CZECH TECHNICAL UNIVERSITY IN PRAGUE

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DIPLOMA THESIS

Amendment of GNSS systems in hard conditions by 'Opportunity signals'

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'Opportunity signals' pro podporu systémů GNSS v nepříznivých podmínkách.

Amendment of GNSS systems in hard conditions by 'Opportunity signals'

Diploma Thesis

Study program: Communication, Multimedia and Electronics
Study specialization: Wireless Communication
Supervisor: Prof. Ing. František Vejražka, CSc.

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Pokyny pro vypracování:

Pro podporu určování polohy systémy GNSS za nepříznivých podmínek se využívají tzv. "Opportunity Signals". Pojednejte stručně o těchto systémech a zaměřte se především na signály digitální televize.
Popište tento systém a navrhněte jeho použití pro určování polohy, tj. navrhněte hardware uživatelského přijímače, jakož i jeho programové vybavení. Sestavte experimentální zařízení a jeho funkčnost ověřte pomocí vhodných laboratorních přístrojů, příp. simulací a pokuste se realizovat zpracování signálů reálných vysílačů.
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Abstrakt:
Tato práce je zaměřena na možnost využití takzvaných 'Signals of Opportunity' (SoO) pro určování polohy. Zabývá se převážně využitím digitálního televizního vysílání jako podpůrného systému pro Global Navigation Satellite Systems (GNSS) v tzv. nepříznivých podmínkách. Je představena metoda zpracování signálu Digital Video Broadcasting–Terrestrial (DVB-T) pro výpočet polohy. Dále je práce zaměřena na experimentální výpočet polohy s využitím tohoto systému. K tomuto je využit navrhnutý hardware a vytvořeno jeho softwarové vybavení. Teoretická omezení tohoto systému jsou simulována a porovnána s experimentálním meřením reálného vysílání DVB-T.

Klíčová slova:
Signals of Opportunity; určování polohy; DVB-T; OFDM modulace; iterativní Levenberg Marquardt algoritmus; pozemní rádiové systémy; TDoA; model kanálu

Abstract
The aim of this thesis is to present the possible usage of so–called Signals of Opportunity (SoO) for positioning. This work is focused on possible usage of TV broadcasting standard Digital Video Broadcasting-Terrestrial (DVB-T) as a supporting system for the Global Navigation Satellite Systems (GNSS) in so–called hard conditions. The method how to process the DVB-T signal for position estimation is introduced. It is also aimed at experimental positioning with this system. The hardware and software of the receiver are designed, to achieve it. The technical constraints of the system based on this SoO are simulated and compared with experimental measurements of the original DVB-T broadcast.

Keywords:
Signals of Opportunity; positioning; DVB-T; OFDM modulation; iterative Levenberg Marquardt algorithm; terrestrial radio systems; TDoA; channel model

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List of Abbreviations

1PPS Pulse-per-second signal

ADC Analog-to-Digital Converter

AoA Angle of Arrival

AWGN Additive white Gaussian noise

BeiDou BeiDou Navigation Satellite System

CA-CFAR Cell Averaging - Constant False Alarm Rate

CDMA Code-Division Multiple Access

CP Continual Pilot

DoP Dilution of Precision

DSSS Direct-Sequence Spread Spectrum

DVB-T Digital Video Broadcast - Terrestrial

ECEF Earth-Centered, Earth-Fixed

ENU East, North, Up

ETSI European Telecommunications Standards Institute

FFT Fast Fourier Transform

FIR Finite Impulse Response

FSL Free-Space Loss

GALILEO

GLONASS Globalnaya Navigatsionnaya Sputnikovaya Sistema

GNSS Global Navigation Satellite System

GPS Global Positioning System

GSM Global System for Mobile Communications

GSS Golden Section Search

IFFT Inverse Fast Fourier Transform

IMU Inertial Measurement Unit

ISI Intersymbol Interference

LFSR Linear-Feedback Shift Register

LTE Long Term Evolution

LTI Linear-Time Invariant

MIP Mega-frame Initialization Packet

ML Maximum Likelihood

OFDM Orthogonal Frequency Division Multiplexing

PDF Probability Density Function

PRBS Pseudo-Random Binary Sequence

PRS Positioning Reference Signal

PSS Primary Synchronization Signal

SDR Software-define Radio

SFN Single Frequency Network

SNR Signal to Noise Ratio

SoO Signal of Opportunity

SP Scattered Pilot

SSS Secondary Synchronization Signal

TDoA Time Difference of Arrival

ToA Time of Arrival

TPS Transmission Parameter Signalling

VOR VHF Omnidirectional Radio Range

WGS84 World Geodetic System 1984

1 Introduction

The position is essential information in many areas of human interest, and its increasing precision is enabling many new ways how to use it. An example might be geodetic measurements, aviation navigation and very challenging automotive industry with the need for extremely precise reference positioning system for safety systems testing such as emergency breaking, blind spot detection or comfort features like parking assistance or autonomous driving.

For positioning the Global Navigation Satellite Systems (GNSS) are used in most cases. These systems such as Global Positioning System (GPS), Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS), BeiDou and GALILEO provide high precision position and global availability. However, in many scenarios, GNSS suffer from decrease of accuracy or even unavailability caused by the low power of the received signal, reflections and other errors which are binded with atmospheric phenomena. A typical example of this hard environment can be narrow streets with a large building surroundings or indoor locations. The main problem is that direct beam of the propagated signal is highly attenuated and cannot be detected or reflected beam is wrongly identified as direct beam causing an error of ranging. The question is whether it is necessary to build up whole new infrastructure or whether it is possible to use something that is already present worldwide. The problematics of positioning at hard conditions is the object of research which is far from a sufficiently accurate solution.

One of the possible ways how to improve present positioning systems is to use a supplementary system based on the independent method of positioning. A typical example of the independent positioning system is Inertial Measurement Unit (IMU).

Another group of positioning systems is systems based on so–called Signals of Opportunity (SoO). These systems use signals which are not primarily intended for positioning service but have properties (wide band signals), which can be utilized for positioning. It is based on the passive system because it is only receiving available transmissions. Typically, the broadcasting and data services are predetermined to be used as SoO, because of its wide-band properties allowing the higher precision of time estimation which is usually used for position evaluation. The main advantage of these systems is high transmitting power, which can be detectable even after passage through obstacles such as treetops and even building walls.

One of the possible services can be Digital Video Broadcasting-Terrestrial (DVB-T). It is European standard for TV broadcasting which is also used worldwide. Its main advantage is a relatively wide-band signal structure using Orthogonal Frequency Division Multiplexing (OFDM). The narrow correlation function of the signal, resulting from its wide-band characteristic is the main feature necessary for accurate time measurement.

This publicly available service is studied in this work to manage how to utilize it for positioning. For this reason, the testing hardware was proposed and assembled to receive DVB-T signal. The structure of the signal was studied in order to create a generator for simulations of the DVB-T based positioning system. And finally, the software part of the receiver had to be programmed to process the received signal and to evaluate position using DVB-T signal.

This work is aimed at SoO and mainly on DVB-T and its usage for position evaluation. The output of this work is intended as supporting setup for a positioning system, developed by the Technology Agency of the Czech Republic, grant No. TE01020186, combining GNSS receiver with IMU and possibly other navigation methods such as SoO.

2 Positioning

Positioning is a sequence of operations which leads to obtaining position information. Many methods have been developed since the beginning of this discipline, but the positioning using radio signaling is relatively young discipline, yet currently the most used one. Before we get to positioning itself, we need to define what is position and how is stored. The position is always relative information related to some point or even to plane or surface of some object. There is more than one possibility how to mark this relative position. The most obvious one is to write down position as the difference vector of a reference and measuring point in Cartesian coordinates. However, for positioning near the Earth surface, it is more natural to use a system which assigns to every position on its surface an exclusive vector of coordinates. Sometimes it is convenient to recalculate between several systems. The most used ones are described in section 2.1.

Now, when we are able to store and display position using understandable way, we can focus on the individual methods how to use electromagnetic waves to determine position. There are numerous of methods used for positioning. Some of them differ only in nuisance details, and some are completely different. In this work, only convenient principles are described, but much more derived methods and their descriptions can be found in Avionics Navigation Systems [1].

2.1 Coordinate Systems

The coordinate system is basically the basis of an N—dimensional space to which is position in the space decomposed. It is known many types of coordinate systems which are mutually equivalent, and thus one can easily transform between them. The transformation is a fundamental operation and is represented by a matrix. The coordinates in a new system can be obtained from the equation:

$$c_n = \langle \mathbf{b}_n \mid \mathbf{v} \rangle = \begin{cases} \sum\limits_k b_{nk}^* v_k & \mathbf{b}, \mathbf{v} \in l^2 \\ \int\limits_{-\infty}^{+\infty} b_n^*(t)\, v(t)\, \mathrm{d}t & b(t), v(t) \in L^2, \end{cases} \tag{1}$$

where $\mathbf{v}$ is an object decomposed into the n-th basis element $\mathbf{b}_n$ obtaining decomposition coefficient c_n. Objects have to be in Hilbert space of square-summable sequences

(l^2) or square-integrable functions (L^2). Following coordinate systems are used in Time Difference of Arrival (TDoA) based positioning algorithm. For transformations between them, functions from diploma thesis [2] are used.

2.1.1 World Geodetic System 1984

The World Geodetic System 1984 is the most used of all coordinate system because of mass expansion of GPS which uses the standard physical model of the Earth. In WGS84 definition [3] mathematical parameters of a reference ellipsoid are defined. It is right–handed, Earth–fixed orthogonal coordinate system. The origin point is defined as Earth's center of mass. The Z-axis, is the direction toward the Reference Pole (IRP), the X-axis is defined as the intersection of the Reference Meridian (IRM) and the plane passing through the origin and normal to the Z-axis and finally the Y-axis completes the right-handed orthogonal system. This system is usually called Earth–Centered, Earth–Fixed (ECEF) system.

Usually, the ECEF coordinate system is affixed to reference ellipsoid, and then the coordinates are transformed into a geodetic coordinate system consisting of paramaters of latitude, longitude, and altitude (LLA). The transformation equations for these systems are provided in [4]. The conversion from geodetic to ECEF is possible in closed form according to the equations:

$$\begin{aligned} x &= \frac{a\cos\lambda}{\sqrt{1+(1-e^2)\tan^2\phi}} + h\cos\lambda\cos\phi, \\ y &= \frac{a\sin\lambda}{\sqrt{1+(1-e^2)\tan^2\phi}} + h\sin\lambda\cos\phi, \\ z &= \frac{a\left(1-e^2\right)\sin\phi}{\sqrt{1-e^2\sin^2\phi}} + h\sin\phi, \end{aligned} \tag{2}$$

where $a = 6378137$ m is semimajor axis, $b = 6356752$ m is semiminor axis, $e^2 = 0.00669438002290$ is ellipsoid quantity, λ is longitude, ϕ is latitude and h is altitude.

The inverse transformation is not possible in closed form and is performed numerically according to Bowring method described in [4].

2.1.2 East, North, Up

This coordinate system is Cartesian same as the ECEF. It is defined by a reference point. The origin is placed at this point, X-axis is oriented toward East, Y-axis toward North and Z-axis completes right handed orthogonal system, so it heads Up.

The transformation between this scheme and ECEF is straightforward, and it is made in two steps. In the first step, the origin is moved into reference point ($\mathbf{r}$). In the second phase, the system is rotated to obtain a position in ENU coordinates ($\mathbf{v}$). Rotation matrix R is specified by the relation:

$$\mathbf{R} = \begin{pmatrix} -\sin\lambda & \cos\lambda & 0 \\ -\cos\lambda\sin\phi & -\sin\lambda\sin\phi & \cos\phi \\ \cos\lambda\cos\phi & \sin\lambda\cos\phi & \sin\phi \end{pmatrix}. \tag{3}$$

The forward transformation from the position in ECEF ($\mathbf{u}$) to ENU ($\mathbf{v}$) using reference point ($\mathbf{r}$) is defined by the equation:

$$\mathbf{v} = \mathbf{R}\left(\mathbf{u} - \mathbf{r}\right). \tag{4}$$

The inverse transformation is obtained by modification of equation (4) as is shown in the equation:

$$\mathbf{u} = \mathbf{R}^{-1}\mathbf{v} + \mathbf{r}. \tag{5}$$

2.2 Positioning Methods

The principles of the most common methods used for position evaluation are described in this section. Only electromagnetic wave based positioning is considered in this work. There are more approaches how to use signal propagation to evaluate the position, but in most cases these methods are only an extension of the elemental principles presented in this section.

The Angle of Arrival (AoA) is a method based on measurement of the angle between the receiver axis and the direct link between the receiver and transmitter. If we measure AoA between two or more links, it is possible to triangulate position. Usually, the receiver antenna is constructed to obtain directivity pattern with one sharp minimum and system measures the angle by rotating this antenna to its minimum. This principle is used e.g. in aviation system called VHF Omnidirectional Radio Range VOR [1].

The fascinating method of positioning is Doppler frequency shift based position evaluation. The phenomenon of Doppler shift is known in general. If the transmitter and receiver are mutually moving, the frequency of the receiving signal is shifted. The Doppler effect is described as

$$f = f_0\left(\frac{c+v_R}{c+v_T}\right), \tag{6}$$

where f is the received frequency if the transmitter moving with the velocity v_T transmits signal with frequency f_0 and the receiver moves with the velocity v_R. The first satellite navigation system was based on this phenomenon, and it is still used as a possible method in positioning using GPS. If we know satellite position, its velocity, and received signal is shifted by frequency f_D, we can evaluate radial speed which corresponds to satellite velocity and the angle between its course and the receiver. Then if we repeat this measurement a moment later, the satellite position is changed. Thus we obtain different angle. It is obvious that this method is just another application of the AoA.

The Time of Arrival (ToA) is based on measuring propagation time between the transmitter and the receiver. The velocity of the electromagnetic wave is known, and it is used to convert propagation time to physical distance. If we are aware the position of the transmitters and distances to at least three of them, it is possible to evaluate the receiver position. This method is the primary positioning method used in GPS receivers. Usually, it is not possible to estimate exact propagation time, only relatively to the local time, leaving one more unknown parameter (time offset). It is necessary to measure the distance to one more transmitter to be able to get correct position.

2.2.1 Time Difference of Arrival

The method using the information about the difference between signal arrival from several transmitters is called Time Difference of Arrival (TDoA). This approach is so–called hyperbolic navigation because it uses measured differences which in 2D correspond to estimating the point where at least two hyperbolas intersect. The TDoA can be evaluated according to the equation:

$$d_{ij} = \frac{1}{c}\left(\|\mathbf{r}_R - \mathbf{r}_i\| - \|\mathbf{r}_R - \mathbf{r}_j\|\right), \tag{7}$$

where d_{ij} are measured differences in meters, c is the speed of light, $\mathbf{r}_R$ is position vector of the receiver, the $\mathbf{r}_i$ and $\mathbf{r}_j$ are position vectors of the individual transmitters. This system of equations can be adjusted to obtain the position of a receiver. An iterative algorithm solving this problem is implemented in this work and it will be described in section 4.3.4. TDoA method is used e.g. by marine systems called Loran-C and Chayka [1].

3 Signals of Opportunity

There are numerous of radio frequency systems using different methods of data transmission. Many of them are public services, and there are also private ones. Some of them use signal structures with properties similar to navigation systems which make the opportunity to use them for positioning. For this reason, signals transmitted by such systems are called Signals of Opportunity (SoO). Mainly broadcasting services are considered to be used for position evaluation because broadcasting is usually continuous, omnidirectional and provide sufficient transmitting power.

3.1 Global System for Mobile Communications

The Global System for Mobile Communications (GSM) is standard developed by European Telecommunications Standards Institute (ETSI) initially used for voice services and currently for voice and data services with the possibility to access the Internet. Several generations of GSM system was introduced in the past. Currently, the fourth generation (4G) called Long Term Evolution (LTE) is used. The signal specification is given by ETSI standard [6].

The OFDM modulation is used in LTE. There are two types of synchronization signals, for the downlink stream. The Primary Synchronization Signal (PSS) and the Secondary Synchronization Signal (SSS). These sequences are generated according to the Cell identification. The signal can be used to identify from which cell was the signal transmitted. Also, cells uses Code-Division Multiple Access (CDMA). There is special signal called Positioning Reference Signal PRS which is transmitted in order to be used for positioning. This made the system possible to be used for position estimation, that is, the Signal of Opportunity.

3.2 Digital Video Broadcasting

Another system which has properties usable for positioning is Digital Video Broadcasting-Terrestrial (DVB-T). It is used for broadcasting digital TV, and its signal structure is defined by ETSI standard [7]. It is important that it can work in so–called Single Frequency Network (SFN) defined by the norm [8]. In this mode more than one transmitter is used to broadcast signal containing the same data at the same time. These identical streams are synchronized using GPS timing receivers, which are available on all DVB-T SFN transmitters. Along with its pilot signal based on the pseudorandom process with wideband frequency spectrum, is DVB-T predetermined to be used as SoO.

3.2.1 DVB-T Signal Description

The DVB-T service is described in detail in [7]. Briefly it is summarized in following.

