which has a single significant tracking peak within ±1 chip delay from the correct code delay, whereas CBOC modulations (i.e. CBOC(+) for data channel and CBOC(-) for pilot channel) are used to modulate Galileo E1 signal, each of which has more than one significant tracking peak within ±1 chip delay from the correct code delay. Non-coherent (i.e., absolute value of the correlation function) correlation functions for the above modulations are shown in Fig. 2, where the extra peaks

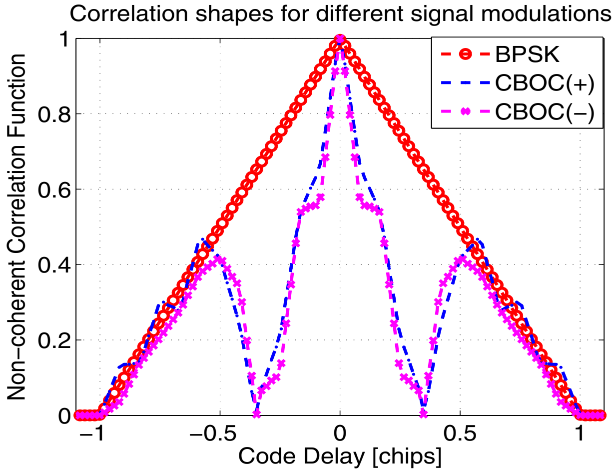

Fig. 2. Non-coherent correlation functions for different signal modulations.

can be clearly observed in case of CBOC modulations. This is the situation in the most ideal single path scenario. The situation would get far worse in the presence of multipath signals, for example, in a typical fading channel model with a two to four path assumption. Fig. 3 shows the distorted correlation shapes of different signal modulations in a two path static channel with path delays [0 0.1] chips and with path powers [0 -6] dB. As seen in Fig 3, the presence of an additional peak (in case of CBOC(+) and CBOC(-)) due to multipath imposes a challenge for the signal acquisition and tracking techniques to lock to the correct peak. If the receiver fails to lock to the correct peak, a multipath error in the order of few tens of meters is of no surprise.

The front-end filter bandwidth used for band-limiting the received signal also has some impact on the correlation shape. The bandwidth, if not chosen sufficiently high, may round off the correlation peak as well as flatten the width of the correlation function, as shown in Fig. 4. For this particular reason, the choice of correlator spacing depends on the receiver's available front-end bandwidth (and off course, on the sampling frequency), that follows the

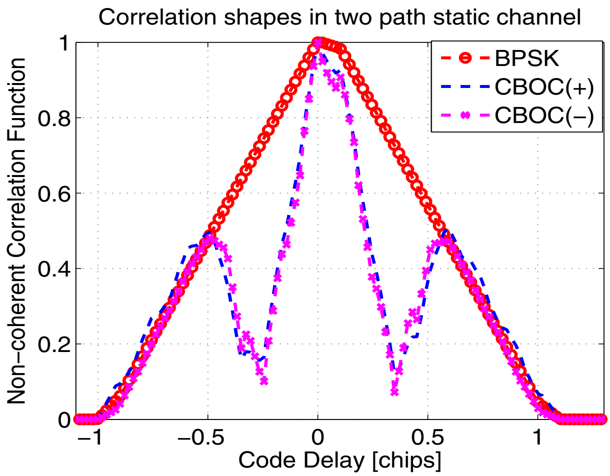

Fig. 3. Non-coherent correlation functions for different signal modulations in two path static channel.

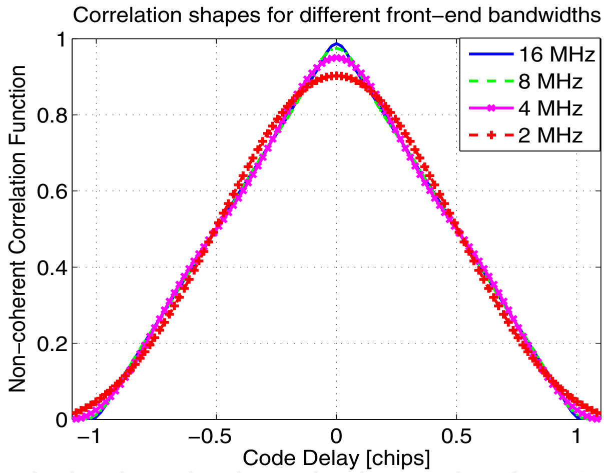

Fig. 4. Non-coherent correlation functions for BPSK modulated GPS L1 C/A signal in different front-end bandwidths.

relation: the more the bandwidth, the smaller the correlator spacing. As mentioned in Betz & Kolodziejski (2000), the early-late spacing Δ_{EL} (i.e., twice the correlator spacing) is related to the front-end bandwidth (double-sided) BW and the code chip rate f_{chip} according to the following equation:

$$\Delta_{EL} \geq \frac{f_{chip}}{BW} \tag{1}$$

The type of the discriminator and the correlator spacing used to form the discriminator function (i.e., nEML, HRC, SC, etc.) determines the behavior of the code discriminator that strongly influences the resulting multipath performance. Generally speaking, a narrower correlator spacing leads to a reduced multipath error and a tracking jitter error, as long as sufficient front-end bandwidth is ensured Dierendonck et al. (1992).

