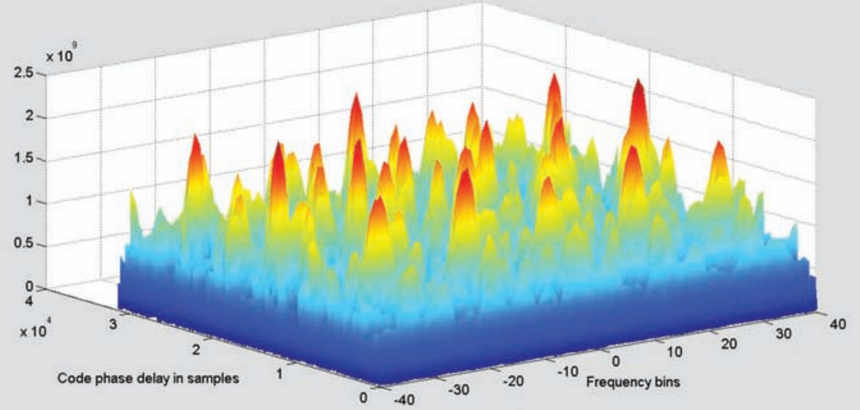
Interference Mitigation in the E5a Galileo Band

Using an Open-Source Simulator



Acquisition output of the Galileo E5 signal when no interference mitigation is used to cope with DME interference of 3,000 pps density.

InsideGNSS

A channel impairment that may affect the functionality of a GNSS receiver is the presence of narrowband interference – either intentional, from malicious third-party attacks, or unintentional, from other systems sharing the same frequency bands, or from harmonics of other systems using nearby frequency bands. Researchers describe the result of investigations into three narrowband interference mitigation methods based on time and frequency processing and compare them in terms of acquisition and tracking performance.

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Four global navigation satellite systems are scheduled to be fully operational orbiting Earth in the coming years: the NAVSTAR Global Positioning System (GPS) from the United States, the GLObal NAvigation Satellite System (GLONASS) from Russia, the Compass/BeiDou-2 System (BDS) from China, and Galileo from Europe. A considerably high number of signals, coming from the satellites of those constellations, will share the radio electric spectrum.

Moreover, some aeronautical radio navigation systems (ARNS) operate in the E5 Galileo band. For example, distance measuring equipment (DME) and tactical air navigation (TACAN) systems (both in the ARNS category) broadcast strong pulsed ranging signals that interfere with Galileo E5a and GPS L5 signals. As analyzed in the work by F. Bastide *et alia,* listed in the Additional Resources section near the end of this article, DME/TACAN interferences can severely degrade the receiver performance if left unmitigated.

Galileo receiver simulators are a powerful way to investigate the initial performance of Galileo receivers without the need of heavy measurement campaigns. Applications of open-source Galileo simulators, especially regarding the E5 band, are still hard to find in the current literature. This article presents the development of an open-source 64-bit Galileo simulator, including the acquisition and tracking parts and the interference mitigation blocks for continuous wave interference (CWI) and DME. The simulator is available on demand and upon agreeing to its open-source conditions (Details listed in the Manufacturers section at the end of this article).

This article thoroughly analyzes three narrowband interference mitigation methods explained in the next sections (*notch filtering, zeroing,* and *pulse blanking*) with Galileo E5a signals based on the open-source simulator created in our group (Signal Processing for wireless positioning group at Tampere University of Technology). The performance studies are done with both the benchmark CWI and the DME interferences.

The novelty of our work comes from analyzing jointly these three techniques with a practical Galileo simulator and from selecting the best method according to the interference type. We show that zeroing methods are best used for robustness and with strong narrowband CWI while pulse blanking methods are better than notch filtering methods for strong DME interferers. We also show that interferers with up to 10–15 decibels stronger power than the E5a signal power can be tolerated relatively well and that all considered approaches have relatively similar performance for medium strength interferers.

GNSS Interferences

Very simply put, GNSS interference can be defined as any signal, from any service, working in the same frequency as the satellite receiver. *Wideband interference* refers to interference with bandwidth comparable to or higher than the GNSS signal bandwidth, e.g., ultra-wideband (UWB) technology that transmits a huge amount of information with a very low power using a large bandwidth, inter-system interferences between satellites from different GNSSs, or intra-system interferences between satellites from the same GNSS (here Galileo). The spectrum is becoming overwhelmed by all the satellite systems deployed.

Some interference can be mitigated well using time or frequency processing methods. However, when dealing with wideband interference, the performance of these methods degrades, and additional processing has to be carried out, such as space-based processing methods (i.e., antenna array–based methods). Minimum variance distortionless response (MVDR) and minimum power distortionless response (MPDR) beamformers are some examples.

These spatial approaches are not assessed in this article, however, and we focused our research on *narrowband interference* — those whose bandwidth is much lower than the bandwidth of the GNSS signal of interest. Narrowband interference can be created, for example, by TV harmonics, inter-modulation products or signals from very high frequency (VHF) and ultra high frequency (UHF) stations, or signals generated by systems such as DME or TACAN. **Figure 1** illustrates the different types of interference in Galileo bands.

Another criterion can be the intentionality. Within the *unintentional interference* group, we can emphasize: DME/TACAN, amateur radio, TV, surveillance radars, or wind profiler radars. Under the name of *intentional interference* (see **Figure 2** and **Figure 3**), three different interference signals can be distinguished: *jamming signals*, which deliberately block or interfere with authorized wireless communications through illegal devices decreasing the signal-to-interference-plus-noise ratio (SINR); *spoofing signals,* which falsely imitate the signal-in-space (SIS) and may hack a targeted GNSS receiver; and *meaconing signals,* which are the interception and delayed-rebroadcast of actual GNSS signals.