DVB-T signal is defined by the equation:

$$r(t) = \Re\left\{ e^{j2\pi f_c t} \sum_{m=0}^{\infty} \sum_{l=0}^{67} \sum_{k=0}^{6816} q_{m,l,k} \times e^{j2\pi \frac{k-6816/2}{T_U}(t-\Delta-l\times T_S)} \right\}. \tag{8}$$

The DVB-T signal is modulated using Orthogonal Frequency Division Multiplexing (OFDM) modulation defined as:

$$s\left(t\right) = \sum_{n} \mathbf{q}_n^{\mathrm{T}} \mathbf{g}\left(t - nT_S\right). \tag{9}$$

Here $\mathbf{q}_n^{\mathrm{T}}$ is transposed vector of data symbols which are defined by mapping pattern [8]. In this work, QAM64 mapping pattern is used. The $\mathbf{g}\left(t - nT_S\right)$ is so–called expansion part of the modulation. It contains the modulation pulse shape. For the OFDM is defined by:

$$\mathbf{g}\left(t\right) = \frac{1}{\sqrt{T_S}} e^{j2\pi\Delta f t\mathbf{k}} \left(u\left(t\right) - u\left(t - T_s\right)\right), \tag{10}$$

where $u\left(t\right)$ is a unit step function. It is defined as zero for $t < 0$ and one for $t > 0$. The step functions are used to mask the modulation pulse, so that it is zero outside the interval from 0 to T_S. The number of the subcarrier is given by $\mathbf{k}$ and separation between subcarriers is given by Δf.

The framing structure is also given by equation (8). The DVB-T channel is defined by the carrier frequency of the modulation (f_c). The following description is valid for so–called 8k mode which is usually used for broadcasting, and all experiments and measurements in this work presume the 8k mode. The details about other possible modes can be found in [7].

The signal is divided into the frames indexed by m. Each frame consists of 68 OFDM symbols, and each symbol contains 8192 subcarriers. They are divided into data and pilot subcarriers. Data subcarriers are modulated by QAM64 and BPSK modulation is used for pilot subcarriers.

In DVB-T there are three types of pilot sequences. The first one is called Continual Pilot (CP) sequence. The subcarriers containing CP symbols are always the same, and their numbers are given in [7]. The second sequence is called Scattered Pilot (SP). There are four possible patterns how SP are mapped into the signal provided by:

$$\begin{aligned} \mathbf{SP} &= 3 \times (l \bmod 4) + 12\mathbf{p}, \\ \mathbf{p} &= < 0, 567 >; \mathbf{p} \epsilon \mathbb{Z}. \end{aligned} \tag{11}$$

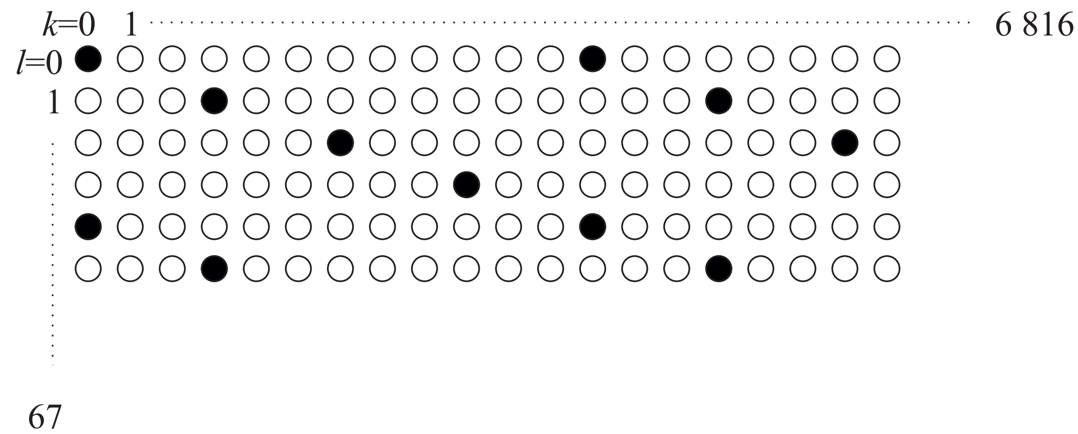


Figure 1: The time-frequency grid of the DVB-T signal with marked SP subcarriers.

For the better visualization, figure 1 is used. The grid shows all subcarriers contained in DVB-T signal. The frequency increase with the index of subcarrier k. The time runs with the number of OFDM symbol l. The SP subcarriers is marked black. Every twelfth subcarrier is containing SP symbol, and in every OFDM symbol, the pattern is shifted by three subcarriers.

The Transmission Parameter Signalling (TPS) is the third type of the pilot sequence. It contains parameters related to the transmission. The whole list of possible parameters which can be carried in TPS is listed in [7].

All of the pilot subcarriers are modulated using BPSK modulation. The BPSK modulated data can acquire only two possible values (0 and 1). In pilot sequences, CP and SP consist only of ones. The TPS consist in whole OFDM symbol only one value, depending on message it carries. But these values are further scattered by Pseudo Random Binary Sequence PRBS. Values of the PRBS are given by Linear-Feedback Shift Register (LFSR) defined by block schema shown in figure 2. Initially, the register is filled with ones.

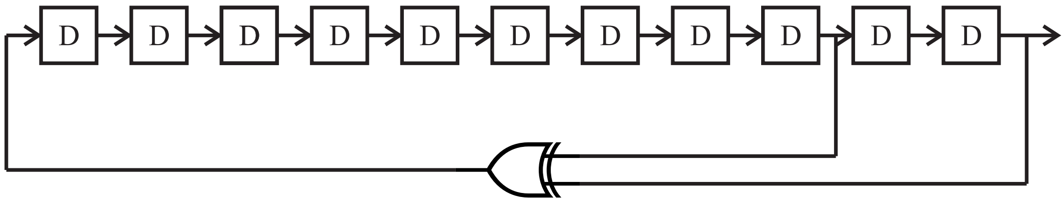


Figure 2: Schematic diagram of the LFSR used for the scattering of the pilot subcarrier values.

LFSR can be described by its polynomial :

$$X^{11} + X^2 + 1. \tag{12}$$

The last part of the DVB-T signal is the guard interval (Δ). It is the part of the signal placed before every OFDM symbol. It contains the cyclic continuation of the given OFDM symbol. This is used to suppress the Intersymbol Interference (ISI). Duration of the guard interval is given by partial of the OFDM symbol duration (T_Δ/T_U) and can acquire four possible values ($1/4, 1/8, 1/16, 1/32$).

4 DVB-T Based Positioning

DVB-T is a broadband system used for the video and audio broadcasting according to ETSI EN 300 744 [7]. Some DVB-T channels use more than one transmitter for broadcasting. In this case, the SFN is used. Synchronous transmitters allow us to use the TDoA positioning method. At least three synchronous transmitters or two pairs of synchronous transmitters are necessary for positioning in two dimensions. In Prague, it is possible to utilize channel 46 which is using three transmitters in the SFN mode and channel 42 with three transmitters in the SFN mode.

4.1 DVB-T Channel Impulse Response Based Receiver

Positioning via DVB-T can be built on the channel impulse response ($h(t)$) estimation. SP sequence is used for estimation of the $h[k]$. Since the PRBS is known and remains the same for every OFDM symbol, values of carriers containing SP correspond to samples of the $h(t)$ spectrum ($H[\Omega]$). For obtaining values of relevant carriers, the guard interval (Δ) of the OFDM symbol must be removed. After removing Δ the frequency offset (ε) and the time offset (θ) must be found for synchronization.

Estimated $h[k]$ includes maxima corresponding to delayed signal replicas transmitted from DVB-T transmitters and multipath. The algorithm used in radar makes detection and decision. For that, the CA-CFAR detection algorithm is applied in this work.

After detection of transmitters in $h[k]$, cell identification must be done. Transmission of the Cell Identification is according to [7] optional, and it is not usually used. DVB-T based navigation system should be a supplement for the GNSS when it is not available. The method assumes last known position of a receiver provided by GNSS at the beginning of DVB-T based positioning. This premise allows identifying individual transmitters and then they are tracked.

After identification, it is possible to evaluate the position of the receiver. For receiver positioning TDoA method is used, which uses hyperbolas. Hyperbolas are approximated with first–order Taylor polynomials at the point of intersection. An iterative algorithm is used to find such point, where all hyperbolas intersect.

4.1.1 Finding the Guard Interval Duration

DVB-T uses guard interval (Δ) containing Cyclic Prefix, part of an OFDM symbol of the symbol end is copied to the beginning of the symbol. Duration of the guard interval (T_Δ) is the fraction of a symbol duration (T_U). For successful synchronization, T_Δ must be known.

Correlation between the Cyclic Prefix and the end of a symbol is used to determine T_Δ. Equations

$$\begin{aligned} \gamma(\tau) &= \int_0^{T_{\Delta MAX}} s(t-\tau) \cdot s^*(t-\tau-T_U) dt. \\ \gamma'(\tau) &= \frac{d\gamma(\tau)}{d\tau}. \\ T_\Delta &= \max_\tau \left(\gamma'(\tau)\right). \end{aligned} \tag{13}$$

describe the method used for this purpose. Maximal length of the guard interval $T_{\Delta MAX} = 1/4 \cdot T_U$ is used as the upper limit of integration. Function $\gamma(\tau)$ is mutual energy between received signal $s(t)$ and its delayed replica $s(t - T_U)$ dependent on the shift of the integration limits by τ. The mutual energy grows when integration limits contain larger part of the cyclic prefix. The slope of the rising edge of the function corresponds to the duration of the cyclic prefix T_Δ. The principle of this algorithm is shown in figure 3.

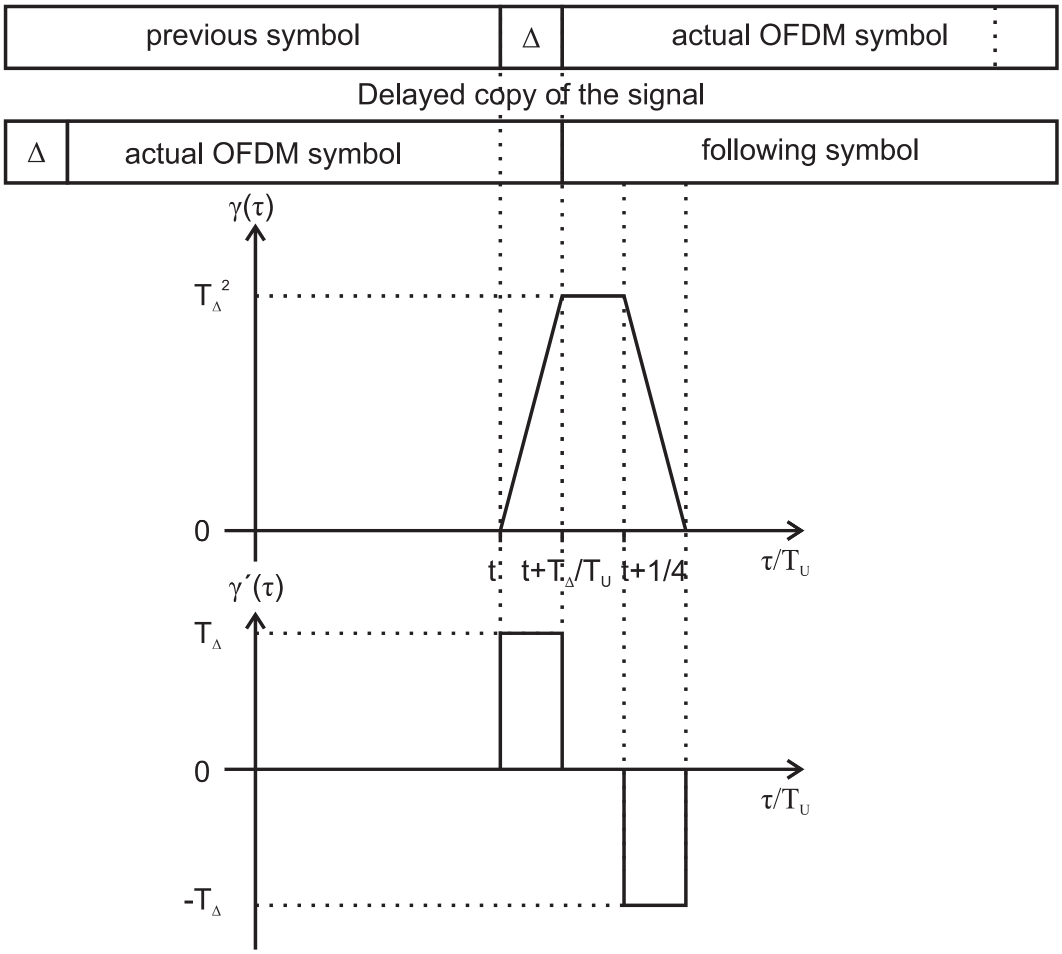


Figure 3: Principle of the algorithm for finding the T_Δ.

The aforementioned algorithm is an idealized example. It assumes a signal $s(t)$ with constant complex envelope and normalized amplitude. However, the real signal is OFDM with QAM64 alphabet summed with two BPSK modulations with different symbol energy (ε_S), and it is distorted by noise and by the influence of the transmission channel. Also, digital signal processing is used for the realization of the algorithm and therefore integration of continuous signal (s(t)) is not possible.

Continuous band signal is digitalized and mixed into the baseband to obtain the digital complex envelope of the signal (s[k]). By this, integration is converted to summation and derivation into differentiation. Averaging can be used to suppress the problem with inconstant complex envelope. Summation ensures averaging over the interval T_Δ which is N_Δ samples long. If the N_Δ was too short, it is possible to use more following OFDM symbols, but it was experimentally found that it is not necessary. Implementation of differentiation also uses averaging to obtain reliable results. To suppress signal amplitude influence, discrete function $\gamma[k]$ is normalized. It causes that the function $\gamma'[k]$ is divided by $N_\Delta{}^2$ and therefore $\frac{1}{N_\Delta} = \max_k \gamma'[k]$.

Realization of the algorithm is shown in figure 4. Function $\gamma[k]$ is already normalized. The maximum value of the function $\frac{1}{\gamma'[k]}$ is rounded to 904. Only four T_Δ are possible, so decision intervals are used for determination N_Δ. In this case, the maximum value is in decision interval corresponding $N_\Delta = 1024$ which is correct value at this channel 42 in Prague. The functionality of the algorithm was tested on different channels and multiple measuring points.

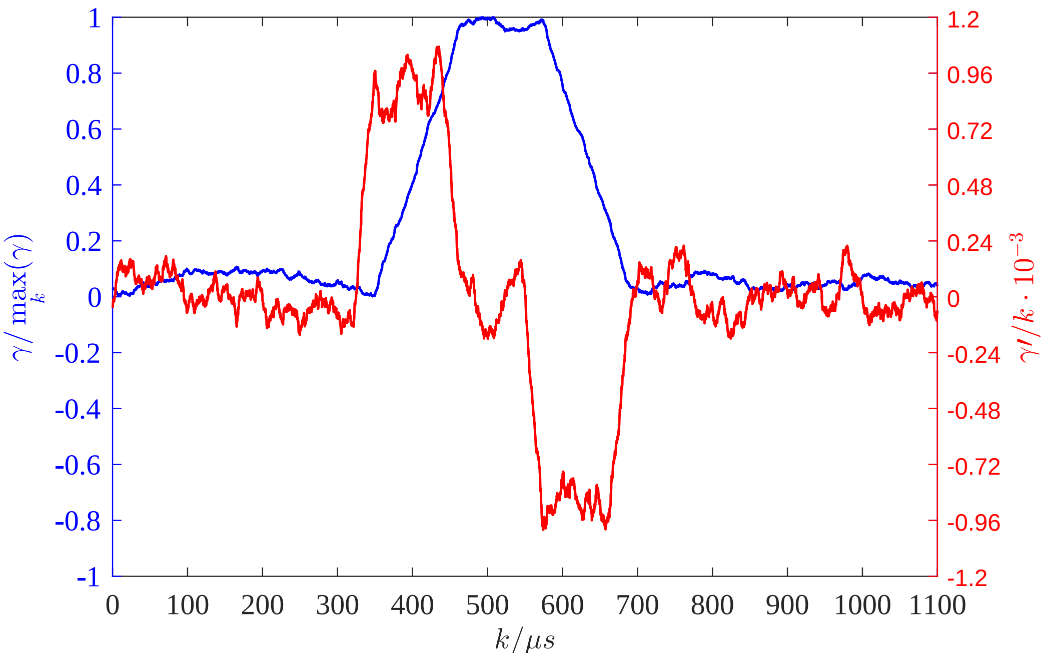


Figure 4: Principle of the algorithm finding T_Δ.

4.1.2 Finding the Beginning of the OFDM Symbol and Frequency Offset

Since T_Δ is known, it is possible to proceed to the next step which is finding the OFDM symbol beginning. For that ML estimation [9] based algorithm is used. This algorithm was implemented in previous work [10], and it is possible to describe it with equation similar to (13), which was used to find the guard interval duration. The T_Δ is now known, and algorithm is defined by equations

$$\begin{aligned} \gamma(\tau) &= \int_0^{T_\Delta} s(t-\tau) \cdot s^*(t-\tau-T_U)dt, \\ \theta &= \arg\max_\tau \gamma(\tau), \\ \varepsilon &= \angle \max_\tau \gamma(\tau). \end{aligned} \tag{14}$$

Ideally, there is only one maximum in the interval $u \leq \tau < u + N_U + 2 \cdot N_\Delta$. The value of the τ at this maximum corresponds to the symbol beginning. This value is indicated by operator *arg max*. The time between the signal beginning and the maximum is a time offset (θ). The angle of the complex maximum value corresponds to frequency offset (ε). Operator $\angle$ indicates the angle of a complex value. The absolute value of the frequency offset has to be smaller than π. If it is greater than π, it is not possible to decide the right sign nor the integer multiplier of that value.

The principle of the algorithm is shown in figure 5. It is an idealized example which assumes signal s(t) with constant complex envelope and normalized amplitude.

The blue line characterize the absolute value of the complex function $|\gamma(\tau)|$, red line corresponds to the real part of the complex function $\Re(\gamma(\tau))$ and yellow is the imaginary part of the complex function $\Im(\gamma(\tau))$.