The code chipping rate determines the chip length (T_c), which ultimately decides the resulting ranging error caused by the multipath. This means that a signal with a larger chip length results in a smaller multipath error contribution. That is why, the modernized GPS L5 signal can offer ten times smaller multipath error contribution than the legacy GPS L1 C/A signal, as it has ten times higher chipping rate than that of L1.

The remaining multipath related parameters (i.e., amplitudes, delays, phases and number of multipath signals) depend on the multipath environment, and have direct influence on the tracking performance of the receiver. These parameters are generally used to define a simulation model (for example, multipath fading channel model) in order to analyze the performance of different multipath mitigation techniques.

3.1 Multi-correlator based delay tracking structure

A unified multi-correlator based delay tracking structure is developed to fit all the multipath mitigation techniques in one common tracking structure. In a multi-correlator based delay tracking structure, a bank of correlators is generated, unlike the conventional DLL-based tracking structure, where only few correlators (i.e., in the range of three to seven complex correlators depending on the type of techniques) are used. This large number of correlators are required by the advanced multipath mitigation techniques in order to estimate the channel properties and to take a decision on the correct LOS code delay. As shown in Fig. 5, after

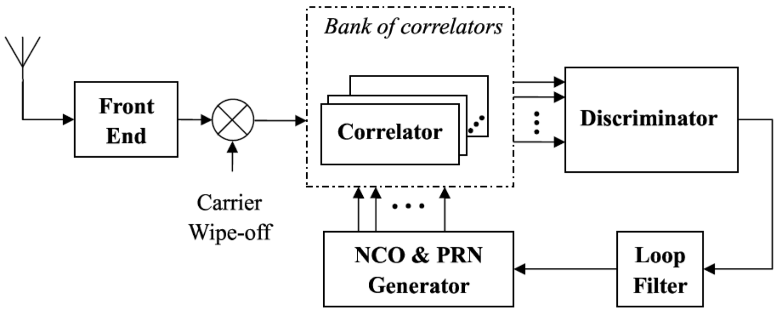

Fig. 5. Block diagram for multi-correlator based DLL implementation.

the necessary front-end processing, and after the carrier has been wiped-off, the received post-processed signal is passed through a bank of correlators. The NCO (Numerically Controlled Oscillator) and PRN generator block produces a bank of early and late versions of replica codes based on the delay of the LOS signal $\hat{\tau}$, the correlator spacing Δ, and the number of correlators M. In case of an EML tracking loop, the corresponding early-late spacing is equal to 2Δ. The received signal is correlated with each replica in the correlator bank, and the output of the correlator bank is a vector of samples in the correlation envelope. Therefore, we obtain the correlation values for the range of $\pm M\Delta$ chips from the prompt correlator, where M is the number of correlators and Δ is the correlator spacing between successive correlators. The various code tracking techniques (named as Discriminator in Fig. 5) utilize the correlation values as input, and generate the estimated LOS delay as output, which is then smoothed by a loop filter. A loop filter is generally used to improve the code delay estimate, reducing the noise present at the output of the discriminator, and to follow the signal dynamics. The order of a loop filter determines the ability of the filter to respond to different types of dynamics, whereas the filter bandwidth ensures that a low bandwidth leads to a good filtering with a high amount of noise filtered, but also requires that the dynamics of the signals are not too high. The loop bandwidth is usually determined by the coefficients of the filter, and can thus be considered as a design parameter for the filter. In accordance with Kaplan & Hegarty (2006), the code loop filter is a 1st order filter, which can be modeled as:

$$\widehat{\tau}(k+1) = \widehat{\tau}(k) + \omega_0 d(k), \tag{2}$$

where ω_0 is calculated based on the loop filter bandwidth, B_n. As shown in Bhuiyan & Lohan (2010), the multi-correlator based tracking structure being used by the advanced multipath mitigation techniques, offers a superior tracking performance to the traditional nEML DLL at the cost of higher number of correlators.

4. State-of-the-art multipath mitigation techniques

The GNSS community has started the correlation-based multipath mitigation studies since early 1990s with the advent of Narrow Correlator (NC) or narrow Early-Minus-Late (nEML) DLL Dierendonck et al. (1992). This section highlights some of the most prominent state-of-the-art techniques, which have gained a lot of interest in the research community by now.

4.1 Early-minus-late delay lock loop

The classical correlation-based code tracking structure used in a GNSS receiver is based on a feedback delay estimator and is implemented via a feedback loop. The most known feedback delay estimator is the Early-Minus-Late (EML) DLL, where two correlators spaced at one chip from each other, are used in the receiver in order to form a discriminator function, whose zero crossings determine the path delays of the received signal Baltersee et al. (2001); Bischoff et al. (2002); Chen & Davisson (1994); Fine & Wilson (1999); Fock et al. (2001); Laxton (1996); Lohan (2003). The classical EML usually fails to cope with multipath propagation Dierendonck et al. (1992). Therefore, several enhanced EML-based techniques have been introduced in the literature for last two decades in order to mitigate the impact of multipath, especially in closely spaced path scenarios. A first approach to reduce the influences of code multipath is based on the idea of narrowing the spacing between the early and late correlators, i.e., nEML or narrow correlator Dierendonck et al. (1992); Fenton (1995); Fenton & Dierendonck (1996). The choice of correlator spacing depends on the receiver's available front-end bandwidth along with the associated sampling frequency Betz & Kolodziejski (2000). Correlator spacings in the range of 0.05 to 0.2 chips are commercially available for nEML based GPS receivers Braasch (2001).