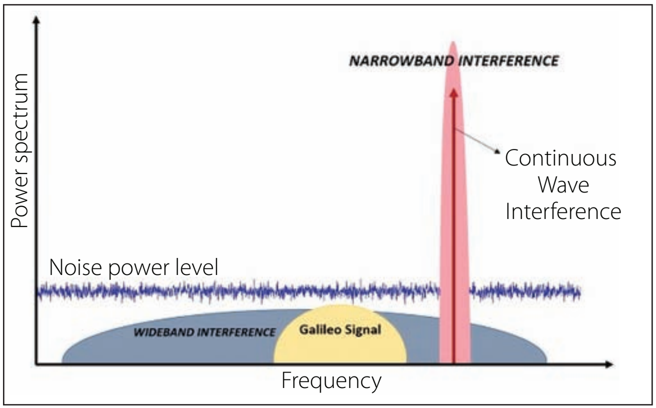

FIGURE 1 Illustration of wideband and narrowband interference in the Galileo radio frequency bands

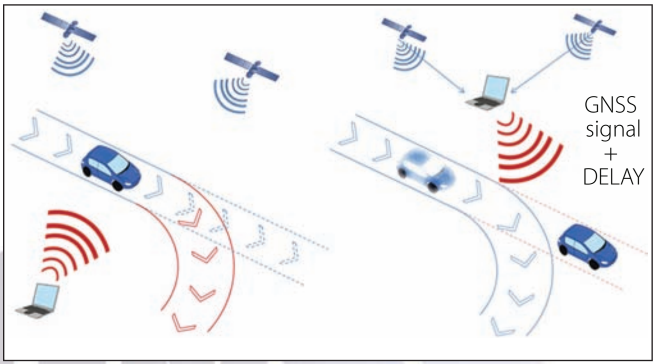

FIGURE 2 Spoofing (left) and meaconing (right)interferences

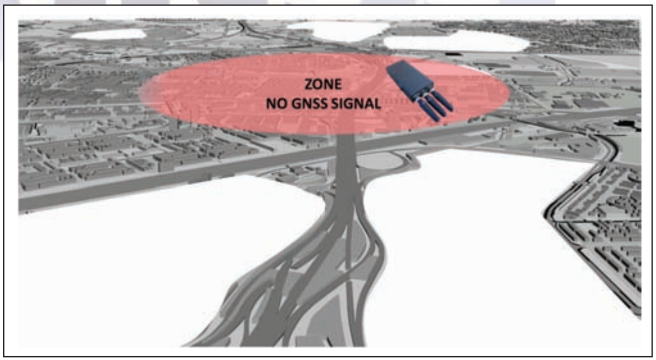

FIGURE 3 Jamming interference

In this article, we have simulated and studied two interference signals: CWI and pulsed signals such as those generated by the DME or TACAN systems. A *CWI signal* can be modelled as

$$j_{cwi}(t) = A \cdot \sin(2\pi\Delta f_{cwi} + \phi_0) \quad (1)$$

where Δf_{cwi} is the frequency offset with respect to the GNSS carrier, A is the CWI amplitude, and ϕ_0 is the CWI signal initial phase.

Signals from air radionavigation systems, such as DME or TACAN, consist of Gaussian RF paired pulses. Pulse separation is 12 microseconds with each pulse lasting 3.5 microseconds. The maximum repetition rate is about 3,000 pulse pairs per second (pps).

DME systems are designed to provide service for 100 planes simultaneously and the transmitted power may vary from 50 watts to 2 kilowatts. A DME signal is typically modeled as:

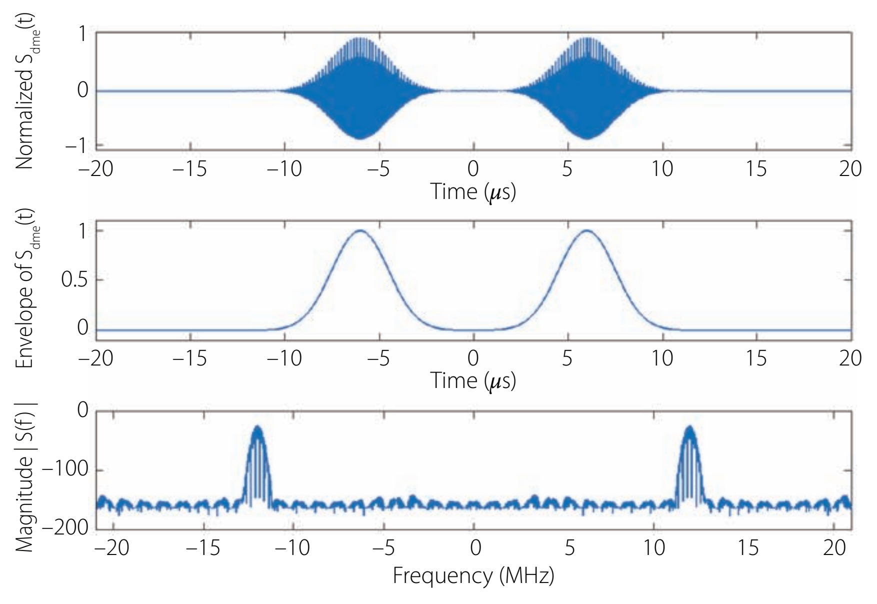

FIGURE 4 Example of a DME interferer in time (upper) and frequency (lower) domain. Middle plot shows its envelope