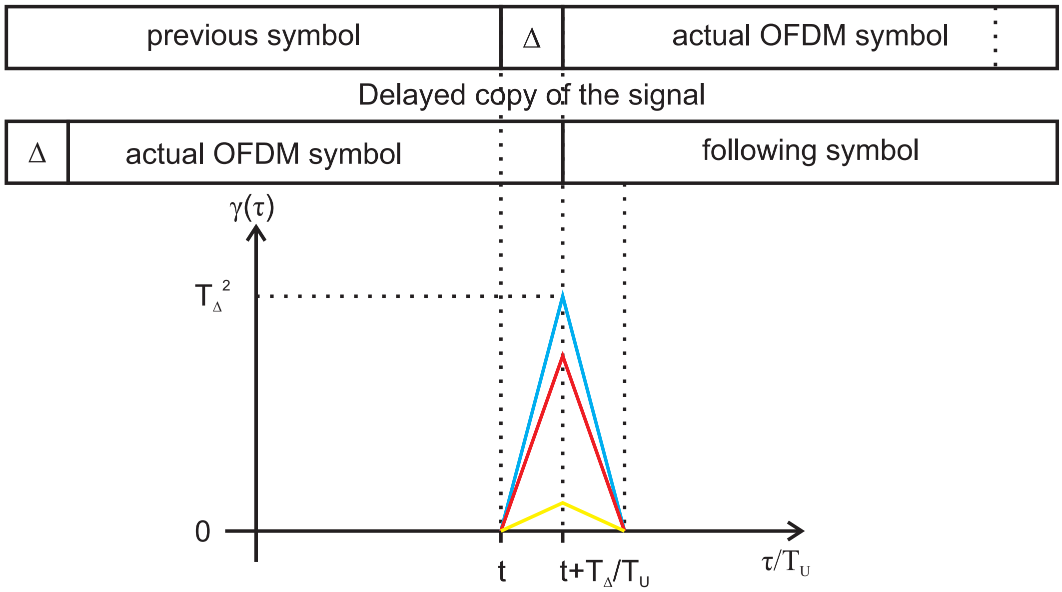


Figure 5: Principle of the finding the beginning of the OFDM symbol algorithm.

When the situation is not ideal, the signal is distorted by many influences. For example, by noise and by multipath. In general, signal distortion is described by channel parameters and its likelihood functions [11]. It would be almost impossible to marginal all channel parameters. Fortunately, for finding the beginning of the OFDM symbol, it is not necessary. This estimator produces values of offsets with lower precision, but in return, the estimator is extremely simple. A method used for increasing accuracy of the time offset estimation which is necessary for the correct function of the DVB-T based navigation system will be described in the next chapter. An example of the function generated by described algorithm applied on the measured real signal is shown in figure 6. It is evident that the angle of the complex value around a maximum of the function is nearly zero. Therefore, the frequency offset is almost zero.

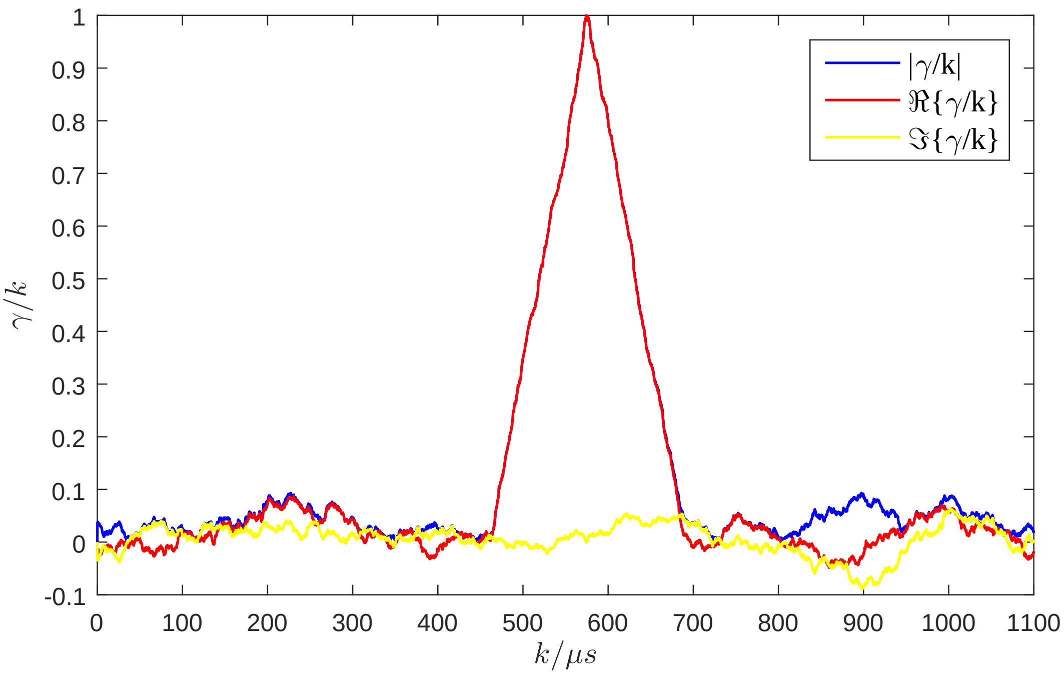


Figure 6: Example of the finding the beginning of the OFDM symbol algorithm applied on the real DVB-T signal.

4.1.3 Time Offset Estimation

The time offset obtained from equation (14) is not precise enough. For correct demodulation, it is necessary to get time offset with accuracy better than a tenth of the period of the maximal used frequency (period of the sampling frequency). For 8k DVB-T mode, accuracy better than 10 ns is needed. Algorithm for finding the beginning of the OFDM symbol described in section 4.1.2 cannot offer better precision than half of the period of the sampling frequency in the ideal case because of the unsynchronized receiver and transmitter. In real case scenario due to channel noise and multipath, the accuracy is approximately ten times worse. Because of that, the fine time offset estimator is necessary.

Unsynchronized signal causes rotation of the constellation points in the constellation diagram. Deviation of received values from originally transmitted values is given by Channel Transfer Function (CTF). Because some values are known (Pilot Symbols), it is possible to use them for synchronization. When all CTF values have the same phase, then time offset is suppressed, and rotation of the constellation points is also suppressed. The synchronizer is using this property to evaluate time offset and suppress it.

For this task, iterative one-dimensional algorithm Golden section search (GSS) was implemented. This algorithm is used for efficient maximum or minimum search of a function. Algorithm presumes unimodal function. The unimodal function is defined as monotonically increasing to its maximum, and then monotonically decreasing from this maximum and zero derivation is only at this point.

Because at this point previously mentioned condition could be violated it is necessary to enforce unimodal condition. This task is initialization for the GSS algorithm. At first, function $c(\theta)$ is evaluated in bounds of the θ given by uncertainty of the Finding the Beginning of the OFDM Symbol algorithm described in 4.1.2 which can be ones of the microseconds. The function $c(\theta)$ is given by equation

$$\begin{aligned} \mathrm{c_{CP}}(\tau) &= \sum_{\Omega=CP_{min}}^{CP_{max}} \mathrm{S}_S(\Omega) \times \mathrm{PRBS}(\Omega) \times \mathrm{e}^{-j2\pi\Omega\tau}. \\ \theta &= \arg\max_{\tau} \left(\mathrm{c_{CP}}(\tau)\right), \end{aligned} \tag{15}$$

where $c(\theta)$ is a criterial function of the optimization method used for the time offset estimation. $\mathbf{S_S}[\Omega]$ is frequency spectrum of the signal $s(t)$ obtained by FFT. Phase shift given by $\mathbf{e}^{-j2\pi\Omega\theta}$ is the time shift of the signal in the time domain according to shift property of the Fourier Transform. $\mathbf{PRBS}(\Omega)$ is a vector of the values used for Pilot Symbol modulation according to [7]. Sequence CP contains indexes of the continual pilot subcarriers. Then the maximum is found suboptimally, and interval of the function $c(\theta)$ can be narrowed to ensure unimodality. The example of the function $c(\tau)$ is shown in figure 7. More than one local maximum is present. This is caused by the multipath. Maximal value is the path with the strongest signal, and it is used for synchronization.

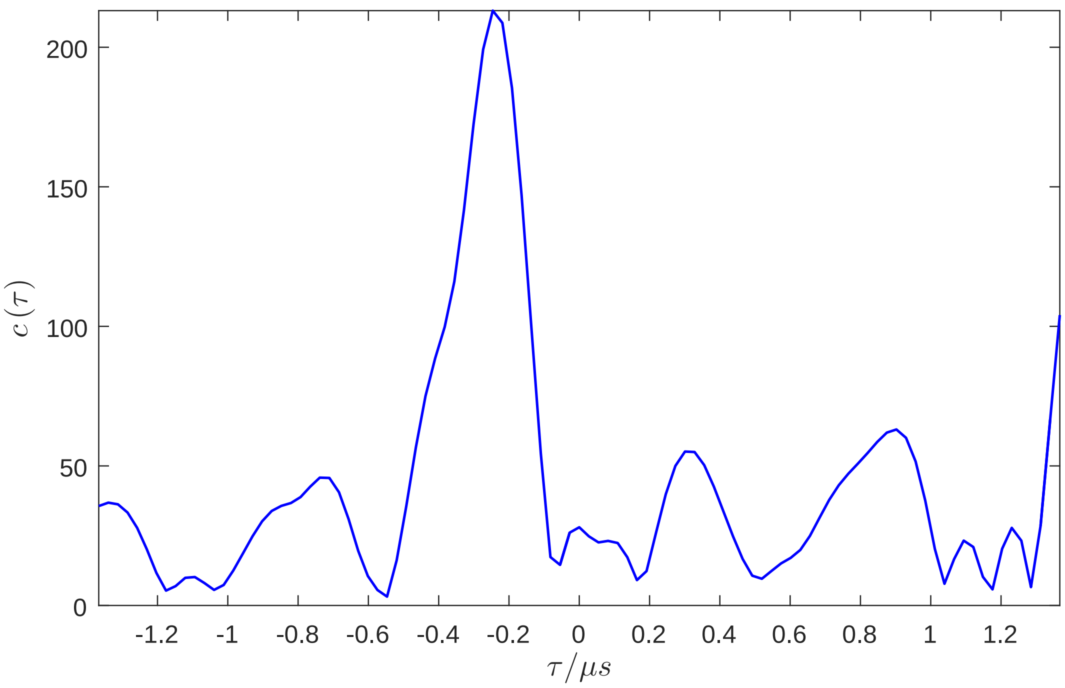


Figure 7: Example of the $c(\tau)$ function.

When time offset of the first OFDM symbol was found by the algorithm mentioned above, the time offset of the following symbol can be estimated by the GSS algorithm because time offset value will be similar to the value of the previous symbol. Therefore, the interval of the θ values can be narrowed enough to ensure unimodality. For better resolution, SP sequence can be used. Every twelfth subcarrier is reserved for SP, and there are four possible sequences given by equation (11) where **SP** is a sequence of subcarrier indexes given by equation (11) containing Scattered Pilot symbols, and l is the index of the OFDM symbol.

In a real scenario, l is unknown. It is not necessary to determine the number of the OFDM symbol. For generating the correct sequence **SP**, it is enough to test only four values ($m = \{0, 1, 2, 3\}$) and next OFDM symbol increment l by one. After estimation time offset (θ) with algorithm given by equation (15), actual parameter l is estimated by the algorithm described by

$$\begin{aligned} \mathrm{y}(m) &= \sum_{p=0}^{567} \mathrm{S}_S(3m+12p)\,\mathrm{PRBS}(3m+12p)\,\mathrm{e}^{-j2\pi\theta(3m+12p)}, \\ l &= \arg\max_m (\mathrm{y}(m)). \end{aligned} \quad (16)$$

The principle is based on a property of data symbols which are uncorrelated. Hence average value is close to zero, unlike pilot symbols which have modulated values 1 and -1 according to PRBS. After multiplication with this sequence pilot symbols become strongly correlated. If summation in equation (11) is performed over the data, its value is close to zero, unlike if it is carried out the demodulated pilot symbols. Value of the index m, where the function ($\mathrm{y}(m)$) takes the highest value, is used like parameter l to generate sequence **SP** according to equation (11).

Now Golden Section Search optimizing algorithm can be used for estimation of the time offset of following symbols. The utility function is similar to the function used in equation (15), but summation is realized over SP only. This is given by the following equation:

$$\begin{aligned} \mathrm{c}_{\mathrm{SP}}(\tau) &= \sum_{\Omega=SP_{min}}^{SP_{max}} \mathrm{S}_S(\Omega) \times \mathrm{PRBS}(\Omega) \times \mathrm{e}^{-j2\pi\Omega\tau}. \\ \theta &= \arg\max_\tau (\mathrm{c}_{\mathrm{SP}}(\tau)). \end{aligned} \quad (17)$$

The key property of the GSS algorithm is a method how parameter τ is chosen. In initialization task parameter θ for the first received OFDM symbol is determined. For the following OFDM symbol the time offset θ is similar. Therefore it is necessary to look for the time offset of the actual symbol in the small interval around the previous value by the Golden Section Search method. This algorithm is described further.

Interval around the previous value of θ is divided into three intervals in the golden ratio which is given by $\frac{\sqrt{5}-1}{2}$. In the beginning, two values of the function $c(\tau)$ are evaluated with two values of the variable τ using equations

$$\begin{aligned} \tau_1 &= \theta + \tfrac{\sqrt{5}-1}{2}(x_U - x_L) + x_L, \\ \tau_2 &= \theta + \left(1 - \tfrac{\sqrt{5}-1}{2}\right)(x_U - x_L) + x_L. \end{aligned} \quad (18)$$

If $\mathrm{c}_{\mathrm{SP}}(\tau_1) > \mathrm{c}_{\mathrm{SP}}(\tau_2)$, the lower bound is moved into τ_2, τ_1 became τ_2, and the new value of the τ_1 is evaluated according to equation (18) with changed bounds. If $\mathrm{c}_{\mathrm{SP}}(\tau_2) > \mathrm{c}_{\mathrm{SP}}(\tau_1)$, the upper bound is moved into τ_1, τ_2 became τ_1, and the new value of the τ_2 is evaluated by equation (18) with changed bounds. If values of the utility function are equals, both bounds are moved into τ_1 and τ_2, and new values of τ_1 and τ_2 are evaluated. This procedure is repeated until the distance between upper and lower bound dropped under the selected threshold. The new value of the time offset is evaluated from new upper and lower bound by $\theta_{NEW} = \theta_{OLD} + \frac{x_U + x_L}{2}$. In this task, the algorithm converges very fast. Necessary precision is given by using modulation. Ideally, for BPSK phase error in constellation lower than $|\pi/2|$ is required for a correct decision. This can be used for estimation of the necessary time offset value. For that, FFT properties are used. If the signal is shifted by one sample, the phase shift in the frequency domain is $2 \cdot \pi$. Now it is evident that time offset has to be lower than a quarter of a sampling period. The same value is used for the threshold to ensure condition for correct demodulation.

An example of the GSS algorithm convergence is shown in figure 8. Lower and upper initial bound is marked by the blue and red plus sign, respectively. The value in each iteration is shown by dots and color indicates which bound is shifted at this point. Final θ value is shown by black plus sign. A number of iterations are generally lower than ten. It is multiple times lower than number of values needed for achieving the same precision using only initialization algorithm for all OFDM symbols.

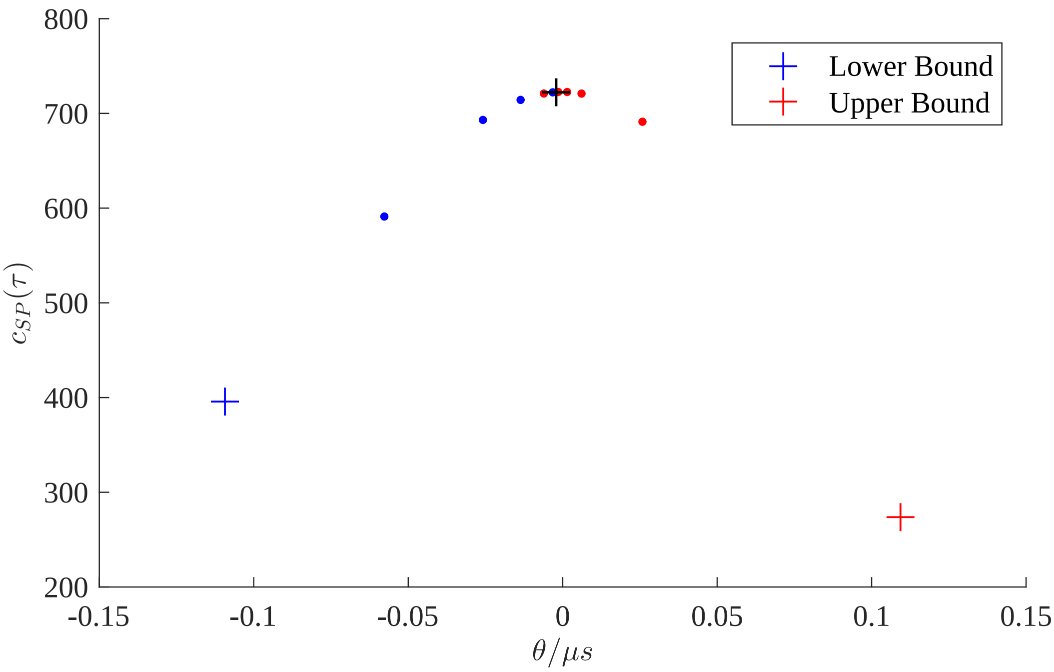


Figure 8: Example of the GSS iterative algorithm convergence speed.