4.2 Double delta ($\Delta\Delta$) technique

Another family 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) Irsigler & Eissfeller

(2003). ΔΔ technique offers better multipath rejection in medium-to-long delay multipath in good C/N_0 Hurskainen et al. (2008); McGraw & Braasch (1999). Couple of well-known particular cases of ΔΔ technique are the High Resolution Correlator (HRC) McGraw & Braasch (1999), the Strobe Correlator (SC) Garin & Rousseau (1997); Irsigler & Eissfeller (2003), the Pulse Aperture Correlator (PAC) Jones et al. (2004) and the modified correlator reference waveform Irsigler & Eissfeller (2003); Weill (2003). One other similar tracking structure is the Multiple Gate Delay (MGD) correlator Bello & Fante (2005); Bhuiyan (2006); Fante (2003; 2004); Jie (2010), 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 Hurskainen et al. (2008); Jie (2010). While coping better with the ambiguities of BOC correlation function, the MGD provides slightly better performance than the nEML at the expense of higher complexity and is sensitive to the parameters chosen in the discriminator function (i.e., weights, number of correlators and correlator spacing) Bhuiyan (2006); Hurskainen et al. (2008); Jie (2010). In Hurskainen et al. (2008), it is also shown that ΔΔ technique is a particular case of MGD implementation.

4.3 Early-late-slope

Another feedback tracking structure is the Early-Late-Slope (ELS) Irsigler & Eissfeller (2003), which is also known as Multipath Elimination Technique (MET) Townsend & Fenton (1994). The ELS is based on two correlator pairs at both sides of the correlation function's central peak with parameterized spacing. Once both slopes are known, they can be used to compute a pseudorange correction that can be applied to the pseudorange measurement. However, simulation results performed in Irsigler & Eissfeller (2003) showed that ELS is outperformed by HRC with respect to Multipath Error Envelopes (MEEs), for both BPSK and SinBOC(1,1) modulated signals. An Improved ELS (IELS) technique was proposed by the Author in Bhuiyan et al. (2008), which introduced two enhancements to the basic ELS approach. The first enhancement was the adaptation of random spacing between the early and the late correlator pairs, while the later one was the utilization of feedforward information in order to determine the most appropriate peak on which the IELS technique should be applied. It was shown in Bhuiyan et al. (2008) that IELS performed better than nEML only in good C/N_0 for BPSK and SinBOC(1,1) modulated signals in case of short-delay multipath, but still had poorer performance than HRC.

4.4 A-Posteriori multipath estimation

A new multipath estimation technique, named as A-Posteriori Multipath Estimation (APME), is proposed in Sleewaegen & Boon (2001), which relies on a-posteriori estimation of multipath error. Multipath error is estimated independently in a multipath estimator module on the basis of the correlation values from the prompt and very late correlators. The performance of APME in multipath environment is comparable with that of the Strobe Correlator: a slight improvement for very short delays (i.e., delays less than 20 meters), but rather significant deterioration for medium delays Sleewaegen & Boon (2001).

4.5 Multipath estimating delay lock loop

One of the most promising state-of-art multipath mitigation techniques is the Multipath Estimating Delay Lock Loop (MEDLL) Nee (1992); Nee et al. (1994); Townsend et al. (1995)

implemented by NovAtel for GPS receivers. MEDLL uses several correlators per channel in order to determine accurately the shape of the multipath-corrupted correlation function. Then, a reference correlation function is used in a software module in order to determine the best combination of LOS and NLOS components (i.e., amplitudes, delays, phases and number of multipath). An important aspect of MEDLL is an accurate reference correlation function that can be constructed by averaging the measured correlation functions over a significant amount of total averaging time Nee et al. (1994). However, MEDLL provides superior multipath mitigation performance than nEML at a cost of expensive multi-correlator based delay tracking structure.

4.6 Vision correlator

A completely different approach to mitigate multipath error is used in NovAtel's recently developed Vision Correlator Fenton & Jones (2005). The Vision Correlator (VC) is based on the concept of Multipath Mitigation Technique (MMT) developed in Weill (2002). It can provide a significant improvement in detecting and removing multipath signals as compared to other standard multipath resistant code tracking algorithms (for example, PAC of NovAtel). However, VC has the shortcoming 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.

5. Advanced multipath mitigation techniques

The advanced multipath mitigation techniques generally require a significant number of correlators (i.e., tens of correlators) in order to estimate the channel characteristics, which are then used to mitigate the multipath effect. Some of the most promising advanced multipath mitigation techniques are presented in the following sub-sections. In most occasions, references are made to the original publications in order to avoid too many technical details.

5.1 Non-coherent multipath estimating delay lock loop

MEDLL is considered as a significant evolutionary step in the correlation-based multipath mitigation approach. Moreover, MEDLL has stimulated the design of different maximum likelihood based implementations for multipath mitigation. One such variant is the non-coherent MEDLL, developed by the authors, as described in Bhuiyan et al. (2008). The classical MEDLL is based on a maximum likelihood search, which is computationally extensive. The authors implemented a non-coherent version of MEDLL that reduces the search space by incorporating a phase search unit, based on the statistical distribution of multipath phases. It was shown in Bhuiyan et al. (2008) that the performance of this suggested approach depends on the number of random phases considered; meaning that the larger the number is, the better the performance will be. But this will also increase the processing burden significantly. The results reported in Bhuiyan et al. (2008), show that the non-coherent MEDLL provides very good performance in terms of RMSE, but has a rather poor Mean-Time-to-Lose-Lock (MTLL) as compared to the conventional DLL techniques.