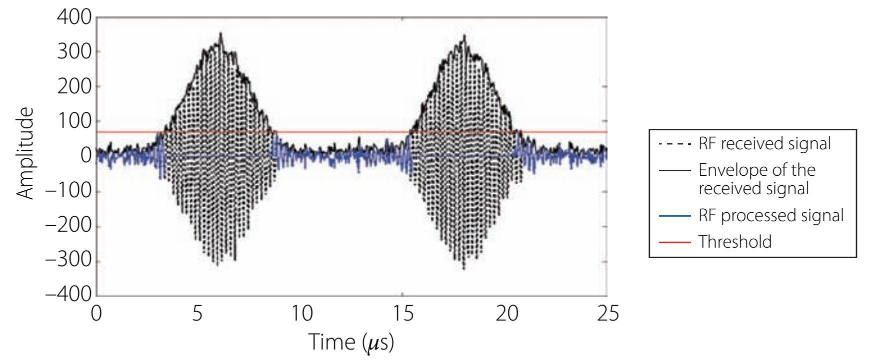

FIGURE 5 Pulse blanking method

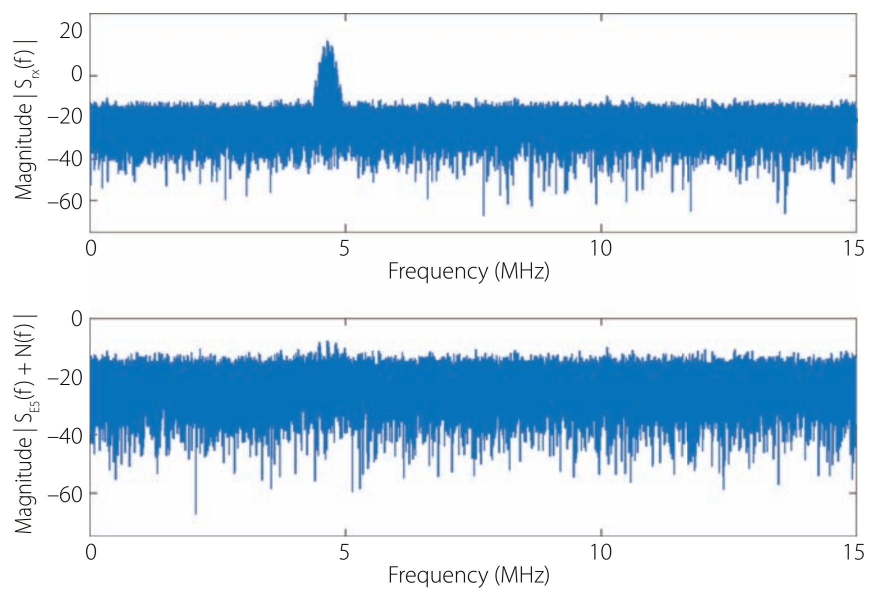

FIGURE 6 Pulse blanking for a Galileo signal affected by a DME interferer. Upper plot: no interference mitigation; lower plot: spectrum after pulse blanking.

$$j_{dme}(t) = A\left(\exp\left(-\frac{\alpha}{2}\left(t-\frac{\Delta t}{2}\right)^2\right) + \exp\left(-\frac{\alpha}{2}\left(t+\frac{\Delta t}{2}\right)^2\right)\right) \quad (2)$$

where $\alpha = 4.5 \cdot 10^{11}\ s^{-2}$ is a parameter controlling the pulse width and $\Delta t = 12 \cdot 10^{-16}\ s$ is a parameter controlling the gap between paired pulses. The DME system operates between 960 and 1215 MHz; hence, it overlaps the Galileo E5 band.

Figure 4 shows an example of a DME signal in the time domain, its envelope, and its frequency spectrum.

State-of-the-Art Narrowband Interference Mitigation

Mitigation approaches can be categorized into two groups: time-domain and frequency-domain techniques. Time-domain mitigation techniques are those that make use of only mathematical calculation without any operation in the frequency domain. Heavy computational loads are avoided and complexity is lower. Non-linear methods, filtering methods based on convolution operations, or blanking methods are some of the proposed approaches in the literature.

Frequency-domain approaches are those based on signal alterations in the frequency domain. The article by A. Rusu and E. S. Lohan listed in the Additional Resources section near the end of this article presents a filtering method that exploits the cyclostationarity property using the spectral correlation function (SCF) and, therefore, can suppress additive white Gaussian noise (AWGN). Another, even simpler method is called *zeroing*, which is an excision-based method that we will explain in the next section.

The literature also presents various transformed domain mitigations that are worth mentioning briefly. One is the *wavelet transform* which is a time-scale representation technique that overcomes the common limit of fast Fourier transform (FFT) transformations using the short time Fourier transform (STFT), and another is the Gabor transform. Both of these methods separate useful signal and interference, removing the coefficients with high energy before the

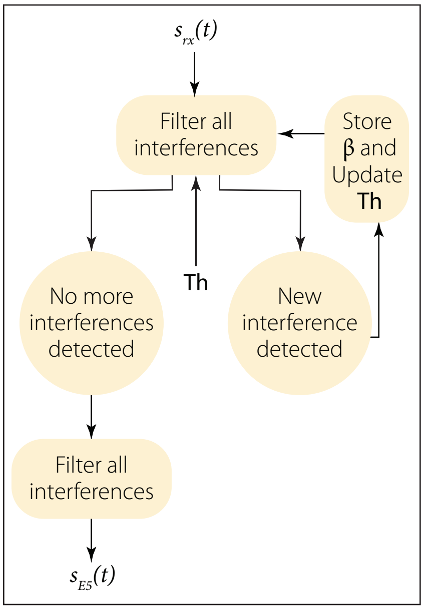

FIGURE 7 Illustration of the steps of an adaptive notch filtering mitigation algorithm

inverse transform. (These methods are described in articles by E. Anyaegbu *et alia* and K. Ohno and T. Ikegami, respectively, cited in the Additional Resources section.