4.1.4 Channel Impulse Response Estimation

Channel impulse response estimation is based on idealized model which presumes ideal transmitters and Linear, Time-Invariant (LTI) radio channel with AWGN. At the beginning of this work, there were mentioned two possible approaches how to estimate time differences of arrival necessary for position estimation. The first idea was using full signal, data symbols, and pilot symbols. The second method uses only pilot symbols for position estimation. Both methods were implemented and the second method was chosen as more suitable for this problem mainly for its lower computational complexity.

The channel impulse response in low resolution ($h_{LO}[k]$) is estimated using pilot symbols. This sequence is used for deconvolution to suppress the influence of the radio channel to the received signal. Deconvolution is performed in the frequency domain as follows

$$r[k] = \mathfrak{F}^{-1}\left\{\frac{S[\Omega]}{H_{LO}[\Omega]}\right\}. \tag{19}$$

Values of the $H_{LO}[\Omega]$ are included in the pilot symbols. After multiplying pilot symbols with corresponding values of the PRBS sequence, $H_{LO}[\Omega]$ is obtained. Realization of the equation (19) requires interpolation of $H_{LO}[\Omega]$.

The synchronizer finds the signal beam with maximum power and set it as origin. It causes that the function $h_{LO}[k]$ is cyclically rotated to its maximum. It is possible that other transmitter is closer but its corresponding peak in $h_{LO}[k]$ is lower. In such the case the peak is moved at the end of $h_{LO}[k]$. This is not a problem for correct deconvolution, because of the periodical properties of the FFT. It is an issue for correct estimation of the time differences of arrival used for positioning. This will be further described in section 4.3.

Performed deconvolution provides a signal in the time domain with suppressed influence of the radio channel. Thanks to that, successful demodulation of data symbols are possible using Viterbi algorithm [7]. This step provides data symbol sequence $\mathbf{d}$. The data sequence is again encoded into channel data sequence $\mathbf{q}$ of the OFDM symbol. At this point, it is possible to reconstruct ideally transmitted signal according to DVB-T signal defining equation (8). Finally, it is possible to evaluate Doppler spread impulse response, which describes LTI impulse response. This function includes, not only the influence of the radio channel, but also influence of SFN. It causes effect appearing like multipath, but these are caused by direct signal beams emitted from the other transmitters in the SFN. Differences between that maxim can be used directly for the positioning. Doppler spread impulse response is obtained by Fourier transform applied to the absolute time of the time-variant impulse response ($h(t,\tau)$) defined by [12]

$$r\left(t\right) = \int\limits_{-\infty}^{+\infty} s(t-\tau)h\left(t,\tau\right)d\tau. \tag{20}$$

Doppler spread impulse response is then defined by equation [12]

$$H\left(f,\tau\right) = \mathfrak{F}_t\left\{h\left(t,\tau\right)\right\}. \tag{21}$$

like Fourier transform of the time–variant impulse response over absolute time.

Because of enormous computational complexity, an alternative approach is necessary for the realization in a real-time positioning. A method using only SP sequence for positioning is used. The main benefit of this approach is reducing demands on minimal value of the SNR. This is caused by the OFDM modulation. Pilot symbols are BPSK modulated, but data symbols are modulated by MQAM usually using alphabet size M=64. But mainly because the pilot sequence is a priori known thus SNR can be even smaller and $h[k]$ still be successfully estimated. This property is similar to spread spectrum signal transmission because the pilot sequence is similar to sequences used for direct–sequence spread spectrum (DSSS) technique used in telecommunication. This method has so–called code gain, which can be imagined as improvement of the SNR.

Measurements and tests are realized in the static scenario, and therefore time–invariant channel is considered. In a real scenario, Doppler shift could affect the system. It is necessary to search a limited frequency span only because of the static transmitters and relatively low carrier frequency. Every received DVB-T signal beam can be characterized by a function $sinc\,(\pi T f)$ in the frequency cut in the Doppler spread impulse response, where $T = 896$ μs is the duration of the OFDM symbol in DVB-T. The bandwidth of the main lobe of this characteristic is approximately $BW \doteq 2.2$ kHz. For 0.5 dB bandwidth, it is $BW_{-0.5\ \mathrm{dB}} \doteq 584$ Hz. In a real scenario, transmitters are static maximum user speed is 130 km/h, and maximum DVB-T frequency is theoretically 862 MHz. Due to LTE it is even under 800 MHz. Doppler frequency shift in this case is always lower than 100 Hz. Doppler shift in this application can be neglected because attenuation is lower than $a < 0.06$ dB and it is possible to simplify the system to LTI system.

The impulse response of this LTI system is possible to obtain the same as it is described in equation (19). However, this approximation has two fundamental problems. The first issue is that our estimation is summed with noise. If it is presumed AWGN, it is possible to marginalize it from likelihood function as follows

$$h(t) = \int_{-\infty}^{+\infty} h(t) + w(t) dW. \tag{22}$$

Since this is not possible to implement in real–time, it is reduced into a summation of the number of $H_{LO}(\Omega)$ realizations. To do that static channel is necessary but since the receiver can be moving up to 130km/h, it is possible to use an only limited number of realizations to ensure stationary. In this work, summation of 100 OFDM symbols is used. In a case that $\Delta = 1/4$, averaging interval is 112 ms which causes error 4 m if the receiver is moving at maximum speed.

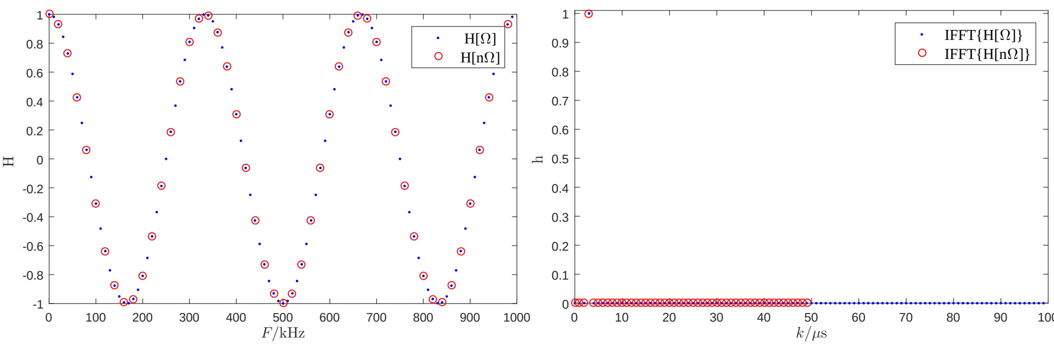
The Gaussian distribution and distributions arising from it are commonly used in signal processing. These distributions are described in the following section 4.3.1. They are also simulated in MatLab, where function *normrnd()* is used to generate random numbers with normal distribution. For simulations, sample of $1 \cdot 10^8$ random numbers was used. Right-tail probability function was evaluated by the Monte Carlo method according to [13].

The second problem is a low density of the pilot symbols. The impulse response obtained from SP is twelve times shorter in time. Since time is relative only to the beginning of the signal beam with the maximum energy, it is necessary to have a duration of the impulse response at least the same as the length of the signal propagation between two the most distant transmitters for positioning via TDoA.

In the DVB-T channel 42, used for experiments in Prague, the maximum distance between transmitters is roughly 13.4 km. If the OFDM symbol duration is 896 μs, then the maximum distance between transmitters can be up to 268.8 km. But to achieve this, whole OFDM symbol would have to be the pilot sequence. If the SP pilot sequence is used, every twelfth subcarrier is occupied by the pilot symbol. Now it is necessary to understand what will happen with the impulse response.

For better understanding, we can use well–known signal processing technique called decimation. If we have discrete signal $s[k]$, it is possible to create new discrete signal created by picking every n-th sample of the original signal. If the Nyquist–Shannon sampling theorem is satisfied for the signal $s[nk]$ then after Fourier transformation the signal spectrum is n times shorter.

A similar effect happens in DVB-T signal processing, only omitting of the samples is performed in frequency domain. The same as in the previous example, after performing inverse Fourier transformation the impulse response become shorter. This effect is shown in figure 9. Figure 9a illustrates the spectrum of the model impulse response 100 μs long, which was sampled by frequency 1 MHz. Then every second frequency coefficient (red circles) was picked to simulate described the effect in DVB-T. In figure 9b, is shown impulse response in temporal domain after performing inverse Fourier transformation. Blue points show the original signal, and the signal displayed by the red circles is a new signal received by omission every second frequency coefficient. It can be noticed, that the new impulse response is half the original impulse response long.



(a) Original spectrum (blue) and picked coefficients of the spectrum (red) of the impulse response.

(b) Original impulse response (blue) and impulse response with omitted spectral coefficients (red).

Figure 9: Influence of the omission frequency coefficients to the impulse response.

Now it is evident, that if the pilot symbol is on the every twelfth frequency coefficient, in every OFDM symbol, the maximum distance between transmitters has to be twelve times smaller than the OFDM symbol duration. It has to be smaller than 22.373 km. In used DVB-T channel this condition is satisfied, but in general, this condition can be violated. This problem can be solved by using more than one symbol in a row. The SP sequence is designed such that in every OFDM symbol is the pilot placement pattern shifted by three subcarriers and corresponding PRBS points are placed. This is described in section 3.2.1. So if we could sum four OFDM symbols, we could be able to estimate position if the maximum distance between receivers would be up to 89.494km.

4.2 DVB-T Matched Filter Based Receiver

The first realized version of the receiver described in section 4.1 suffers from several disadvantages. For general hardware receivers, it is not common to have arbitrary sampling frequency. Usually, it has fixed sampling rate and optional decimation factor parameter to reduce sampling rate. The first version of the receiver presumed ideal sampling frequency derived from DVB-T signal parameters. Ideal sampling rate, in the used 8k DVB-T mode, would be given by duration of the OFDM symbol (T_U) and by the number of subcarriers (K) in the OFDM symbol according to the equation:

$$f_{Sa} = \frac{K}{T_U} = \frac{8192}{896\,\mu\mathrm{s}} \doteq 9142857.143\,\mathrm{Hz}. \tag{23}$$

This sampling frequency would be hard to achieve precisely, and price of such system would be high.

The second problem with the impulse response based receiver is the high complexity of the synchronization process. The high precision of the time synchronization was designed for the first version which assumed that impulse response would be computed using full DVB-T signal including payload data. This method would not be able to compute impulse response in real time, and advantages of this approach are insignificant. The only advantage is a possibility to estimate position unambiguously in a scenario where transmitters are distant up to 268.8 km. This problematics is described in section 4.1.4.

That knowledge was used for the removal of the unnecessary algorithms and reduction of the signal processing complexity while the positioning properties remain the same. Omitting the whole time synchronization task was possible. The new version of the receiver can operate with arbitrary n MSps sampling frequency if the n is integer higher than 6.

Before the matched filter based receiver is described, it is necessary to understand the theory of the matched filtration. This method is used very often in receivers. More details about matched filters theory can be found in [11]. Matched filter is a filter which impulse response is designed to satisfy:

$$\|s(t)\|^2 = \langle s(t) \mid s(t) \rangle = \int_{-\infty}^{+\infty} s^*(t)s(t)dt = \int_{-\infty}^{+\infty} h(-t)s(t)dt = h(t) * s(t). \tag{24}$$

From equation (24) and using the definition of the scalar product, using bra–ket notation (Dirac notation) it is easy to find impulse response of the matched filter ($h(t)$). It has to be the signal to which the filter is matched, it is only conjugated and rotated along the temporal axis:

$$h(t) = s^*(-t). \tag{25}$$

This method has two main properties. First, if the signal $s(t)$ is corrupted by the AWGN, the matched filter maximizes output SNR. Proof can be found in [11]. The second property is the fact, that output SNR depend only on the energy of the $s(t)$, not on the particular characteristic of the $s(t)$. This property is a direct result of the proof of the first mentioned property. Thanks to these properties it is optimal to use this method for our purpose of the DVB-T signal processing.

4.2.1 Initial Signal Processing

Modern constructions of the radio front–end hardware are usually only amplifier, mixer, quadrature demodulator and ADC. Companies usually manufacture these chips for a general purpose and therefore the sampling rate is not optional. For this reason, it is not common that general SDR or other non–laboratory hardware would have arbitrary sampling frequency. It is possible to use techniques like interpolation and decimation to change sampling rate digitally, but this can easily become problematic. The DVB-T can serve as an example of this.

This problem will be presented using our equipment. For experiments with DVB-T, we use SDR USRP N210. This radio has dual 14-bit 100 MSps ADC, and minimal decimation factor is 4. Hence the maximum bandwidth which can be obtained is 25 MHz. It would require to interpolate signal with factor 64 and then decimate with factor 175 to resample the DVB-T stream to the ideal sampling frequency given by equation (23). It would lead to large data flow and consumes a lot of processor memory and time.

To evade the resampling problem the simple trick was used. If we use ideal sampling frequency given by equation (23) to sample one OFDM symbol of the DVB-T signal, we obtain 8192 samples. If we use Fourier transformation to this OFDM symbol, we receive spectrum with 8192 spectral coefficients which spacing would be exactly $\frac{1}{T_U}$. It can be seen, that we received exactly 8192 frequency coefficients spaced $\frac{1}{896\,\mu s}$, in which one can identify the definition of the ideal sampling frequency from the equation (23). Now if we modify this equation to form given as follow:

$$K = f_{Sa} \cdot T_U, \qquad (26)$$

we can see, that if the sampling frequency is wisely selected, then we obtain an integer number of samples. The sampling frequency of the general ADC is usually in MSps, and one can easily notice that 1 MSps provide exactly 896 samples. Thus if we use general ADC with integer sampling frequency n MSps, we obtain an integer number of samples. In OFDM there is usually used Fourier transformation to obtain data symbols modulated on the individual subcarriers. Since we are using this method, it is possible to easily change sampling frequency to ideal frequency only by omitting, or adding integer number of frequency coefficients which is much faster than using interpolation and decimation. It is only necessary to use sampling frequency at least 7 MHz. This will provide $K = 6272$ samples in every OFDM symbol. DVB-T in 8k mode have 8192 subcarriers, but only 6817 are nonzero thus if we use sampling frequency 7 MHz, we can acquire whole DVB-T signal without loss of data.

This method is used in the current version of the matched filter based DVB-T receiver. Thanks to this method we can use hardware receiver with the generic sampling frequency and save a lot of resources because it is not necessary to use high order interpolation and decimation to obtain ideal sampling rate. Actually, it is possible to easily generate an impulse response of the matched filter for DVB-T signal which is sampled with sampling frequency providing an integer number of the subcarrier. This can be obtained using a lot of sampling frequencies, but if we use general hardware with integer n MSps, the number of sampled subcarrier will always be an integer. Due to the fact it is not necessary to change the sampling rate. Only the impulse response of the matched filter have to be generated according to used sampling frequency. If the sampling frequency would be too high, the filtration could easily become much slower than the suboptimal method using high order interpolation and decimation to obtain ideal sampling frequency. For this reason, it is optimal not to use a lot oversampled signal.

The second signal processing technique which can be used in the DVB-T receiver is averaging a number of the OFDM symbols. This step would be performed mainly because of the correlative length of the pilot sequence used in DVB-T signal. The problematics of the correlative length of the pilot sequence and its consequence on the estimated impulse response is described in detail in section 4.1.4. The same effect is also present in matched filter based receiver.

In the receiver based on impulse response estimation was a problem, that it was necessary to demodulate every OFDM symbol to obtain impulse response. To achieve that the cyclic prefix has to be removed and if the signal is not perfectly synchronized in the temporal domain, the arbitrary small phase rotation in frequency domain occur. This causes errors in demodulation process because individual data are phase–shifted. For matched filtration the received signal is parsed into blocks, $N_U + N_\Delta$ long and these blocks are summed together. By summing at least four consecutive OFDM symbols, the whole SP sequence is included in the new averaged signal.

For the averaging, it is necessary to know parameters N_U and N_Δ. The parameter N_U can be computed of T_U and sampling frequency by the equation:

$$N_U = T_U \cdot f_{Sa}. \tag{27}$$

T_U and f_{Sa} are known parameters. The same equation can be used for calculation of N_Δ. The problem is that T_Δ can be changed during broadcasting and cannot be assumed as known parameter. The method described in section 4.1.1 is used without any change for finding T_Δ in the matched filter based receiver. Unfortunately, this type of averaging including phase requires extremely high precise time synchronization. Nevertheless, it is one of the possible techniques used in radar and is called Coherent Integrator [14]. It is necessary to ensure that phase error of the individual symbols modulated on subcarriers is lower than $\pi/4$ for the whole integration period otherwise the pilot signal is canceled by averaging. Even if the signal phase is perfectly synchronized it applies only to one beam, leaving others unsynchronized. It is not possible to synchronize all beams at the same time. Thus, in this work, the video integration is used. This method is based on averaging regardless the phase.

The advantage of the averaging of the OFDM symbols is reduction of the influence of the AWGN and since the data in digital communication are designed to be random and uniformly distributed, the averaging also partially marginalizes the payload. This can provide optimal results even if the signal level is low. The only problem is in a scenario when the averaging time is too long, and the receiver is moving with high radial speed. But if we assume the maximum radial speed of the receiver approximately 130 km/h, the averaging four OFDM symbols long cause maximum error 0.13 m. If the receiver is worn by pedestrians the averaging time can be higher and provide position even if the signal level is low.

4.2.2 SP Matched Filter Generator and Matched Filtration

The filtration can be described by convolution according to the equation:

$$r(\tau) = \int_{-\infty}^{+\infty} s(t)h(t-\tau)d\tau, \tag{28}$$

where $h(t)$ is the impulse response of the filter which is designed as is written in equation (24). To create impulse response the ideal replica of the pilot signal is required. The replica is generated using Fourier transformation approximation of the OFDM modulation. If the number of subcarriers is sufficiently high, the error caused by approximation is low [12]. In this method the data sequence is directly mapped to corresponding frequency coefficients which corresponds to subcarriers and then the signal replica in temporal domain is obtained after inverse Fourier transformation applied directly on subcarriers.