5.2 Second derivative correlator

A new technique to mitigate multipath by means of correlator reference waveform was proposed in Weill (1997). This technique, referred to as Second Derivative correlator, generates a signal correlation function which has a much narrower width than a standard correlation function, and is therefore capable of mitigating multipath errors over a much wider range of secondary path delays. The narrowing of the correlation function is accomplished by using a specially designed code reference waveform (i.e. the negative of the second order derivative of correlation function) instead of the ideal code waveform used in almost all existing receivers. However, this new technique reduces the multipath errors at the expense of a moderate decrease in the effective Signal-to-Noise Ratio (SNR) due to the effect of narrowing the correlation function. A similar strategy, named as Slope Differential (SD), is based on the second order derivative of the correlation function Lee et al. (2006). It is shown in Lee et al. (2006) that this technique has better multipath performance than nEML and Strobe Correlator. However, the performance measure was solely based on the theoretical MEE curves, thus its potential benefit in more realistic multipath environment is still an open issue.

5.3 Peak tracking

Peak Tracking (PT) based techniques, namely PT based on 2nd order Differentiation (PT(Diff2)) and PT based on Teager Kaiser (PT(TK)), were proposed in Bhuiyan et al. (2008). Both the techniques utilize the adaptive thresholds computed from the estimated noise variance of the channel in order to decide on the correct code delay. The adaptive thresholds are computed according to the equations given in Bhuiyan et al. (2008). After that, the advanced techniques generate the competitive peaks which are above the computed adaptive thresholds. The generation of competitive peaks for PT(Diff2) technique is shown in Fig. 6 in two path Nakagami-m fading channel. For each of the competitive peak, a decision variable is formed based on the peak power, the peak position and the delay difference of the peak from the previous delay estimate. Finally, the PT techniques select the peak which has the maximum weight as being the best LOS candidate. It was shown in Bhuiyan et al. (2008) that PT(Diff2) has superior multipath mitigation performance over PT(TK) in two to five path Nakagami-m fading channel.

5.4 Teager Kaiser operator

The Teager Kaiser based delay estimation technique is based on the principle of extracting the signal energy of various channel paths via a nonlinear TK operator Hamila (2002), Hamila et al. (2003). The output $\Psi_{TK}(x(n))$ of TK operator applied to a discrete signal $x(n)$, can be defined as Hamila et al. (2003):

$$\Psi_{TK}(x(n)) = x(n-1)x^*(n-1) - \frac{1}{2}[x(n-2)x^*(n) + x(n)x^*(n-2)] \quad (3)$$

If a non-coherent correlation function is used as an input to the nonlinear TK operator, it can then signal the presence of a multipath component more clearly than looking directly at the correlation function. At least three correlation values (in-prompt, early and very early) are required to compute TK operation. But usually, TK based delay estimation utilizes a higher number of correlators (for example, 193 correlators were used in the simulations reported in

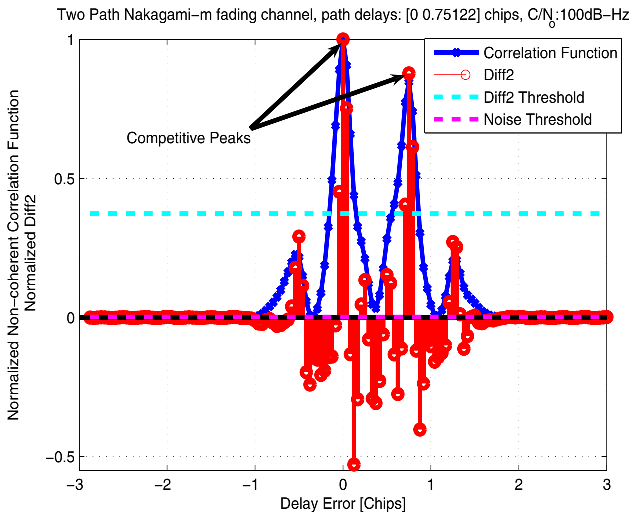

Fig. 6. Generation of competitive peaks for PT(Diff2) technique.

Bhuiyan & Lohan (2010)) and is sensitive to the noise dependent threshold choice. Firstly, it computes the noise variance, which is then used to compute an adaptive threshold. The peaks which are above the adaptive threshold are considered as competitive peaks. Among all the competitive peaks, TK selects the delay associated to that competitive peak which has the closest delay difference from the previous delay estimate.

5.5 Reduced Search Space Maximum Likelihood delay estimator

A Reduced Search Space Maximum Likelihood (RSSML) delay estimator is another good example of maximum likelihood based approach, which is capable of mitigating the multipath effects reasonably well at the expense of increased complexity. The RSSML, proposed by the Author in Bhuiyan et al. (2009) and then further enhanced in Bhuiyan & Lohan (2010), 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. Conceptually, a conventional spread spectrum receiver does the same thing, but for only one signal (i.e., the LOS signal). With the presence of multipath signal, 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 Bhuiyan & Lohan (2010), it also incorporates a threshold-based peak detection method, which eventually reduces the code delay search space significantly. However, the downfall of RSSML is the memory requirement which it uses to store the reference correlation functions.