Studied Mitigations. We selected the methods explained in this section based on the tradeoff between performance in acquisition and tracking and the method's complexity, which in turn is directly proportional to the amount of computational load. The pulse blanking and notch filtering methods are time-based approaches, while the zeroing method is a frequency-based one in which the simulated signal is grouped into blocks that become suitable for FFT processing.

Pulse Blanking. This method is simple to implement: it blanks incoming signals that exceed a certain threshold, as illustrated in **Figure 5**.

The threshold can be chosen, for example, as a factor of the mean value of the absolute value of the received signal, i.e., $\gamma = k \cdot E(|s(t)|)$ with k optimized according to the interference. In our simulations, we used, for example, k = 3.5, chosen empirically. **Figure 6** shows an example of pulse blanking performance in the frequency domain in the presence of a DME interferer.

Notch Filtering. Another time-domain method is notch filtering. A second order infinite impulse response (IIR) notch filter to mitigate the narrowband interference has been proposed, for example, by C. Ying-Ren *et alia* (see Additional Resources), based on the following transfer function:

$$H(z) = \frac{1+\delta}{2}\,\frac{1-2\beta z^{-1}+z^{-2}}{1-\beta(1+\delta)z^{-1}+\delta z^{-2}} \qquad (3)$$

with

$$\delta = \frac{1-\tan(B_{W,3dB}/2)}{1+\tan(B_{W,3dB}/2)}, \quad \beta = \cos(2\pi f_I),$$

$B_{W,3dB}$

is the 3 dB filter bandwidth, and f_I is the frequency of the interferer that must be canceled.

The interfering frequencies are searched in a recursive manner, based on a threshold, as illustrated in **Figure 7**. As an example, **Figure 8** shows the spectrum of a GNSS signal affected by DME interference, with and without notch filtering-based mitigation.

Zeroing. The discrete Fourier transform of a sample GNSS signal *s(n)* can be written as:

$$S(k) = \sum_{n=0}^{N-1} s(n) \cdot \exp\left(-j\frac{2\pi nk}{N}\right) \qquad (4)$$

Narrowband interferences can be rejected just by *zeroing* the spectral samples above a certain threshold. This time, the threshold γ_{FFT} is obtained according to the mean and the variance of the absolute value:

$$\gamma_{FFT} = E(|S(k)|) + \varepsilon\, var(|S(k)|) \qquad (5)$$

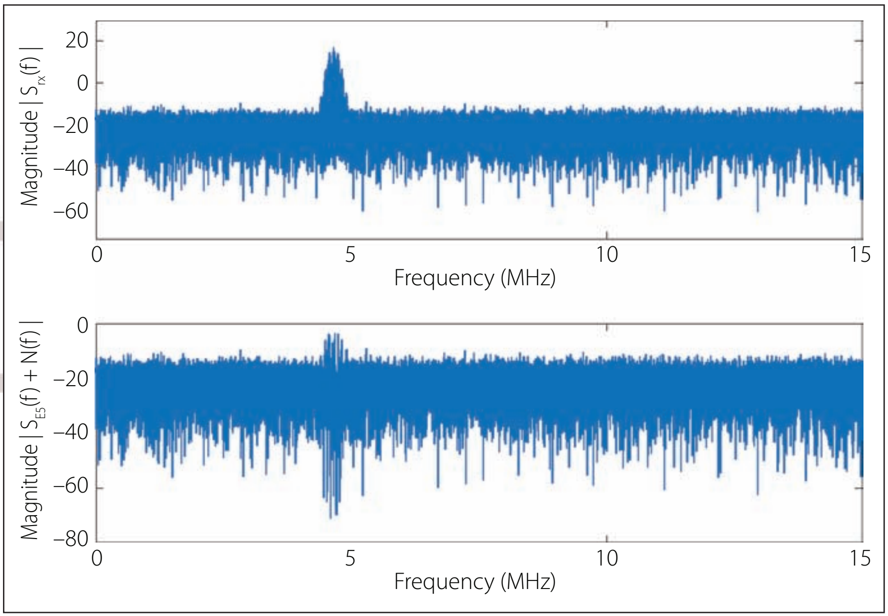

FIGURE 8 Notch filtering for a Galileo signal affected by a DME interferer. Upper plot: no interference mitigation; lower plot: spectrum after notch filtering.

Method	Suitable for DME	Suitable for CWI	Computational load	Time required	Power cancellation (dB) *
Blanking	✓	×	low	low	≈ 25
Zeroing	×	✓	High	Moderate	Inversely proportional to the SINR value.
Dynamic Notch Filtering	✓	✓	Moderate**	High***	25 - 40

* Difference between the spectral maximum of the contaminated signal (dB) and the spectral maximum of the cleaned signal (dB)
** The operations are in themselves very fast.
*** High run time due to frequency sweep

Table 1 Comparative table for three methods of narrowband interference mitigation