At first, the PRBS ($PRBS(k)$) is generated. Then the corresponding bits of the $PRBS(k)$ are mapped to subcarriers. The relation representing the mapping can be written as

$$S\left(k_0 + 3n\right) = \tfrac{4}{3} \cdot \sqrt{42} \cdot PRBS(3n); n \in \mathbb{Z} \cap \left\langle 0, 2272 \right\rangle, \tag{29}$$

where k_0 is the frequency coefficient corresponding to the first used subcarrier used in DVB-T signal. k_0 can be calculated, if the number of sampled subcarriers K is known as follows:

$$k_0 = \tfrac{K-6816}{2} + 1. \tag{30}$$

This equation applies, if the number of sampled subcarriers is even. This condition is always met when the sampling frequency is n MSps, where n is an integer number and $n > 6$. At this point, the frequency spectrum $S\left[\Omega\right]$ contains K frequency coefficients with pilot sequence mapped to it. Now we can obtain pilot signal replica ($s\left[k\right]$) by applying inverse Fourier transformation on $S\left[\Omega\right]$. The autocorrelation function of the pilot signal replica is shown in figure 10. The correlation length is approximately 89.494 km as mentioned in 4.1.4.

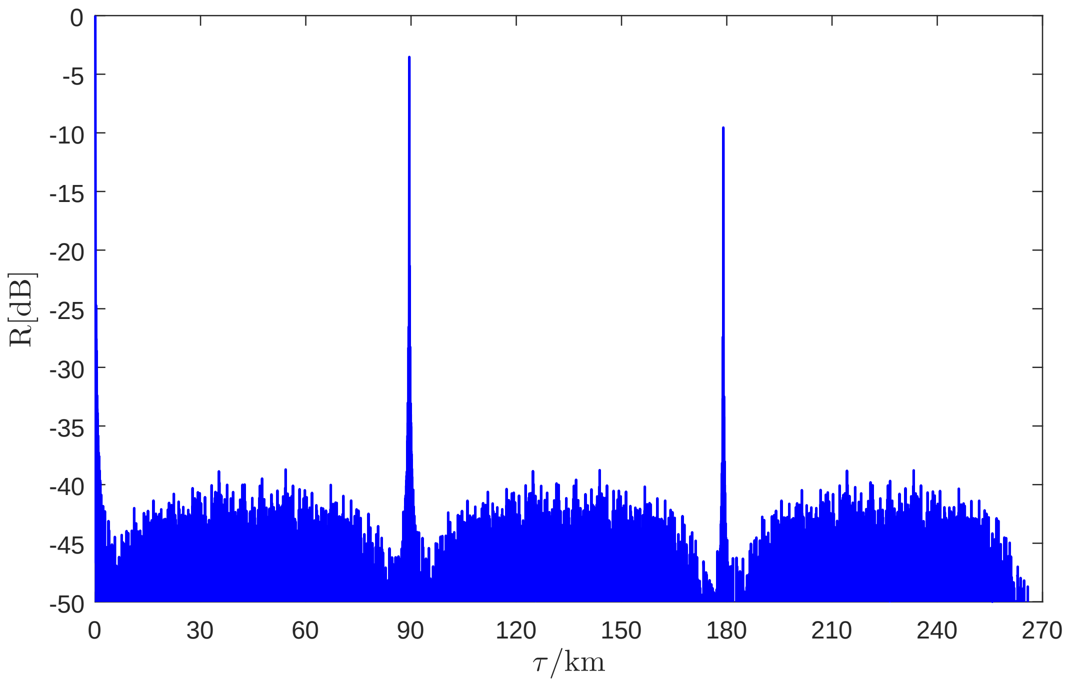


Figure 10: The autocorrelation function of the pilot signal replica used for generation of the impulse response of the matched filter.

The impulse response of the matched filter is obtained from equation (25). This impulse response is used for the matched filtration applied on the received DVB-T sequence obtained after performing the initial signal processing described in section 4.2.1. Matched filtration is done in discrete time and can be mathematically written as follows

$$r[\tau] = \sum_{k=0}^{K} s[k]h[k-\tau]\,. \tag{31}$$

Now let us look closely at correlation parameters of the pilot signal. For precise navigation it is necessary to find maximum of the correlation function. The spectrum of the OFDM is wideband and close to rectangular. For this reason, in temporal domain its characteristic is close to the *sinc* function. Thence the side lobes of the correlation function are approximately −13 dB lower than its maximum. This side lobe can be easily detected as signal from transmitter and cause error. To suppress side lobes it is necessary to enhance impulse response of the matched filter. This practice is described in [14] in chapter 8 (Pulse Compression Radar). The main idea is to weight frequency coefficients by window function. Reference [15] is aimed to study the window functions properties. The filtration using windowed impulse response of the filter is sometimes called as Mismatched filtration. Every weighting of the frequency coefficients results in the extension of the main lobe of the correlation function. The higher is the suppression of the side lobes the wider the main lobe becomes. It is necessary to find compromise between side lobe suppression and width of the main lobe, because of this property. The narrowest main lobe has Chebyshev windowing function, but Taylor window is used to weight the frequency coefficients, because this type of window allows to make tradeoffs between the main lobe width and the side lobe level. The level of the side lobes is set to −23 dB with two nearly constant–level side lobes (for details see Help in Matlab for *taylorwin* function). This setting leads to minimal main lobe extension while the CA-CFAR detection algorithm is not detecting side lobes as signal from transmitters. The comparison of the correlation main lobe width of the matched filter with the mismatched filter is shown in figure 11. Filtration was performed with pilot signal without windowing in both cases.

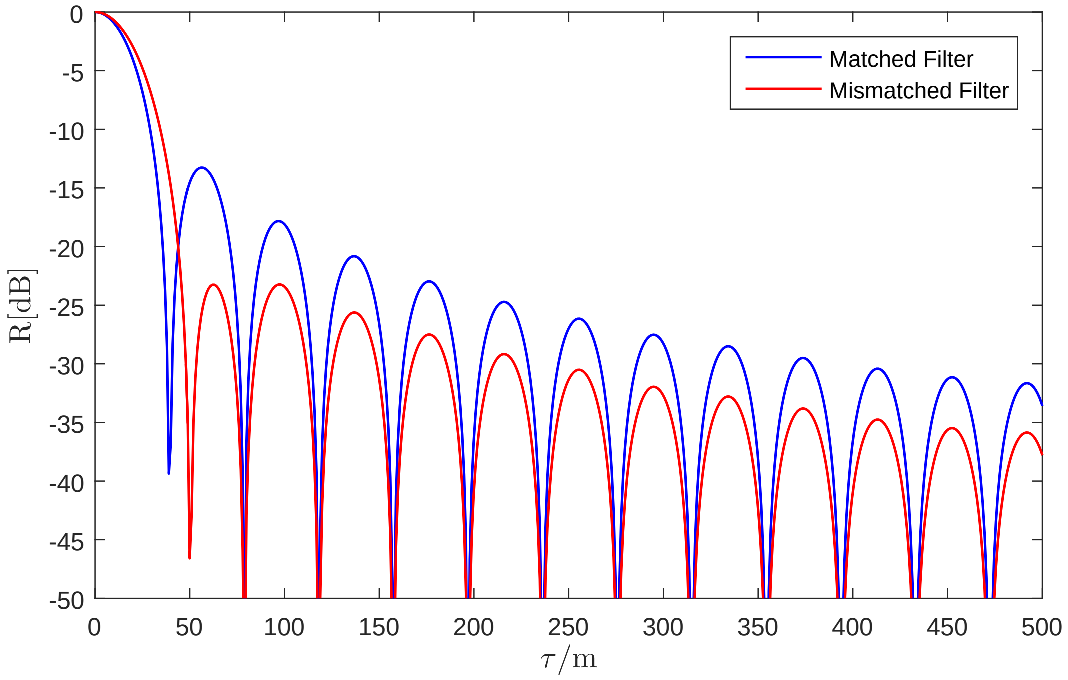


Figure 11: The comparison of the matched filter and mismatched filter correlation function.

The method how to acquire matched filtrated signal $r[\tau]$ was described. This signal is necessary for the position evaluation because this signal can be used for detection of the time differences between the individual transmitters, which are then used for position evaluation using hyperbolic navigation method. The process of the position evaluation using filtered signal $r[\tau]$ is divided into detection and positioning algorithm. This process is described in section 4.3.

4.3 Position Evaluation

The position evaluation using DVB-T signal can be separated into four basic steps. The first step is the detection of the delayed signal received from individual transmitters. The detection is the problem of statistics and can be proven, that optimal method of the detection of the signal corrupted by the AWGN is correlation [13]. Matched filtration and correlation gives the same results thus it does not matter which method is used. Typically if the signal is transmitted by a number of transmitters, then in optimal case, we detect signal more than ones, only delayed. This delay between detections is the fundamental parameter for the used method of the position evaluation. This problematics is described in detail in section 4.3.1.

The DVB-T should work in so–called single frequency network (SFN). In this mode, the individual transmitters are synchronized via GNSS time according to [8].

In this document, the method of the mega-frame synchronization is described. The SFN adapter is located in the broadcasting center where from the DVB stream is distributed via a distribution network to the individual transmitters. The synchronization time stamp is inserted into DVB stream and then distributed to transmitters. In the every transmitter the SYNC system is used for the evaluation of the necessary delay according to the time when the DVB stream was received and the Synchronization Time Stamp. This method should secure SFN operation with time synchronization better than 100 ns. The method works only if the delay of the distribution network is lower than 1 s. However, this is the synchronization between the center and the SYNC system. Between the SYNC system and the actual time when the signal is transmitted can be an arbitrary delay and this delay can differ for each transmitter. It is even not known the precision of the so–called MIP inserter. This can cause unknown time offset between the actual start of the broadcasting of the individual transmitters. The next step described in section 4.3.2, is focused on method how to determine if the DVB-T transmitters are correctly synchronized and how to estimate the potential offset.

The next part of this section is aimed at the problem of cell identification. For the position evaluation, it is necessary to determine which transmitter transmitted the detected signal. The DVB-T signal contains optional cell identifier. Since it is optional we cannot rely on this information. Also if we use an omni-directional antenna and we receive a signal from several cells simultaneously, we receive only superposition of the identifiers, and the actual identification would be difficult. For this reason, the alternative method of the identification is used and described in the section 4.3.3.

In the last part, the method for position evaluation is described. For the positioning algorithm, we need to have information about the transmitters real position saved in a look up table. Then we use information obtained from received DVB-T signal. The time delays between the signal arrival from individual transmitters. In this thesis, TDoA using Newton–Raphson method [16] is utilized in position evaluation. Its principle is described in section 4.3.4.

4.3.1 Threshold Estimation and Transmitter Detection

For positioning, via TDoA it is necessary to detect delayed signal replicas corresponding to the signal beams transmitted from individual transmitters. This problem is similar to the radar detection problem. For detail study of the detection theory and the radar theory [13] and [17] was used.

The basic idea of the detection algorithm is to set some value and use it as a threshold. When received signal exceeds this value, a system sets the alarm. It is possible that the signal is present, but the influence of the noise causes that the signal will not exceed the threshold value. The probability that the signal is detected when present is called the probability of detection (P_D) and can be evaluated from the probability density function (PDF) of the signal with noise. It is possible that noise value exceeded a threshold value and system set the alarm when the signal was not present. This false detection occurs with a probability which can be evaluated from

PDF of the noise without the signal and it is called probability of false alarm (P_{FA}). In statistics, these probabilities are called *right–tail* probability (*Q(x)*). *Right–tail* probability is evaluated of PDF according to equation (32) where x is the threshold value, and $p(t)$ is the corresponding PDF.

$$Q(x) = \int_{x}^{\infty} p(t)\,\mathrm{d}t. \tag{32}$$

The most common distribution is called *normal* or *Gaussian* distribution. When a random variable (X) is normally distributed, it is indicated as follows: $X \sim \mathcal{N}(\mu, \sigma^2)$, where μ is the mean value of the distribution and σ^2 is a variance of the distribution. PDF of the normal distribution is described by the equation:

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2\sigma^2}(x-\mu)^2} \quad -\infty < x < +\infty. \tag{33}$$

Then the evaluation of *Q(x)* is given by

$$Q(x) = \int_{x}^{\infty} \frac{1}{\sqrt{2\pi}} e^{\left(-\frac{1}{2}t^2\right)} \mathrm{d}t. \tag{34}$$

It is not possible to solve this equation in closed form. It must be evaluated numerically. One of the possible method, how to calculate this equation is Monte Carlo method. Realizations of the normally distributed random variable were generated in MatLab using function *normrnd()*. The histogram of the normally distributed variable and ideal theoretical shape of the PDF according to equation (33) are shown in figure 12. Corresponding *right–tail* function generated by Monte Carlo method is shown in figure 13.

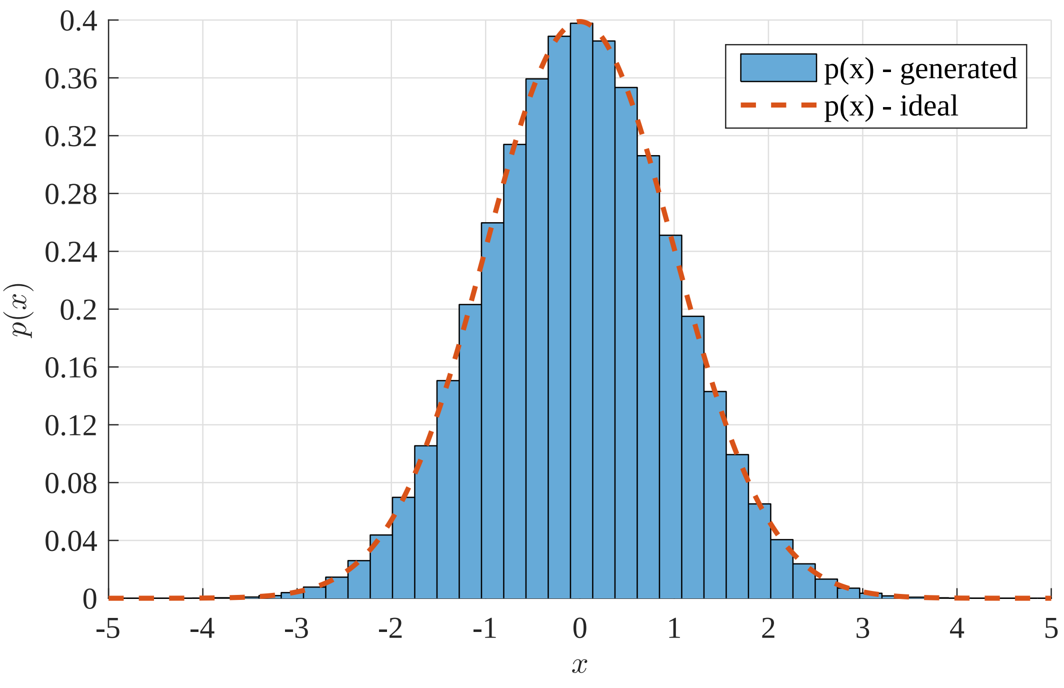


Figure 12: PDF of the normal distribution generated in MatLab and its ideal shape ($x \sim \mathcal{N}(0, 1)$).

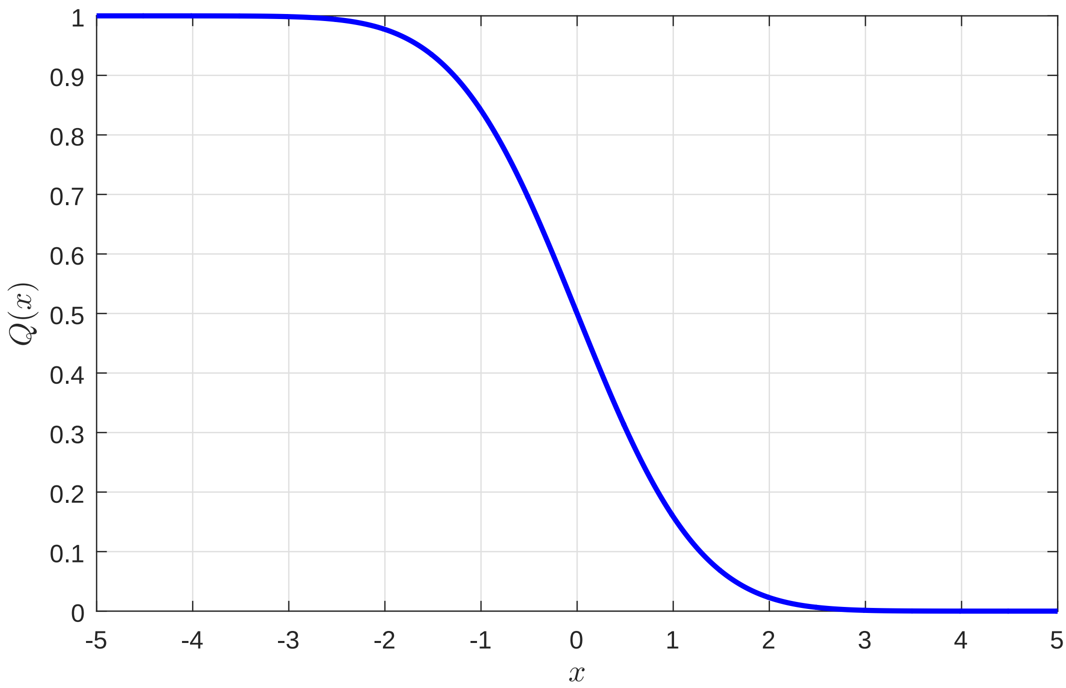


Figure 13: Right-tail function (Q(x)) of the normal distribution generated in MatLab.