In a multi-correlator based structure, the estimated LOS delay, theoretically, can be anywhere within the code delay window range of $\pm\tau_W$ chips, though in practice, it is quite likely to have a delay error around the previous delay estimate. The code delay window range essentially depends on the number of correlators (i.e., M) and the spacing between the correlators (i.e., Δ) according to the following equation:

$$\tau_W = \pm \frac{(M-1)}{2}\Delta \quad (4)$$

For example, in Bhuiyan & Lohan (2010), 193 correlators were used with a correlator spacing of 0.0208 chips, resulting in a code delay window range of ±2 chips with respect to prompt correlator. Therefore, the LOS delay estimate can be anywhere within this ±2 chips window range. The ideal non-coherent reference correlation functions are generated for up to L_{max} paths only for the middle delay index (i.e., $(\frac{M+1}{2})$-th delay index; for $M = 193$, the middle delay index is 97). These ideal correlation functions for the middle delay index are generated off-line and saved in a look-up table in memory. In real-time, 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. Instead of considering all possible LOS delays within a predefined code delay window as delay candidates, the search space is first reduced to some competitive peaks which are generated based on the computed noise thresholds as explained in Bhuiyan & Lohan (2010). This will eventually reduce the processing time required to compute the MMSE (i.e., MMSE needs to be computed only for the reduced search space). An example is shown in Fig. 7, where RSSML estimates a best-fitted non-coherent correlation function at a cost of $3.6 \cdot 10^{-4}$ MMSE in a two-path Rayleigh channel with path delays [0 0.35] chips, path powers [0 -2] dB at a C/N_0 of 50 dB-Hz.

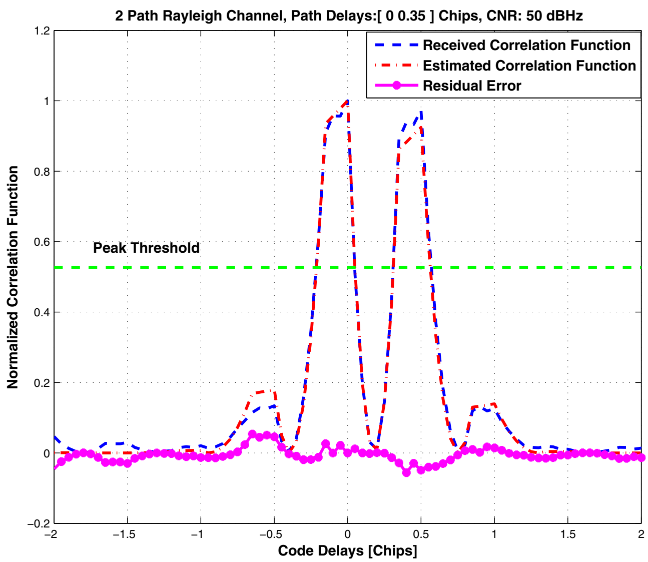

Fig. 7. Estimated and received non-coherent correlation functions in two path Rayleigh channel, path delay: [0 0.35] chips, path power: [0 -2] dB, C/N_0: 50 dB-Hz.

5.6 Slope-based multipath estimator

A simple slope-based multipath mitigation technique, named as Slope-Based Multipath Estimator (SBME), in Bhuiyan, Lohan & Renfors (2010). Unlike the multipath mitigation techniques discussed above, SBME does not require a huge number of correlators, rather it only requires an additional correlator (as compared to a conventional DLL) at the late side of the correlation function. In fact, SBME is used in conjunction with a nEML tracking loop Bhuiyan, Lohan & Renfors (2010). It 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. The derivation of the multipath estimation equation for BPSK modulated GPS L1 C/A signal can be found in Bhuiyan, Lohan & Renfors (2010). It is reported in Bhuiyan, Lohan & Renfors (2010) that SBME has superior multipath mitigation performance than nEML in closely spaced two path channel model.

5.7 C/N_0 -based two-stage delay tracker

A C/N_0 based two-stage delay tracker is a combination of two individual tracking techniques, namely nEML and HRC (or MGD). The tracking has been divided into two stages based on the tracking duration and the received signal strength (i.e., C/N_0). At the first stage of tracking (for about 0.1 seconds or so), 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. And, at the second or final stage of tracking (i.e., when the DLL tracking error is around zero), the two-stage delay tracker switches its DLL discriminator from nEML to HRC (or MGD), since HRC (or MGD) has better multipath mitigation capability as compared to nEML. While doing so, it has to be ensured that the estimated C/N_0 level meets a certain threshold set by the two-stage tracker. This is because of the fact that HRC (or MGD) involves one (or two in case of MGD) more discrimination than NEML, which makes its discriminator output much noisier than nEML. It has been empirically found that a C/N_0 threshold of 35 dB-Hz can be a good choice, as mentioned in Bhuiyan, Zhang & Lohan (2010). Therefore, at this fine tracking stage, the two-stage delay tracker switches from nEML to HRC (or MGD) only when the estimated C/N_0 meets the above criteria (i.e., C/N_0 threshold is greater than 35 dB-Hz).