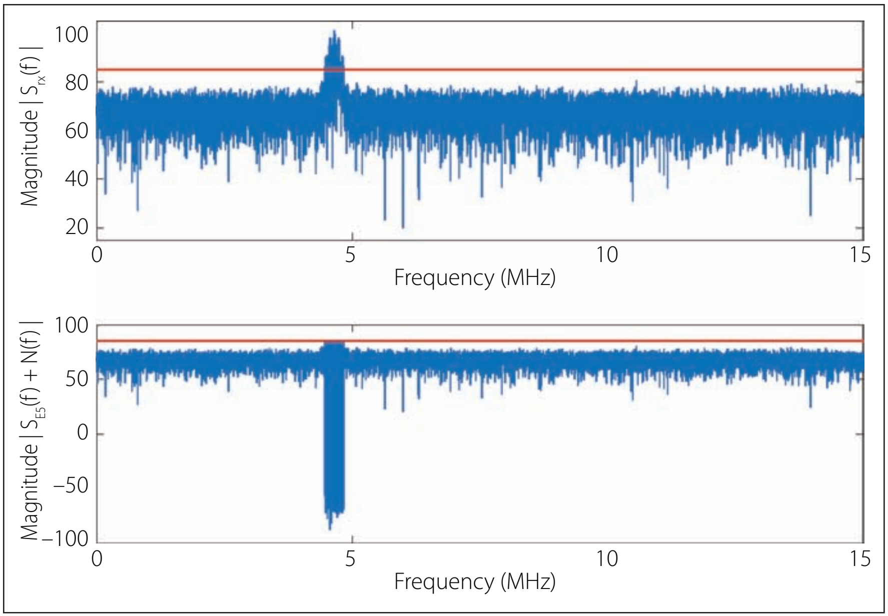

FIGURE 9 Zeroing method for a Galileo signal affected by a DME interferer. Upper plot: no interference mitigation; lower plot: spectrum after zeroing. The red line marks the threshold used.

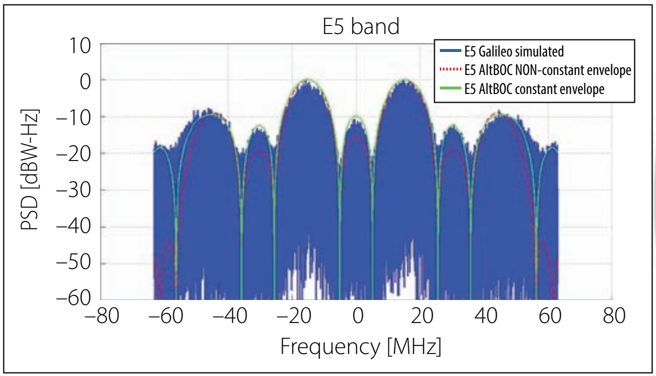

FIGURE 10 E5 Power Spectral Density

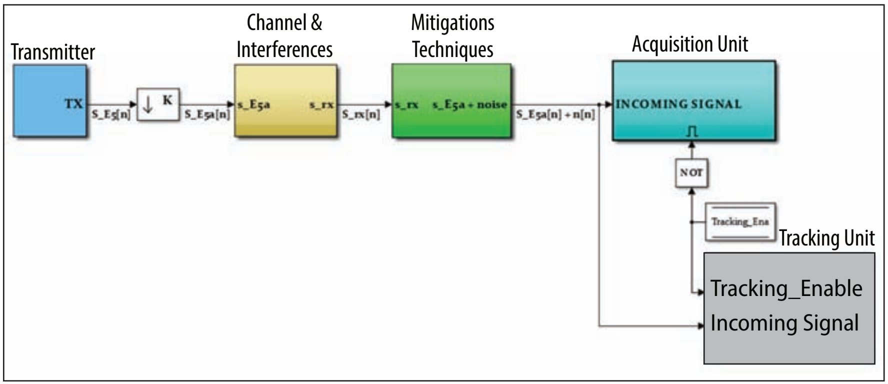

FIGURE 11 Simulator transmitter-receiver chain

where ε is a parameter adjusting the threshold (in our simulations ε = 0.5). **Figure 9** presents an example of the zeroing method (in the frequency domain).

Qualitative Comparison Among Narrowband Mitigation Techniques

Table 1 shows the strengths and weaknesses of each solution. Unlike the blanking approach, the zeroing and notch methods can be used for both CWI and DME interference. However, zeroing is much less effective than blanking against DME interference, and therefore it is not suitable for pulsed interference. The spread of the spectrum due to the steep variation in the time domain makes it more difficult to separate the useful signal from the DME signal. Some energy from the DME pulses remains after processing the signals employing the zeroing method.

Open-Source Simulator

The E5 Galileo band comprises two bands, an E5a band centered at 1176.45 MHz and an E5b band centered at 1207.140 MHz. The Galileo E5 signal is an AltBOC(15,10) modulated signal with a chipping rate of 10.23 Mcps. **Figure 10** illustrates simulated and theoretical power spectral densities (PSDs) of an AltBOC(15,10).

Our team at Tampere University of Technology developed a simulator with which to analyze Galileo signals; **Figure 11** illustrates an overview of this development. The simulator was initially started within the European Union's Galileo Ready Advanced Mass MArket Receiver (GRAMMAR) project and is now offered via free licensing for research purposes.

The simulator implements the transmitted signal based on an AltBOC(15,10) modulation with a constant envelope signal, according to the Galileo Open Service SIS Interface Control Document (SIS-ICD). The signal is sent over a multipath channel with up to five Rayleigh fading paths; noise and interference are added inside the channel block.

Due to computing capacity, the signal is transmitted at an intermediate frequency (IF) of 20 megahertz. The down-sampling factor is applied before the channel is employed to reduce the simulation time. Because the processing of the E5a band is only carried out at the receiver, a lower bandwidth is needed. The E5a sampling rate in our simulator is 31.5 megahertz, while the transmitter sampling rate is four times higher. The interference generation block, included inside the channel simulation, is detailed in **Figure 12**.

The receiver includes the interference mitigation block, the acquisition, and the tracking unit. **Figure 13** illustrates the interference mitigation block.