For signal processing, it is common to work with complex envelope, i.e. a signal is a complex number where the real part is called in–phase (I), and imaginary part is called quadrature (Q). According to normal complex operations, the magnitude of complex envelope sample c is defined by $|c| = \sqrt{I^2 + Q^2}$. The result of this operation is no longer normally distributed. Two distributions are considered. The first possibility occurs when I and Q are both $\mathcal{N}\left(0, \sigma^2\right)$, which means both have zero average value and the same variance and they are also independent. This distribution is then called Rayleigh, and its PDF is given by the equation:

$$p\left(x\right) = \begin{cases} \frac{x}{\sigma^2} e^{-\frac{1}{2\sigma^2} x^2} & x > 0 \\ 0 & x < 0. \end{cases} \tag{35}$$

The PDF of this distribution is shown in figure 14 together with its ideal shape given by equation (35). The PDF was generated from two normally distributed random vectors. It is interesting that its Q(x) can be solved in closed form [13], which can be written as:

$$Q\left(x\right) = \int_{x}^{\infty} p\left(t\right) \mathrm{d}t = e^{-\frac{x^2}{2\sigma^2}}. \tag{36}$$

Figure 15 shows that simulated values correspond to the ideal theoretical shape. Q(x) was evaluated by the Monte Carlo method. This distribution can be considered when only AWGN is present.

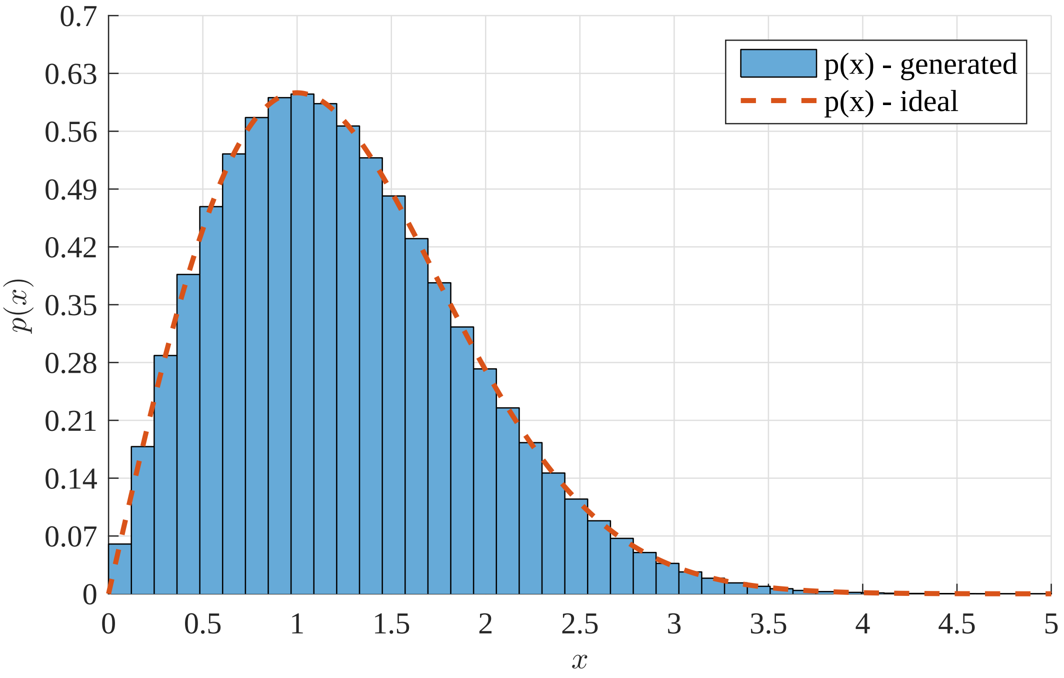


Figure 14: PDF of the Rayleigh distribution generated in MatLab and its ideal shape ($I \sim \mathcal{N}(0,1)$,$Q \sim \mathcal{N}(0,1)$)).

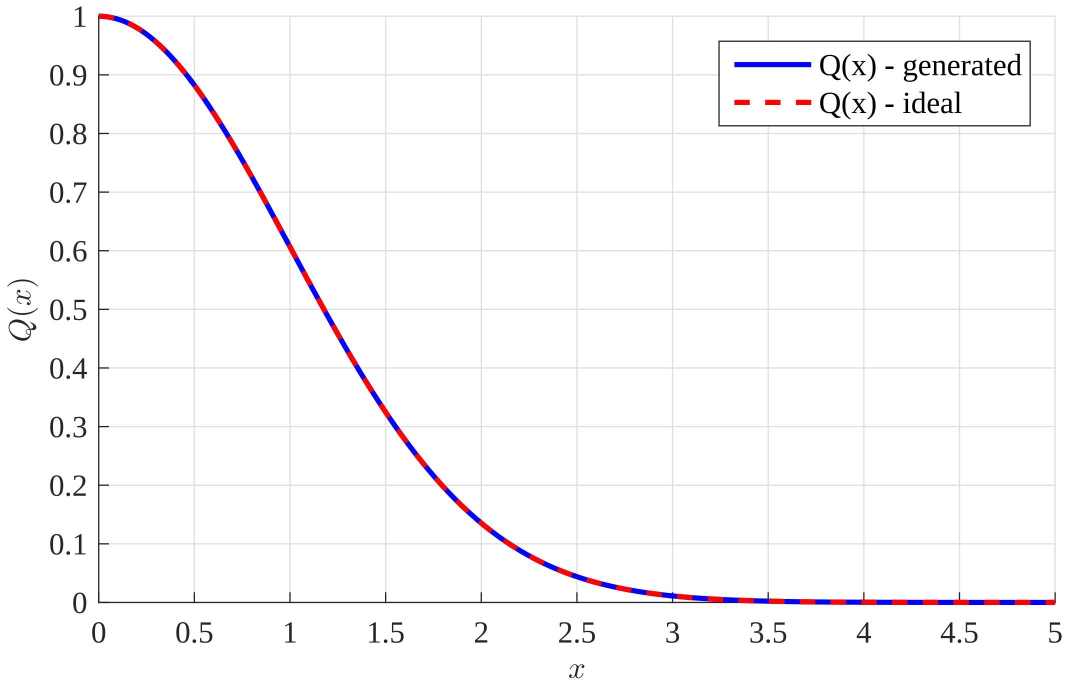


Figure 15: Right–tail function (Q(x)) of the Rayleigh distribution and its ideal shape generated in MatLab.

When the signal is present in received data sequence, it usually does not have zero mean value. This affects the PDF, and in common case when $I \sim \mathcal{N}\left(\mu_I, \sigma^2\right)$ and $Q \sim \mathcal{N}\left(\mu_Q, \sigma^2\right)$ are also independent the PDF of complex envelope sample magnitude become Rician distributed. Rician PDF is given by the equation:

$$p(x) = \begin{cases} \frac{x}{\sigma^2} e^{-\frac{1}{2\sigma^2}(x^2+\alpha^2)} I_0\left(\frac{\alpha x}{\sigma^2}\right) & x > 0 \\ 0 & x < 0, \end{cases} \tag{37}$$

where $\alpha^2 = \mu_I^2 + \mu_Q^2$ and $I_0(\xi)$ is modified Bessel function of the first kind and zero order. The histogram of the Rician distributed random variable generated of two normally distributed random variables without zero mean values, and its ideal theoretical shape is shown in figure 16. Figure 17 shows Q(x) function which was evaluated by the Monte Carlo method. This Q(x) function is defined by the equation:

$$Q(x) = \int_x^\infty p(t)\,\mathrm{d}t, \tag{38}$$

and cannot be evaluated in closed form.

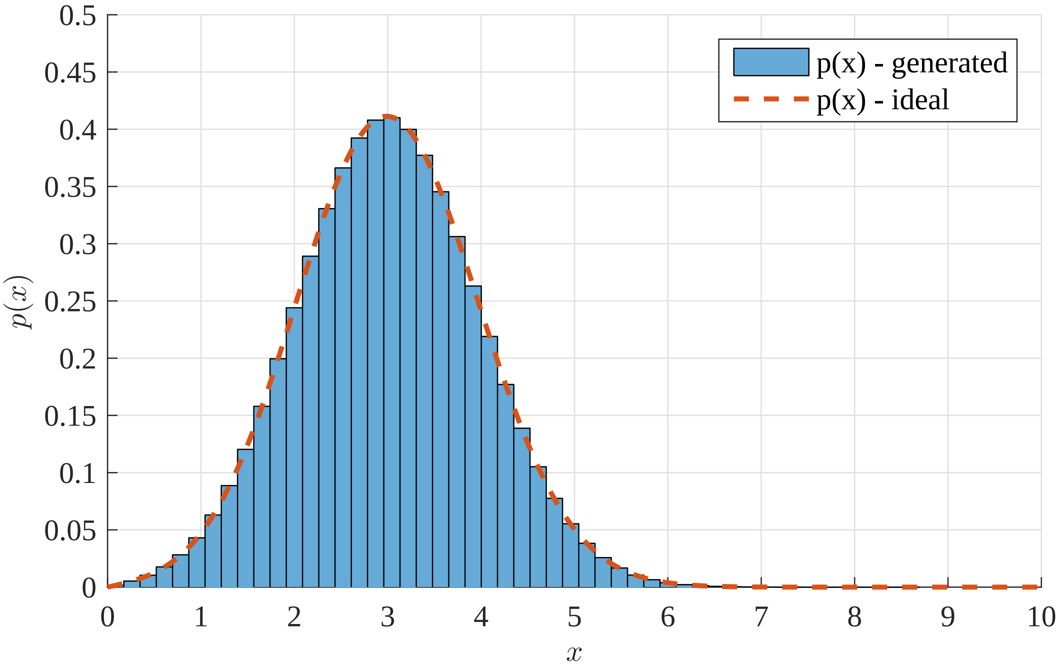


Figure 16: PDF of the Rician distribution generated in MatLab and its ideal shape ($I \sim \mathcal{N}(2,1)$,$Q \sim \mathcal{N}(2,1)$).

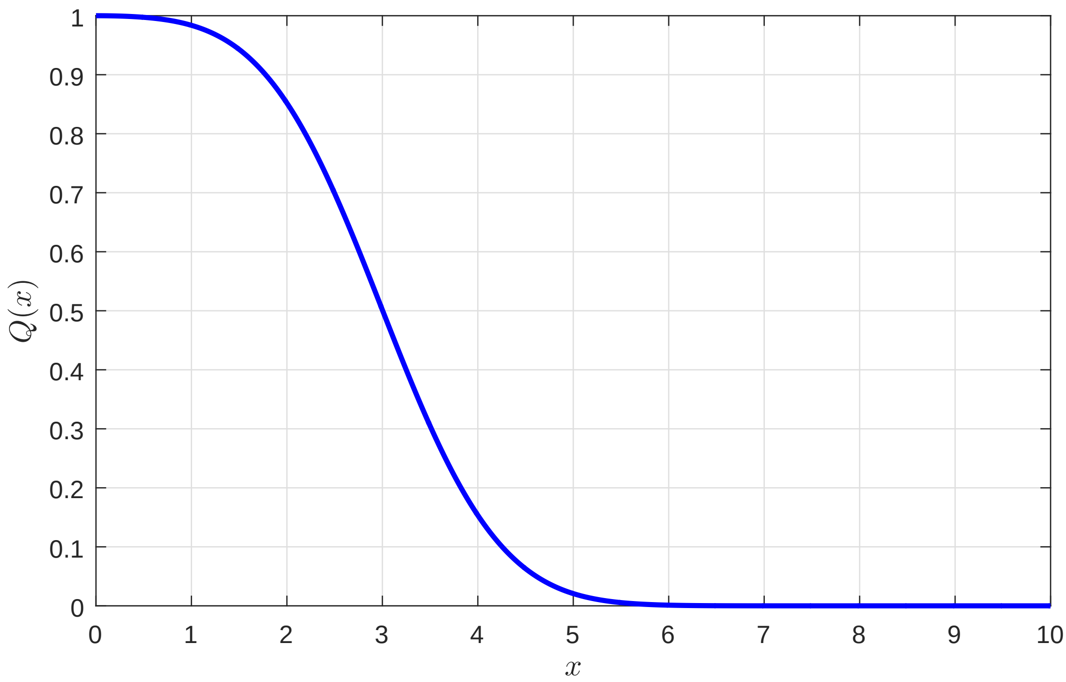


Figure 17: Right–tail function (Q(x)) of the Rician distribution generated in MatLab.

The underlying problem in detection theory is to decide between two or more events. This problematics is described in detail in [13]. In our study, it is a decision between event when only noise is received and event when a signal with noise is received with the smallest probability of the error. This task is called hypothesis testing. In general, it could be more than two hypotheses to test, but in this work, we consider only two hypothesis. If only two hypotheses are tested, they are called *null hypothesis* ($\mathcal{H}_0$) and the *alternative hypothesis* ($\mathcal{H}_1$). In the previous part, it is shown, that if the PDF is known it is possible to evaluate the probability of the variable whether it is smaller or bigger than chosen threshold value. Usually, the probability that alternative hypothesis is chosen while null hypothesis has been presented is called probability of false alarm P_{FA} ($P_{FA} = P(\mathcal{H}_1; \mathcal{H}_0)$), and probability $P_D = P(\mathcal{H}_1; \mathcal{H}_1)$ is called probability of detection P_D. These probabilities are dependent on the value of a threshold. Due to this fact, it is necessary to constrain one probability to a constant value while optimizing other. This task is possible to solve by the Neyman-Pearson theorem which maximizes P_D for a constant P_{FA}. This theorem is given by the equation

$$L(x) = \frac{p(x; \mathcal{H}_1)}{p(x; \mathcal{H}_0)} > \gamma, \tag{39}$$

where the threshold (γ) is given by

$$P_{FA} = \int_{x: L(x) > \gamma} p(x; \mathcal{H}_0) \,\mathrm{d}\, x = \alpha. \tag{40}$$

In receivers the mean value of the signal noise power is arbitrary and evaluation of mean value needs infinity realizations. Therefore practically, only estimation of the parameter is calculated from the finite set of realizations. For detection in DVB-T based positioning system, the Cell–averaging Constant false alarm rate (CA-CFAR) algorithm is used [17]. The algorithm is used to estimate mean value of the noise and decides if the signal is present. The principle of the algorithm is shown in figure (18).

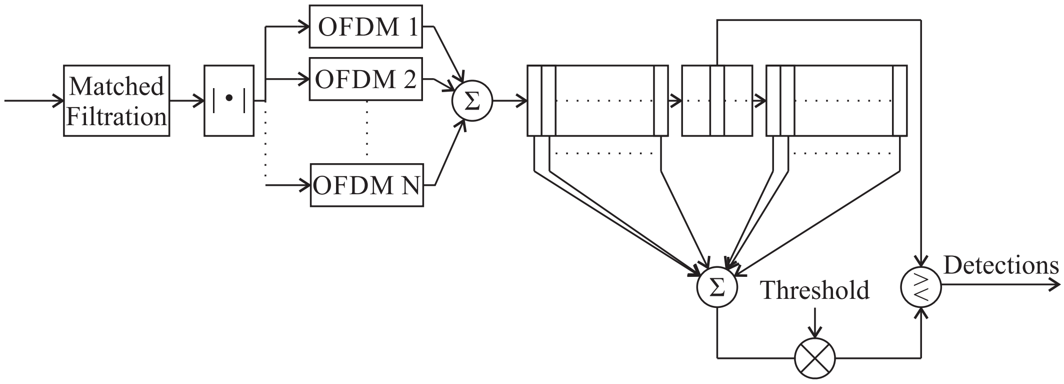


Figure 18: Principle of the CA-CFAR algorithm used for detection of the delayed DVB-T pilot signal replicas.

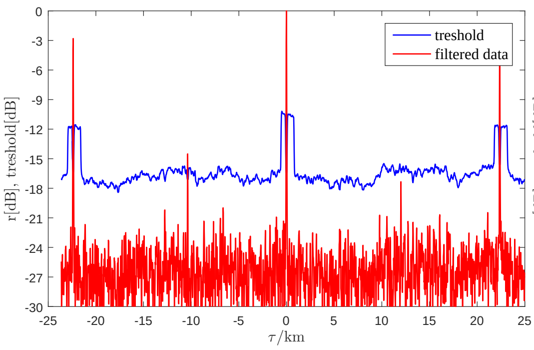
At first, the received signal is filtered according to section 4.2.2. Next, the signal is parsed into the N OFDM symbols in absolute value. Then the averaging is performed by summation of the N individual OFDM symbols. This approach is called video integration, or noncoherent integration [14]. The detection algorithm starts after these first processes.

The detection algorithm can be imagined as First In, First Out memory with random access to the individual memory cells. This memory is separated into three blocks, the left window, the guard interval and the right window. In the classical theory, for detection of the signal distorted with noise, the length of the left and the right window is the same, and the guard interval has to be long enough to cover the whole correlation maximum. The samples in both windows are summed together, and the product is multiplied by the threshold value. This weighted value is then compared with the corresponding value in the guard interval. If it is higher than the threshold value, then the detection will appear, and then the new sample is inserted into memory, and the oldest one is thrown out, the decision is performed and again.