An example non-coherent S-curve is shown in Fig. 8 for CBOC(-) modulated signal in single path static channel Bhuiyan, Zhang & Lohan (2010). The nearest ambiguous zero crossings for HRC (around ± 0.16 chips) is much closer as compared to that of nEML (around ± 0.54 chips) in this particular case. This indicates the fact that the probability of locking to any of the side peaks is much higher for HRC than that of nEML, especially in the initial stage of tracking when the code delay may not necessarily be near the main peak of the correlation function. This is the main motivation to choose a nEML tracking at the initial stage for a specific time duration (for example, 0.1 seconds or so). This will eventually pull the delay tracking error around zero after the initial stage.

5.8 TK operator combined with a nEML DLL

A combined simplified approach with TK operator and a nEML DLL was implemented in Bhuiyan & Lohan (2010), in order to justify the feasibility of having a nEML discrimination after the TK operation on the non-coherent correlation function. In this combined approach, TK operator is first applied to the non-coherent correlation function, and then nEML

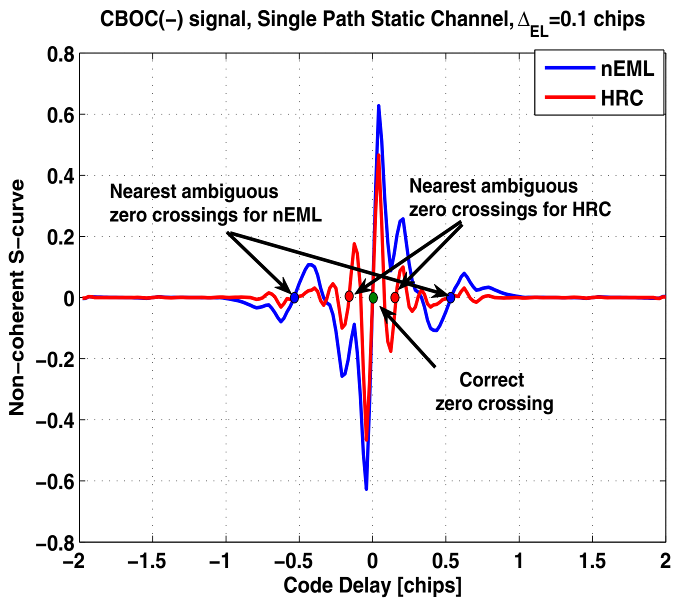

Fig. 8. A non-coherent S-curve for CBOC(-) modulated single path static channel. Bhuiyan, Zhang & Lohan (2010)

discrimination is applied to the TK output. The motivation for this combined approach comes from the fact that, when we apply TK operation to the non-coherent correlation function, it usually makes the main lobe of the non-coherent correlation function (after TK operation) much steeper than before. This eventually reduces the effect of multipath in case of TK based nEML (TK+nEML) as compared to nEML.

6. Performance analysis

The multipath performance of some of the discussed techniques are evaluated in different simulation models, i.e., the semi-analytical simulation in a static channel model and the Matlab-based simulation in a multipath fading channel model. Each simulation model is briefly described first before presenting the results.

6.1 Semi-analytical simulation

The most typical way to evaluate the performance of a multipath mitigation technique is via Multipath Error Envelopes (MEE). Typically, two paths, either in-phase or out-of-phase, are assumed to be present, and the multipath errors are computed for multipath delays up to 1.2 chips at maximum, since the multipath errors become less significant after that. The upper multipath error envelope can be obtained when the paths are in-phase and the lower multipath error envelope when the paths are out-of-phase (i.e., 180° phase difference). In MEE analysis, several simplifying assumptions are usually made in order to distinguish the performance degradation caused by the multipath errors only. Such assumptions include zero Additive-White-Gaussian-Noise (AWGN), ideal infinite-length PRN codes, and zero residual

Doppler. Under these assumptions, the correlation $\mathcal{R}_{rx}(\tau)$ between the reference code of the modulation type MOD (for example, BPSK or CBOC(-)) and the received MOD-modulated signal via an L-path channel can be written as:

$$\mathcal{R}_{rx}(\tau) = \sum_{l=1}^{L} \alpha_l e^{j\theta_l} \mathcal{R}_{\text{MOD}}(\tau - \tau_l) \tag{5}$$

where $\alpha_l, \theta_l, \tau_l$ are the amplitude, phase, and delay, respectively, of the l-th path; and $\mathcal{R}_{\text{MOD}}(\tau)$ is the auto-correlation function of a signal with the modulation type MOD. The analytical expressions for MEEs become complicated in the presence of more than two paths due to the complexity of channel interactions. Therefore, an alternative Monte-Carlo simulation-based approach is presented here, in accordance with Bhuiyan & Lohan (2010), for multipath error analysis in more than one path scenarios (i.e, for $L \geq 2$). First, a sufficient number of random realizations, N_{random} are generated (i.e., in the simulation, we choose N_{random} equals to 1000), and then we look at the absolute mean error for each path delay over N_{random} points. The objective is to analyze the multipath performance of some of the proposed advanced techniques along with some conventional DLLs in the presence of more than two channel paths, which may occur in urban or indoor scenarios.