The acquisition block estimates the time and frequency initial values that

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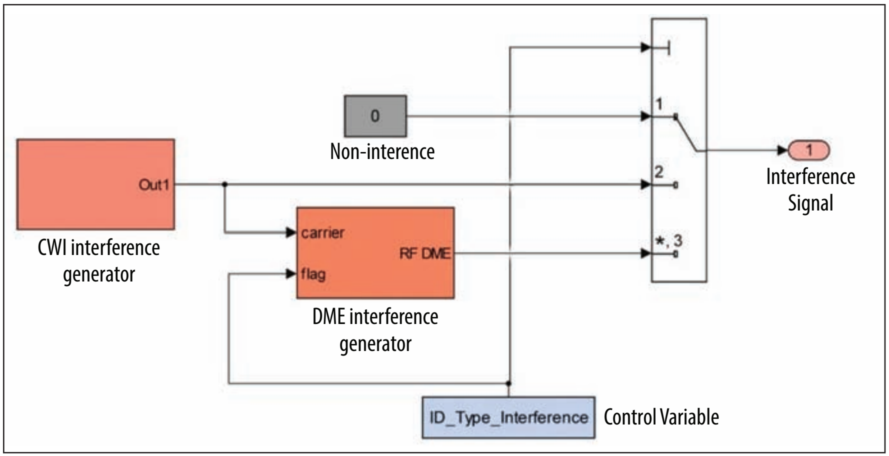

FIGURE 12 Interference generation block (inside the channel portion of the simulator)

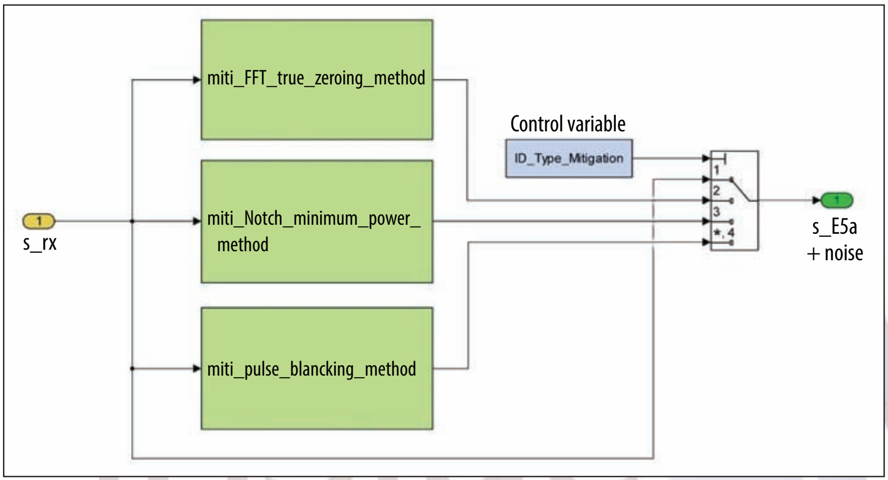

FIGURE 13 Interference mitigation block (inside the receiver part)

are then fed into a tracking block. **Figure 14** and **Figure 15** show, respectively, examples of the time-frequency acquisition mesh without and with interference mitigation, in the case of a CWI interferer at 1176.45 MHz, i.e., an E5a carrier frequency.

The acquired signal is passed through a narrow correlator tracking block, including a delay lock loop (DLL) and a joint frequency lock Loop (FLL) – phase lock loop (PLL). **Figure 16** presents the tracking unit block diagram.

Performance Comparison

We compared the performance of the mitigation techniques and present the results here in terms of detection probability at various carrier-to-noise (C/N_0) levels. **Figure 17** shows the acquisition performance in the presence of CWI for the zeroing and notch filtering methods (as the pulse blanking does not work for CWI cases). **Figure 18** shows the acquisition performance in the presence of DME interference for the pulse blanking and notch filtering methods (as the zeroing method is not so suitable for DME interference). Both figures also show the situation without interference mitigation.

In order to achieve a high detection rate, the blanking method for DME pulses and zeroing method for CWI are the most effective techniques among those studied.

Regarding the tracking results, it is worth mentioning how large the tracking error can become if no mitigation is taken into account to deal with the interference. The acquisition threshold is selected based on the highest peak of the time-frequency mesh. (For further discussion of this point, see the article by E. Pajala *et alia* in Additional Resources.)

Due to some type of interference, for instance DME pulses, large fluctuations can appear at some point along this mesh, and as a result the initial values can be extremely large as **Figure 19** shows. The computed position error could even be on the order of kilometers, due to the fact that the acquisition stage would feed an erroneous estimate into the tracking. However, as might be expected, the studied mitigations are able to keep this error within reasonable values as shown in **Figure 20**.

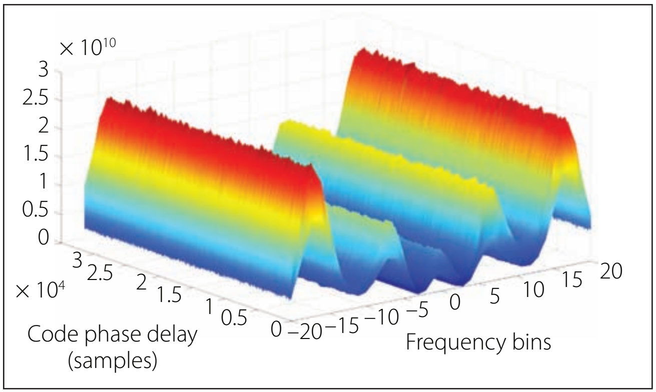

FIGURE 14 Acquisition mesh without interference mitigation. CWI interferer at 1176.45 MHz, SIR = -50 dB, C/N_0 = 50 dB-Hz