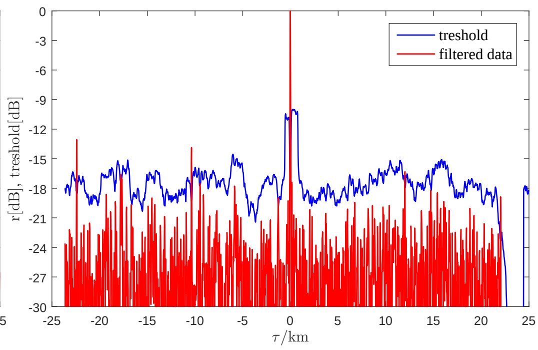
This algorithm was slightly modified and implemented into the receiver. The first problem is how to set the window length. In theory, the larger the window, the better the mean power of the noise is estimated, but in the real signal, it is a problem, that the distance between replicas can be short, and the power of the replica signal will affect the estimated mean power of the noise. Also, the signal can be closely followed by its replica caused by multipath propagation. Because of that, the statistical parameters are not the same on both sides from the guard interval. The last problem is the correlation properties of the SP signal, which is *sinc* type, so the side lobes of the correlation functions are approximately -13 dB of the correlation maximum when unmatched filtration is not used.

This leads to modification of the window lengths. The duration of the left window is 10 the reciprocal value of the frequency spacing between OFDM subcarriers. The right window is 1.5 the left one. Thanks to that the better properties in the multipath distorted environment are achieved. The guard interval duration is 3 times the reciprocal value of the frequency spacing between OFDM subcarriers. This value is chosen to suppress false detection caused by the side lobes of the correlation function of the SP signal. The unit of the reciprocal value of the frequency spacing between OFDM subcarriers is used because this value is the main lobe width of the correlation function of the SP signal in DVB-T. And finally, the threshold value is 3 times the estimated average.

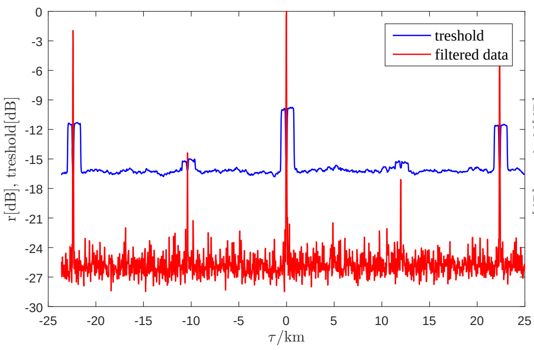
Figure 19 shows an example of the typical data obtained from experimental measurement with the experimental receiver. Measuring was done on the roof of the Czech Technical University in Prague. The DVB-T channel number 42 was received. One can notice that peaks which exceed the threshold value are peaks which would be naturally selected by operator and threshold value are sufficient high outside the obvious maxima.



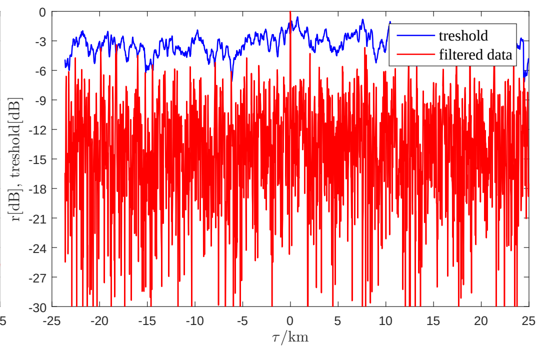
(a) An example of the filtered DVB-T signal using noncoherent integration of 4 OFDM symbols.



(b) An example of the filtered DVB-T signal using coherent integration of 4 OFDM symbols.



(c) An example of the filtered DVB-T signal using noncoherent integration of 50 OFDM symbols.



(d) An example of the filtered DVB-T signal using coherent integration of 50 OFDM symbols.

Figure 19: Example of the filtered DVB-T signal by the matched filter and threshold estimation for detection.

The noncoherent integration used in figure 19a has better properties than coherent in figure 19b, because the phase synchronization is insufficient even for a low number of used OFDM symbols. If the number of symbols is increased the noise variance in noncoherent detector decreases while in coherent, detections vanish as shown in figure 19c and 19d respectively. Unfortunately, it is not possible to extend correlation length of the pilot signal using the summation of the pilot signal parts scattered across 4 OFDM symbols since the coherent integration is not feasible. This leads to the emergence of aliases repeating with a period corresponding to the correlation length of the pilot signal part contained in one OFDM symbol, which is approximately 22.373 km. Recognize that two peaks are aliased is not a problem since their spacing is exactly 22.373 km. The problem is how to determine which of them is the alias.

4.3.2 SFN Time Offsets Estimation

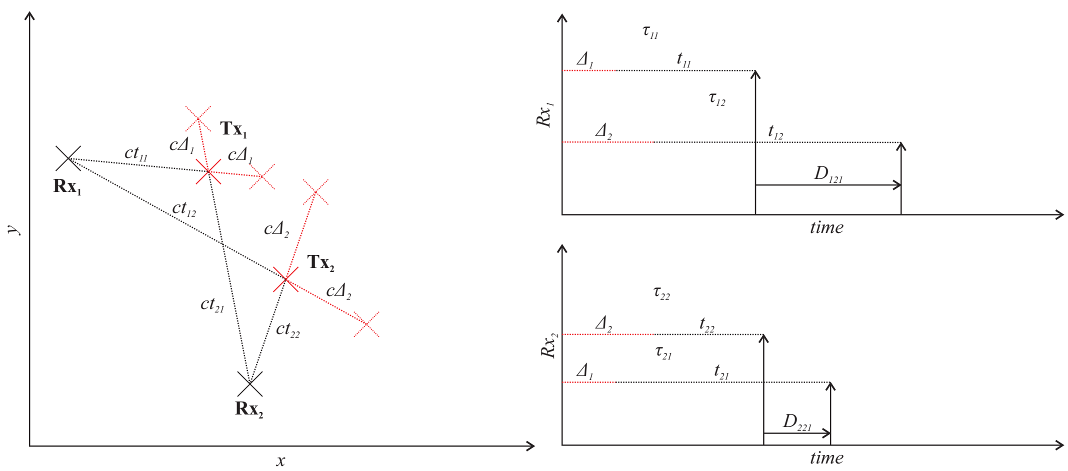
It was already mentioned, due to various reasons, the actual beginning of the transmission may vary in SFN transmitters. For this reason, the algorithm which can estimate the time offset between transmitters beginning of the transmission.

In figure 20 is shown the effect which is caused by a time offset between the beginning of the transmission in the SFN. The receiver is put into position $\mathbf{Rx_n}$. The transmitter located at $\mathbf{Tx_o}$ starts to broadcast, and it takes t_{no} seconds to arrive at the receiver placed at $\mathbf{Rx_n}$. The propagation time can be evaluated from the known position of the transmitter, receiver and the speed of light (c) as follows

$$t_{no} = \frac{1}{c} \left\| \mathbf{Rx_n} - \mathbf{Tx_o} \right\| = \frac{1}{c} \sqrt{\sum_k \left(Rx_{nk} - Tx_{ok} \right)^2}. \tag{41}$$

If there is some offset between the time stamp common to all transmitters and the real beginning of the transmission the transmitter will seem to be further from the receiver. The virtual distance caused by this time offset (Δ_o) is the same no matter where the receiver is placed. This distance is indicated by the red dotted line, and transmitter's virtual position by the red dotted cross in figure 20a.

In figure 20b an example of the output of the matched filter is shown. The beginning of the temporal axis is in this case shown as GPS Pulse-per-second signal (1PPS). In our work, we do not use GPS time synchronization, and because of that, we cannot determine where is the beginning of the temporal axis. Thus, we can obtain only a relative time of detections τ_{np} and use them to evaluate the differences between the signal replicas arrival time (D_{npo}).



(a) The effect caused by the time offset between transmitters in two dimensions.

(b) The effect caused by the time offset between transmitter on filtered signal.

Figure 20: The influence of the time offset of transmitters on the position evaluation.

The algorithm which is used for estimation of the time offsets uses measured time differences obtained as time differences between detections. Obtaining of detections τ_{np} is described in section 4.3.1. In the next step, we need to know the position of the transmitter and measuring points to evaluate signal propagation time from all transmitter to all measuring points. Now, we can organize these values into antisymmetric matrices. The coefficients of the matrix of measured differences (**D**) are defined by

$$D_{npo} = -D_{nop} = \tau_{np} - \tau_{no}. \tag{42}$$

The matrix coefficients of ideal time differences (**T**), evaluated as the difference between propagation time between transmitters and measuring points according to equation (41), are defined as

$$T_{npo} = -T_{nop} = t_{np} - t_{no}. \tag{43}$$

The last matrix (**O**) contains differences between offsets of the individual transmitters. The coefficients of the matrix **O** are given by

$$O_{po} = -O_{op} = \Delta_p - \Delta_o. \tag{44}$$

For the position evaluation, it is not necessary to know absolute time offsets on the individual transmitters. It is only necessary to know differences between these offsets because the position is evaluated of measured time difference of arrival contained in **D** and this matrix is only affected by differences between offsets not by their absolute values.

If the matrix **T** and **O** is known, the coefficients of the matrix **D** can be evaluated by

$$D_{npo} = T_{npo} + O_{po}. \tag{45}$$

Now it is obvious that time differences between transmitters offsets can be calculated if we perform measurement in defined location if we know coordinates of all transmitters and measuring point. We need to add next dimension (n) to matrix **O** if we assume nonzero measurement error. The correct value can be then obtained by averaging of individual measurements (n). Now, this calculation can be performed by necessary adjustment of the equation (45) as is shown in the equation

$$O_{npo} = D_{npo} - T_{npo}. \tag{46}$$

There is still one major problem. Described algorithm would require some kind of cell identification to distinguish to which transmitter detection belongs. In DVB-T signal is the Cell-ID usually set to zero for all the transmitters and even if the Cell-ID is used it would be complicated to use it in the receiver with omnidirectional antenna.

For this reason, it is necessary to create matrix **O** for every possible permutation of the transmitters order. This would lead to four dimensional matrix **D** consisting of elements D_{nkpo}, where n is a number of the measuring point, k is a number of permutation of the transmitters indexing, p and o are indexes of transmitters. Now the matrix **O** will not be the same for measurements on different measuring points, as it was when the transmitters were identifiable. Therefore, the matrix **O** also became four dimensional consisting of elements O_{nkpo}, and it is evaluated by the equation

$$O_{nkpo} = D_{nkpo} - T_{npo}. \tag{47}$$

If only one measurement is provided without any further information, it is not possible to determine which order of transmitter is correct. But if we provide more than one measurement performed in different positions then only for one permutation k of the transmitters order will be all submatrices $\mathbf{O_k}$ the same. A higher number of measurements will provide data for calculation differences of offsets using, for example, the method of least squares to minimize residuals of the measurements.

4.3.3 Cell Identification

Positioning using DVB-T is ambiguous because detections cannot be assigned to the individual transmitters without any other additional information. It is possible to use several methods using different types of the additional information. All of them has to assign detections to the individual transmitters to suppress ambiguities. The influence of the wrong cell identification is shown in figure 21. The correct path is achieved when the detections are correctly assigned to transmitters.

The simulated path when the transmitters order is correct is shown in figure 21a. If one or more transmitters are mutually commuted, the evaluated position differ from correct position and also the shape of the trajectory. In figures 21b to 21d are shown other possibilities caused by ambiguities of the transmitter detection correct order. The scale and the azimuth are common for all images. The other two permutations of the transmitters order lead to the singular matrices, and the position cannot be evaluated.

(a) The correct path when the transmitters are identified correctly.

(b) The wrong path when the transmitter Olšanská is commuted with the transmitter Ládví.

(c) The wrong path when the transmitter Ládví is commuted with the transmitter Novodvorská.

(d) The wrong path when the transmitter Olšanská is commuted with the transmitter Novodvorská.

Figure 21: The ambiguity of the DVB-T based positioning algorithm.

One of the possible methods to resolve the transmitter ambiguity is to use the inertial unit and digital magnetic compass. If the rover carrying the receiver is moving the change in position, given by inertial unit along with the known course which is provided by known direction relative to north and the change in position, can be used to identify transmitters. Transmitters position and the shift in position are known parameters and can be used to predict the change in detected time differences. The comparison with the actual change in time differences will provide necessary information to assign detections to the individual transmitters. This algorithm has one major problem. Despite the shape and the relative change of the position differs from correct trajectory the error could be quite small. An example is in figure 21c where absolute differences between points are almost the same. The azimuth angle differs but for many points can be the error under the precision limit. Thus the transmitter order can be estimated incorrectly.

Another method is assuming that the system is fused with others positioning systems. Nowadays the standard is positioning systems with multi-constellation GNSS receiver often fused with other relative systems like the inertial unit, digital magnetic compass, and others. In this work, the presumption is that DVB-T based positioning system would not be a standalone system, but the only a supplementary system in multi-constellation receiver developed at Department of Radioelectronics. For this reason, the assumption, that in the initial state the correct position of the receiver is known, is made. Thanks to this assumption it is possible to use reliable method for transmitter identification.

The method is using last known position of the receiver which is provided by the multi-constellation receiver. Then the distances between the receiver and transmitters are evaluated. Now, if there are any transmitter time offset it is added to the evaluated distances. If these distances are sorted in ascending order, we obtain the detection set which should be ideally obtained at the receiver position, and we know the transmitters correct order. The ideal detection set is then compared with the actual detection set obtained from the received signal. The order of transmitters is known and should be the same in actual detection set.

If we compare it with the previously mentioned method, the absolute distances between the transmitters and receiver are compared, not only differences between two, usually close, positions. This difference is evident in figure 21. If the order of transmitters is incorrect, the absolute position differs hundreds of meters, but the difference between two measurement points is multiple times smaller. That is the reason why this method is much more reliable and is used in this work.

4.3.4 TDoA Positioning Algorithm

For the position evaluation, the iterative algorithm is used. For the TDoA positioning scenario, the Newton-Raphson method, described in [16], [18] was modified. This modification is described in detail in [5]. It was already mentioned, that in DVB-T based positioning system the used information is a time difference between arrivals of the signal from the individual transmitters. This leads to the TDoA positioning method. At first, the time difference of arrival is converted to the difference of the distances between the receiver and transmitters by multiplication with the propagation speed of light. The distance differences can be inserted into the matrix using the norms of the differences between vectors of position; mathematically written

$$d_{ij} = \|\mathbf{r}_u - \mathbf{r}_i\| - \|\mathbf{r}_u - \mathbf{r}_j\| + \epsilon_{12}. \tag{48}$$

Here the $\mathbf{r}_u$ is a vector containing receiver coordinates, the $\mathbf{r}_i$ is a vector containing coordinates of the i-th transmitter and the ϵ_{12} considered in measured time differences.

For the reason of the iterative solver the variables are divided into the predictive ($\mathbf{r}_{up}$) and corrective ($\mathbf{r}_{uc}$) parts. Applying the 1$^{\text{st}}$ order Taylor approximation on the distances between the receiver and transmitters will provide the equation

$$\|\mathbf{r}_{up} + \mathbf{r}_{uc} - \mathbf{r}_i\| \approx \|\mathbf{r}_{up} - \mathbf{r}_1\| + \frac{(\mathbf{r}_{up} - r_i)}{\|\mathbf{r}_{up} - \mathbf{r}_i\|}\mathbf{r}_{uc}, \tag{49}$$

here the second part of the equation contains the unitary direction vector defined by

$$\mathbf{1}_{ui} = \frac{(\mathbf{r}_{up} - r_i)}{\|\mathbf{r}_{up} - \mathbf{r}_i\|}. \tag{50}$$

Now, using the direction vector (50) and the corrective part of the difference matrix $\mathbf{d}$ given by equation (48), it is possible to write the matrix form of the equation for the evaluation of the corrective part as

$$\mathbf{d}_c = \begin{bmatrix} \mathbf{1}_{ui} - \mathbf{1}_{uj} \\ \vdots \\ \mathbf{1}_{ui} - \mathbf{1}_{uj} \end{bmatrix} \mathbf{r}_{uc} = \mathbf{G}\mathbf{r}_{uc}. \tag{51}$$

The matrix $\mathbf{G}$ is called the geometry matrix. The geometry matrix is not generally square. For that reason, for computing of the position correction part, pseudo-inversion is used. Hence the correction part can be evaluated by

$$\mathbf{r}_{uc} = (\mathbf{G}^T\mathbf{G})^{-1}\mathbf{G}\mathbf{d}_c. \tag{52}$$

Now, we can use equation (52) to estimate receiver position iteratively. In the beginning, the arbitrary initial point in the vicinity is used as position prediction $\mathbf{r}_{up}$. From this point, the correction ($\mathbf{r}_{uc}$) is computed using equation (52), and the predicted position is corrected. This algorithm is repeated until the norm of the correction vector is lower than given threshold.

5 DVB-T Positioning System Simulator

The simulator of the DVB-T channel used for the experiments was created, for the simulation of the DVB-T based positioning system behavior. This simulator can be used to simulate measuring on specific places or for the study of the precision capabilities to simulate theoretical results of Dilution of Precision (DoP) derived in [5].

The simulator can be divided into two main parts. The first part is the part which generates distorted DVB-T signal the same way as it was received on defined position by SDR. The second part is processing the generated signal and evaluate the position of the simulated receiver. Then the results are compared with input position.

5.1 Signal Generator

At first, the ideal DVB-T signal according to 3.2.1 is generated using Fourier transformation approximation. Then the signal is distorted according to used propagation model, transmitters and receiver position.

The signal is generated symbol by symbol. At first, the data sequence ($\mathbf{q}$) is filled by random, uniformly distributed data symbols. The data are generated to acquire values according to QAM64 mapping pattern. Then the CP and SP sequence is mapped into data sequence. Now, it is possible to create a spectrum of the OFDM symbol using FFT approximation. The spectrum of the signal is created according to required sampling frequency. There will be an integer number of subcarriers (K) given by equation (26) to which the data sequence is mapped if the integer n MSps sampling frequency condition specified in section 4.2.1 is fulfilled. Mapping is performed by inserting every data symbol to the corresponding bin starting from the subcarrier k_0 given by equation (30). The rest of the subcarriers are set to zero. Now the signal in temporal domain is acquired by applying the IFFT on generated frequency coefficients, and finally, the guard interval is added.