The following assumptions are made while running the simulation for generating the RAE curves Hein et al. (2006). According to Hein et al. (2006), RAE is computed from the area enclosed within the multipath error and averaged over the range of the multipath delays from zero to the plotted delay values. In the simulation, the channel follows a decaying Power Delay Profile (PDP), which can be expressed by the equation:

$$\alpha_l = \alpha_l \exp^{-\mu(\tau_l - \tau_1)}, \tag{6}$$

where $(\tau_l - \tau_1) \neq 0$ for $l > 1$, μ is the PDP coefficient (assumed to be uniformly distributed in the interval $[0.05; 0.2]$, when the path delays are expressed in samples). The channel path phases θ_l are uniformly distributed in the interval $[0; 2\pi]$ and the number of channel paths L is uniformly distributed between 2 and L_{max}, where L_{max} is set to 5 in the simulation. A constant successive path spacing x_{ct} is chosen in the range $[0; 1.167]$ chips with a step of 0.0417 chips (which defines the multipath delay axis in the RAE curves). It is worth to mention here that the number of paths is reduced to only one LOS path when $x_{ct} = 0$. The successive path delays can be found using the formula $\tau_l = l x_{ct}$ in chips. Therefore, for each channel realization (which is a combination of amplitudes $\vec{\alpha} = \alpha_1, \ldots, \alpha_L$, phases $\vec{\theta} = \theta_1, \ldots, \theta_L$, fixed path spacings, and the number of channel paths L), a certain LOS delay is estimated $\hat{\tau}_1(\vec{\alpha}, \vec{\theta}, L)$ from the zero crossing of the discriminator function (i.e., $D(\tau) = 0$), when searched in the linear range of $D(\tau)$ in case of conventional DLLs, or directly from the auto-correlation function in case of advanced multi-correlator based techniques. The estimation error due to multipath is $\hat{\tau}_1(\vec{\alpha}, \vec{\theta}, L) - \tau_1$, where τ_1 is the true LOS path delay. The RAE curves are generated in accordance with Hein et al. (2006). RAE is actually computed from the area enclosed within the multipath error and averaged over the range of the multipath delays from zero to the plotted delay values. Therefore, in order to generate the RAE curves, the Absolute Mean Error (AME) is computed for all N_{random} random points via eqn. 7:

$$\text{AME}(x_{ct}) = \text{mean}\left(\left|\hat{\tau}_1(\vec{\alpha}, \vec{\theta}, L) - \tau_1\right|\right), \tag{7}$$

where $\text{AME}(x_{ct})$ is the mean of the absolute multipath error for the successive path delay x_{ct}. Now, the running average error for each particular delay in the range [0;1.167] chips can be computed as follows:

$$\text{RAE}(x_{ct}) = \frac{\sum_{i=1}^{i} \text{AME}(x_{ct})}{i}, \tag{8}$$

where i is the successive path delay index, and $\text{RAE}(x_{ct})$ is the RAE for the successive path delay x_{ct}.

The RAE curves for CBOC(-) modulated Galileo E1C signal (i.e., pilot channel) is shown in Fig. 9. It is obvious from Fig. 9 that the RSSML and PT(Diff2) show the best performance in terms of RAE as compared to other techniques in this noise-free two to five paths static channel model. Among other techniques, TK+nEML showed very good performance followed by SBME, HRC and nEML. The SBME coefficient and the late slope at very late spacing of 0.0833 chips were determined according to Bhuiyan, Lohan & Renfors (2010) for a 24.552 MHz front-end bandwidth (double-sided). For the above configuration, the SBME coefficient is 0.007 and the late slope is −4.5.

It is worth to mention here that the RAE analysis is quite theoretical from two perspectives: firstly, the delay estimation is a one-shot estimate, and does not really include any tracking loop in the process; and secondly, the analysis is usually carried out with an ideal noise free assumption. These facts probably explain the reason why an algorithm which performs

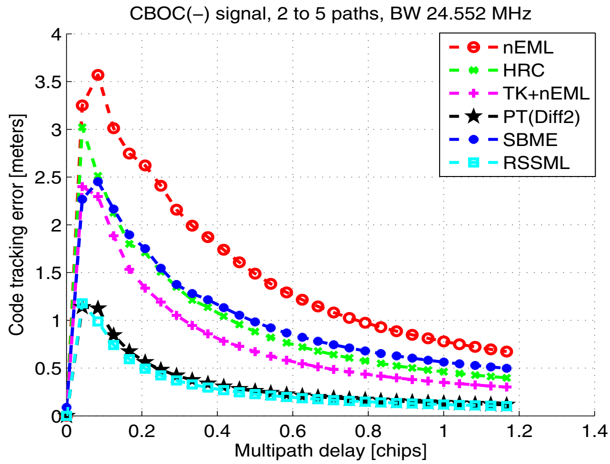

Fig. 9. Running average error curves for CBOC(-) modulated Galileo E1C signal.

very well with respect to RAE may not necessarily provide the same performance in a more realistic closed loop fading channel model, especially in the presence of more than two channel paths. However, MEE or RAE analysis has been widely used by the research community as an important tool for analyzing the multipath performance due to simpler implementation, and also due to the fact that it is hard to isolate multipath from other GNSS error sources in real life.