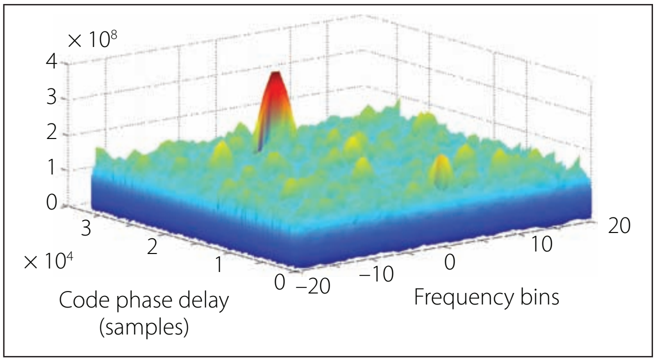

FIGURE 15 Acquisition mesh with interference mitigation. CWI interferer at 1176.45 MHz, SIR = -50 dB, C/N_0 = 50 dB-Hz.

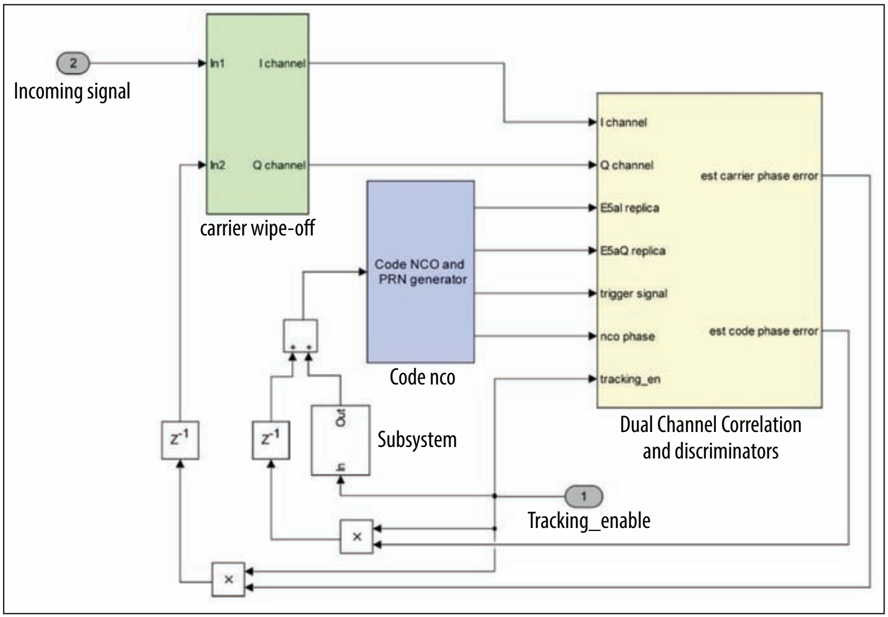

FIGURE 16 Tracking unit block diagram

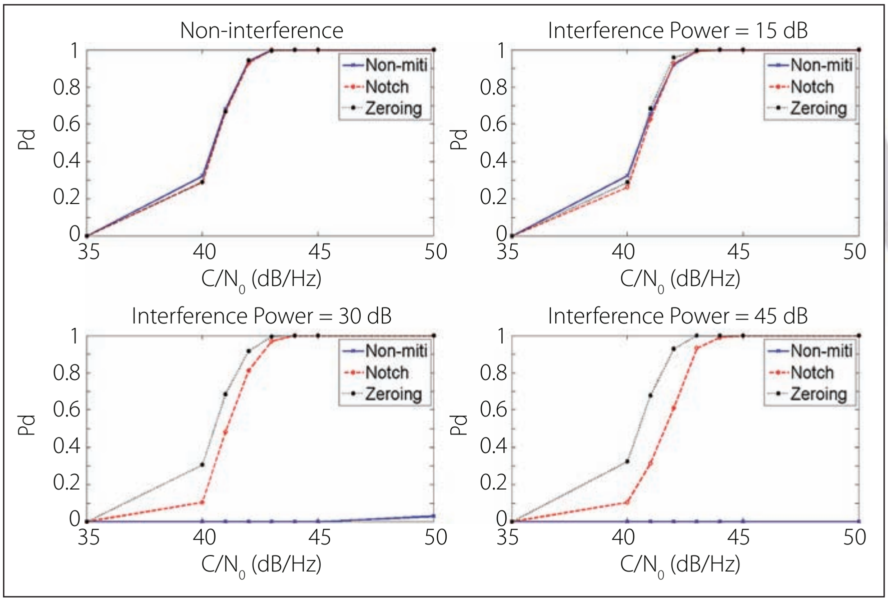

FIGURE 17 Performance with and without interference mitigation in the presence of CWI (various interference power levels)

Conclusions

The main objective of our work has been to analyze the impact of CWI and DME narrowband interference on the performance of the E5 Galileo signal, and more specifically, E5a band when processed independently of the E5b band. We have implemented and evaluated three types of narrowband interference rejections, namely pulse blanking, zeroing, and notch methods. We have shown that the notch filtering has the worst performance among the three of them, while pulse blanking and zeroing methods are the best for DME and CWI, respectively (but none of them works for both interference types). We have also demonstrated that interferers with up to 10–15 decibels stronger power than the E5a signal power can be tolerated relatively well and that all considered approaches have relatively similar performance for medium strength interferers.