6.2 Matlab-based simulation

Simulation has been carried out in closely spaced multipath environments for CBOC(-) modulated Galileo E1C (i.e., pilot channel) signal for a 24.552 MHz front-end bandwidth. The simulation profile is summarized in Table 1. Rayleigh fading channel model is used in the simulation, where the number of channel paths follows a uniform distribution between two and five. The successive path separation is random between 0.02 and 0.35 chips. The channel paths are assumed to obey a decaying PDP according to Eqn. 6, where $(\tau_l - \tau_1) \neq 0$ for $l > 1$, and the PDP coefficient $\mu = 0.1$. The received signal is sampled such that there are 48 samples per chip. The received signal duration is 800 milliseconds (ms) or 0.8 seconds for each particular C/N_0 level. The tracking errors are computed after each $N_c * N_{nc}$ ms (in this case, $N_c * N_{nc} = 20$ ms) interval. In the final statistics, the first 600 ms 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, for the above configuration (i.e., code loop filter parameters and the first path delay of 0.2 chips), the left-over tracking errors after 600 ms are mostly due to the effect of multipath. The simulation has been carried out for 100 random realizations, which give a total of 10*100=1000 statistical points, for each C/N_0 level. The RMSE of the delay estimates are plotted in meters, by using the relationship:

$$\text{RMSE}_m = \text{RMSE}_{\text{chips}} c T_c \tag{9}$$

where c is the speed of light, T_c is the chip duration, and $\text{RMSE}_{\text{chips}}$ is the RMSE in chips.

Parameter	Value
Channel model	Rayleigh fading channel
Number of paths	between 2 to 5
Path Power	Decaying PDP with $\mu = 0.1$
Path Spacing	Random between 0.02 and 0.35 chips
Path Phase	Random between 0 and 2π
Samples per Chip, N_s	48
E-L Spacing, Δ_{EL}	0.0833 chips
Number of Correlators, M	193[1]
Double-sided Bandwidth, BW	24.552 MHz
Filter Type	Finite Impulse Response (FIR)
Filter Order	6
Coherent Integration, N_c	20 ms
Non-coherent Integration, N_{nc}	1 block
Initial Delay Error	$\pm$ 0.1 chips
First Path Delay	0.2 chips
Code Tracking Loop Bandwidth	2 Hz
Code Tracking Loop Order	1st order

Table 1. Simulation profile description

RMSE vs. C/N_0 plot for the given multipath channel profile is shown in Fig. 10. It can be seen from Fig. 10 that the proposed RSSML clearly achieves the best multipath mitigation

[1] Not all the correlators are used in all the tracking algorithms. For example, nEML only requires 3 correlators.

performance in this two to five paths closely spaced multipath channel. Among other techniques, PT(Diff2) and HRC have better performance only in good C/N_0 (around 40 dB-Hz and onwards). It can also be observed that the proposed SBME and TK+nEML do not bring any advantage in the tracking performance as compared to nEML in this multipath fading channel model. Here also, the SBME coefficient and the late slope were set to 0.007 and −4.5, respectively.

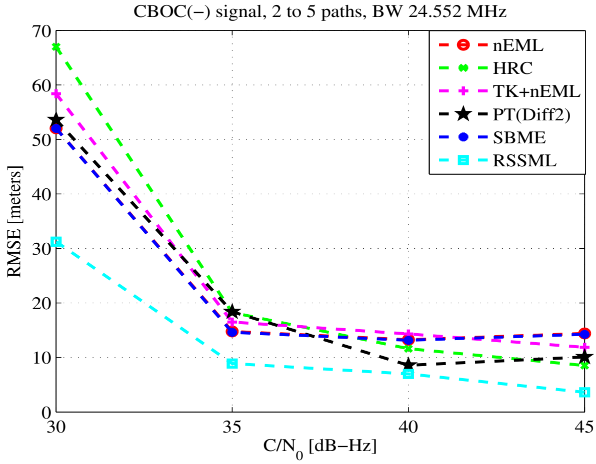

Fig. 10. RMSE vs. C/N_0 plot for CBOC(-) modulated Galileo E1C signal in two to five path Rayleigh fading channel.

7. Conclusion

This chapter addressed the challenges encountered by a GNSS signal due to multipath propagation. A wide range of correlation-based multipath mitigation techniques were discussed and the performance of some of these techniques were evaluated in terms of running average error and root-mean-square error. Among the analyzed multipath mitigation techniques, RSSML, in general, achieved the best multipath mitigation performance in moderate-to-high C/N_0 scenarios (for example, 30 dB-Hz and onwards). The other techniques, such as PT(Diff2) and HRC showed good multipath mitigation performance only in high C/N_0 scenarios (for example, 40 dB-Hz and onwards). The other new technique SBME offered slightly better multipath mitigation performance to the well-known nEML DLL at the cost of an additional correlator. However, as the GNSS research area is fast evolving with many potential applications, it remains a challenging topic for future research to investigate the feasibility of these multipath mitigation techniques with the multitude of signal modulations, spreading codes, and spectrum placements that are (or are to be) proposed.

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Global Navigation Satellite System (GNSS) plays a key role in high precision navigation, positioning, timing, and scientific questions related to precise positioning. This is a highly precise, continuous, all-weather, and real-time technique. The book is devoted to presenting recent results and developments in GNSS theory, system, signal, receiver, method, and errors sources, such as multipath effects and atmospheric delays. Furthermore, varied GNSS applications are demonstrated and evaluated in hybrid positioning, multi-sensor integration, height system, Network Real Time Kinematic (NRTK), wheeled robots, and status and engineering surveying. This book provides a good reference for GNSS designers, engineers, and scientists, as well as the user market.