Acknowledgments

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Manufacturers

The open-source 64-bit Galileo simulator described in this article was developed with the aid of Matlab Simulink graphical programming environment from **The Mathworks, Inc.**, Natick, Massachusetts USA, including the acquisition and tracking portions and the interference mitigation blocks for continuous wave interference and DMEs. The Simulink Galileo E1 and E5a baseband transmitter-receiver chain is available on demand and upon agreeing to its open-source conditions. It can be found at the <http://www.cs.tut.fi/tlt/pos/Software.htm>.

The Simulink-based simulator referenced in Figure 11 was initially started within the EU Galileo Ready Advanced Mass MArket Receiver (GRAMMAR) project <http://www.dlr.de/kn/en/desktopdefault.aspx/tabid-4309/3222_read-20115/admin-1> and is now offered via free licensing for research purposes at /<http://www.cs.tut.fi/tlt/pos/Software.htm>.

Additional Resources

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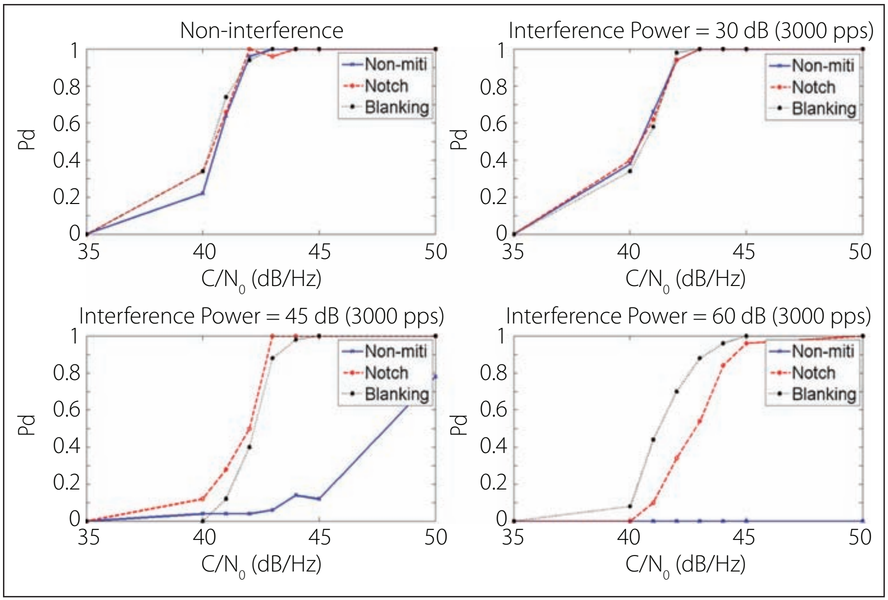

FIGURE 18 Performance with and without interference mitigation in the presence of DME (various interference power levels)

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[23] Zoltowski, M. D.. and A. S. Gecan "Advanced Adaptive Null Steering Concepts for GPS," *Pro-*

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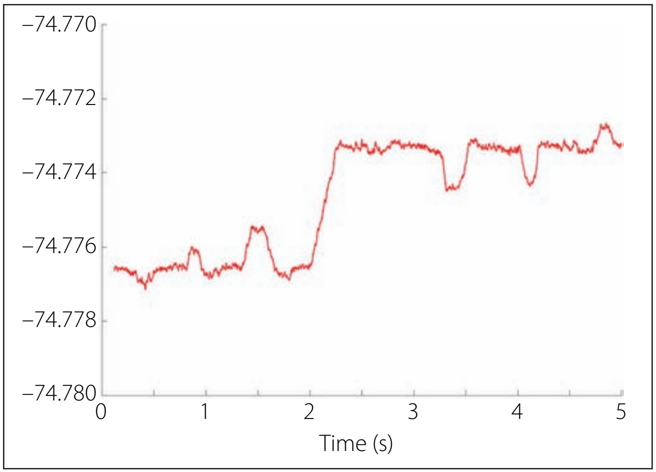

FIGURE 19 Tracking error without interference mitigation in the presence of DME, SIR = -50 dB, C/N$_0$ = 50 dB-Hz. Multipath is not considered.

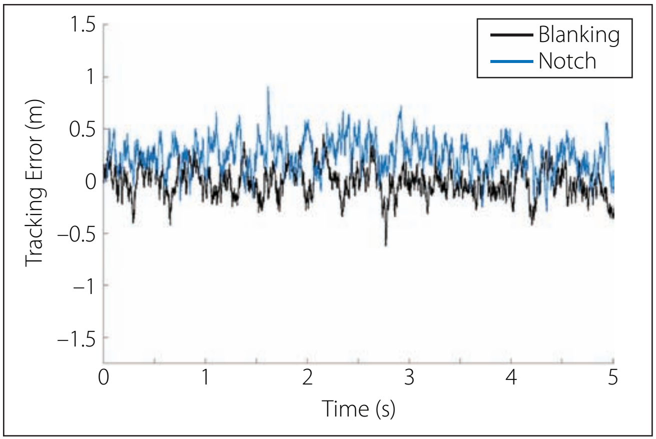

FIGURE 20 Tracking error with interference mitigation (blanking and notch) in the presence of DME, SIR = -50 dB, C/N$_0$ = 50 dB-Hz. Multipath is not considered.

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Authors

Diego Alonso recently joined The Signal Processing for Wireless Positioning <www.cs.tut.fi/tlt/pos> group to be involved in a EU/European Space Agency research Galileo project. This group belongs to the Department of Electronics and Communications Engineering (ELT) at the Tampere University of Technology (TUT). Alonso received a M.Sc. degree in telecommunication engineering at the Technical University of Madrid (UPM) after having developed his master thesis at TUT. His research interest includes unambiguous acquisition and tracking methods for high order binary offset carrier (BOC) modulations, interference mitigation, unmanned air vehicles and radar systems.

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