At this moment the generated signal is ideally transmitted DVB-T signal by transmitters without any distortion. The effect of the channel needs to be added to the signal. This is performed using filtration with the Finite Impulse Response FIR filter. Firstly, the main peaks are added into the impulse response due to the position of the receiver. It is used simple propagation model assuming propagation time, a random number of the multipath of the signal propagating from each transmitter and signal attenuation caused by the Free-Space Loss (FSL) given by the equation

$$\mathrm{FSL} = \left(\frac{4\pi df}{c}\right)^2, \tag{53}$$

where d is the distance between transmitter and receiver, f is signal frequency, and c is the speed of light. To each signal beam random number of multipath beams is added. This number is generated using a uniformly distributed pseudorandom integer.

The maximal number of multipath beams can be specified in the generator. Now two vectors are generated. The first is a vector of delays ($\boldsymbol{\tau}$) which defines time in generated FIR of each signal beam. The main beams are a line of sight from each transmitter to receiver and to each of this beams the number of multipath beams is added with a normal distribution of their offsets. The vector of amplitudes ($\mathbf{A}$) is generated following evaluated FSL of each line of sight beam and amplitude of its multipath beams is a normally distributed value with mean equals to the magnitude of the corresponding line of sight beam. The impulse response is now generated using $\mathbf{A}$ as its values placed at the time given in $\boldsymbol{\tau}$. Others FIR coefficients are zero.

After performing filtration of the generated ideal DVB-T signal with the impulse response, the AWGN is added into the signal to achieve required value of the SNR. This process is repeated until the required number of OFDM symbols is obtained. The last step is to use this generated signal to evaluate the position of the receiver. The position is evaluated using the same approach as described in section 4.2.

The example of the generator functionality is shown in figures 22 and 23. The green points represent the positions used for generating a signal. The evaluated coordinates using DVB-T matched filter based receiver are demonstrated by the red points. The sampling rate used for generating distorted signal used in 22 for positioning was 10 Sps. The estimated standard deviation of the position is approximately $\sigma = 22$ m. Using the speed of light in standard atmosphere with an average value of atmospheric refractivity $N = 315$ [19], the distance step between two samples is approximately 29.97 m. In figure 23 is shown output of the simulator using sampling rate 100 Sps. For this sampling frequency, the distance step between samples is ten times lower, but the estimated standard deviation is approximately $\sigma = 6.14$ m. This effect is caused by the influence of the noise and geometry. The corresponding Cramer-Rao Lower Bound described in [20]:

$$\mathrm{var}\left(\hat{A}\right) \geq \sigma^2 \qquad \text{for all } A \tag{54}$$

means that it is not possible to built estimator of the parameter with lower variance than the variance of the parameter. This is essential for estimating the precision of the positioning and in [4] is shown how it is possible to assess Dilution of Precision DoP and its connection with noise properties. The study of the DoP in this channel and possible solution for increasing the precision using two channels can be found in [5].

Figure 22: Output of the simulator using sampling rate 10 MSps with $SNR = 40$ dB.

Figure 23: Output of the simulator using sampling rate 100 MSps with $SNR = 40$ dB.

6 Measurement Results

The measurements performed for the purpose of this work were designed to study expected phenomena which can have an influence on positioning using DVB-T signal. For the purpose of positioning it was necessary to perform measurement in different places with and without free line of sight to the transmitters to study accessibility of the system. For the study of the offset values in SFN, it was necessary to perform measurements on places with the best possible view without any obstacles in the line of sight to transmitters.

6.1 Measurement Methodology

The experimental setup used for measurements consists of Software Defined Radio SDR ETTUS USRP N210 providing dual 14 bit ADC with sampling frequency 100 MSps. This radio is shown in the picture 24a. The daughterboard UBX 10-6000 MHz Rx/Tx is used as a receiver in SDR. It is possible to connect it with the Matlab and directly download sampled data with specific center frequency and preprocessed by decimation. The minimal decimation factor is 4. Thus, the maximal possible signal bandwidth is 25 MHz. The antenna used for experiments is shown in figure 24b. It is a marine omnidirectional antenna intended for receiving a TV signal. To power receiver, the DC/AC converter connected to car battery was used. It was able to perform measurements on positions only near the car. Unfortunately, many optimal places were not accessible by car. For this reason, the mobile version was assembled. The 6 V/10Ah lead accumulator was used to supply SDR and Matlab was running under the battery powered notebook. Thanks to this the hardware become wearable in a backpack and was possible to reach optimal measuring positions.

(a) The SDR ETTUS USRP N210 used for experimental measurements.

(b) The omnidirectional antenna GLOMEX used for experimental measurements.

Figure 24: The experimental hardware equipment used for measurements.

The measurements were performed using decimation factor 10. Thus, the sampling frequency was 10 MSps. The volume of sampled data was 10 OFDM symbols. At first, the raw data were saved to the hard drive and then the signal was processed by the programmed receiver.

6.2 Measurement of the SFN Offsets

For the offset measurements in the SFN, it is necessary to ensure the best possible properties of the channel to suppress any possible extension of the signal propagation trajectory. The error can be caused by shading of the line of sight. It is possible that the stream from the shaded transmitter will not be detected or the refracted or reflected beam is detected. This is the reason why the choice of the receiver position is essential for the measurement of the offsets in SFN. The next possible problem could be receiving the power of the individual beams. The minimal decrease of the receiving the power depending on distance is given by equation (53). The minimal power decrease is -20 dB per decade of the distance. This can cause problems with detection because if the receiver is close to any of the transmitters, the signal power can be up to 40 dB stronger than signal power from the most distant transmitter. This can be critical because of the pilot signal properties. The standoff between correlation maximum and out–of correlation maximum is close to 40 dB, as is shown in figure 10. Actually, the standoff is usually up to 25 dB if payload data are present because data should be uncorrelated, random with zero mean. Thus the presence of the payload data will be reflected in the presence of the noise signal with high variance decreasing SNR. To study properties of the SFN timing were chosen two optimal measuring positions, assuming these restrictions. Two coordinates are minimum as is mentioned in section 4.3.2. For experiment, three positions were selected to confirm performed measurement.

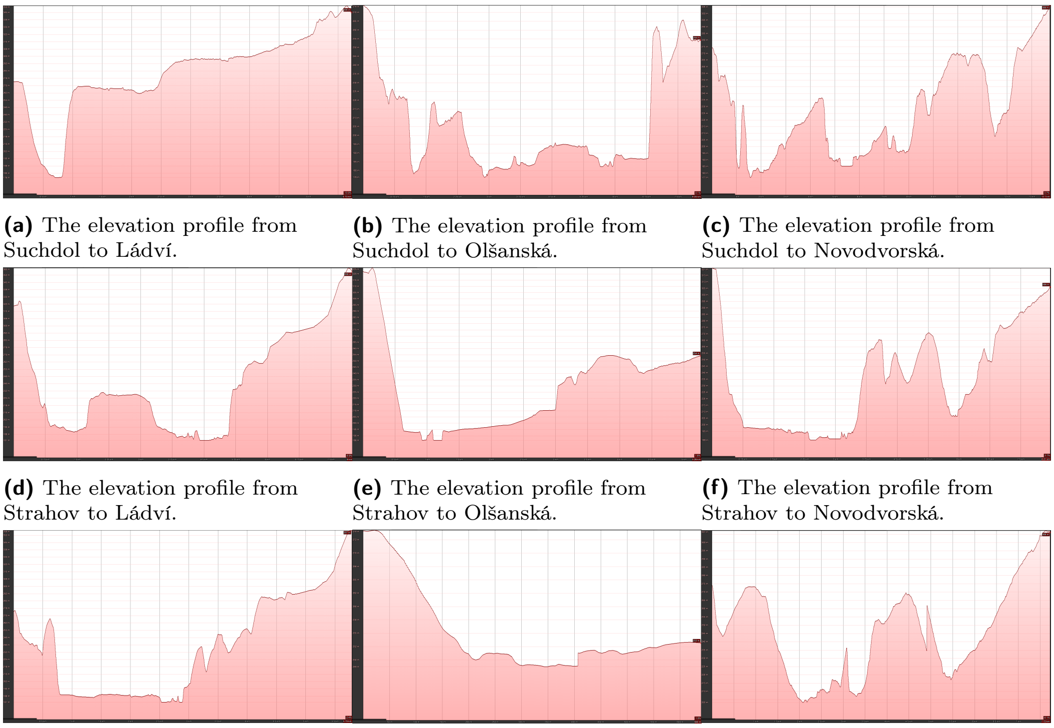
The date 20th of April was set for experimental measurement. It was sunny weather. The mobile version of the receiver was used. This version consists of a laptop with MatLab. SDR powered by 6V/10Ah lead accumulator and marine omnidirectional TV antenna. The DVB-T channel 42 with center frequency 642 MHz was received with sampling rate 10 MSps and 10 OFDM symbols were sampled.

The first measurement was performed in Praha-Suchdol on coordinates 50.1317° N, 14.3858° E. The residential district is eastwards and consists of two stage houses. Transmitters are located westwards where no nearby building causing refraction is located. The elevation profiles shown in figure 26 are generated using Google Earth. The transmitter antennas are located on high points as building (Olšanská, Novodvorská) or on antenna mast (Ládví). The free line of sight is secured on this position. The distances are 5.7 km to 13.7 km. Thus this point should be optimal with respect to the free line of sight and dynamics caused by FSL.

The second measurement took place on the Strahov college number 11 rooftop on coordinates 50.0804° N, 14.3956° E. According to the elevation profiles shown in figure 26 distances are in the range 5.2 km to 8.2 km, this point is even better than the first one to study the timing in SFN. The measurement was performed using the same parameters as described in the previous paragraph.

Finally, as the third position park Parukářka with coordinates 50.0851° N, 14.4602° E was picked. This post was selected because of its high altitude and unobstructed view as shown by elevation profiles. There is one major problem. The proximity of the transmitter Olšanská can cause problems with dynamics. The distance between this transmitter and measured position is more than 10 times lower than the distance between the most distant transmitter and receiver. Unfortunately, the most distant receiver broadcasts with the lowest power ($ERP_{\text{Novodvorská}} = 5$ kW). The signal received from the transmitter Novodvorská can be received with the power level up to 23 dB lower than the signal from the transmitter Olšanská ($ERP_{\text{Olšanská}} = 10$ kW) if we add effective radiated power into account along with the distance differences and the antennas directivity is the same. This received power is almost undetectable, because of the CA-CFAR setting. If the threshold is set lower, then the probability of false alarm increases above the reasonable level.

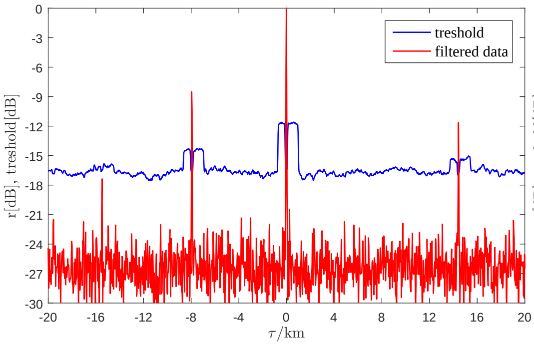
Figure 25: The transmitters of the DVB-T channel 42 and measuring points overview.



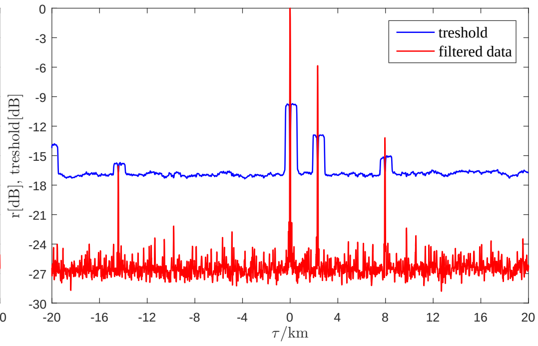
(a) The elevation profile from Suchdol to Ládví.
(b) The elevation profile from Suchdol to Olšanská.
(c) The elevation profile from Suchdol to Novodvorská.
(d) The elevation profile from Strahov to Ládví.
(e) The elevation profile from Strahov to Olšanská.
(f) The elevation profile from Strahov to Novodvorská.
(g) The elevation profile from Parukářka to Ládví.
(h) The elevation profile from Parukářka to Olšanská.
(i) The elevation profile from Parukářka to Novodvorská.

Figure 26: The elevation profiles from receiver placed on measuring points to the individual transmitters.

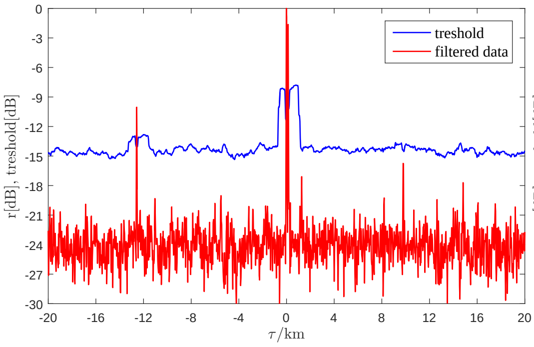
The data received on described positions were processed in MatLab using matched filter based receiver, and detection was made using CA-CFAR detecting algorithm with a noncoherent integrator. The output of the detector for the individual measured data is shown in figure 27. The simulator of the DVB-T positioning system, described in section 5, was used to generate an ideal output of the detector for comparison with the actually received data. Then the time offsets in SFN were estimated using implementation of the algorithm described in 4.3.2.



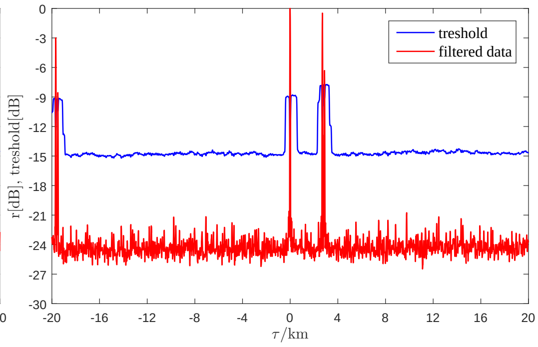
(a) The output of the CA-CFAR applied on data measured at Suchdol.



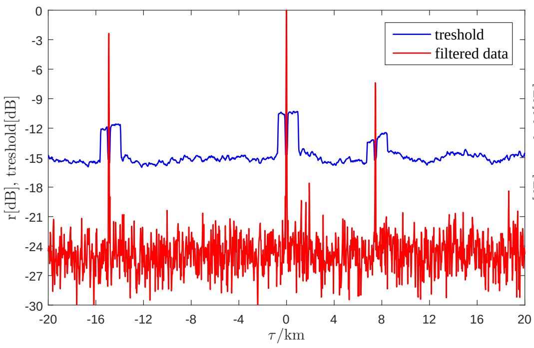
(b) The output of the CA-CFAR applied on simulated data measurement at Suchdol.



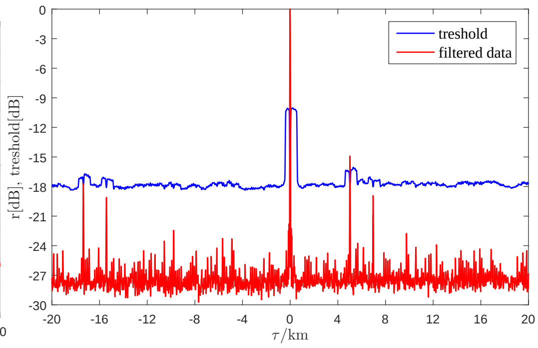
(c) The output of the CA-CFAR applied on data measured at Strahov.



(d) The output of the CA-CFAR applied on simulated data measurement at Strahov.



(e) The output of the CA-CFAR applied on data measured in the park Parukářka.



(f) The output of the CA-CFAR applied on simulated data
measurement in the park Parukářka.

Figure 27: Output of the CA-CFAR detection algorithm applied to measured data and comparison with the ideal output generated using the simulator.

Let us look at the figure 27a with the output of the detector after processing data received in Suchdol and its corresponding simulation in figure 27b. It is evident that the measurement does not correspond with the simulation. This was presumed according to initial experiments and it was the reason why the SFN offset estimation algorithm was created. In simulated data, the maximal detection located at $\tau = -0.006$ km corresponds to the received beam from Ládví. The detection from Olšanská follows at $\tau = 2.308$ km and finally the signal from Novodvorská at

$\tau = 7.954$ km arrives. One can notice the detection on $\tau = -14.427$ km. This is an alias of the Novodvorská. This can be recognized because the distance between the detection and its alias is exactly correlation length of the pilot sequence (22.378 km). On the other hand, in figure 27a is more problematic how to determine which of the detections is genuine and which corresponds to its alias. To do so, the obvious trick was used. The detection closer to maximal detection is used as true. The value at $\tau = -7.948$ km has alias at $\tau = 14.430$ km. True value was guessed using the smallest distance trick. Center detection at $\tau = -0.015$ km has aliases beyond the showed interval. The last value at $\tau = -15.485$ km lack explanation because it should have an alias at $\tau = 6.893$ km which is not visible in 27a. This could have happened because of some random effect. For example, the maximum could have fallen into the zero of the sampling function. The important thing is, following the presumed rule of thumb how to distinguish the true from aliases, that for SFN offset estimation the value $\tau = 6.893$ km should be used, even if it is not visible in the filtered data.

The simulation of the measurement at Strahov is shown in figure 27d. This position is approximately equally distant from all of the transmitters. Thus, no problem with the dynamics should appear as shown in the simulation. The first beam corresponds to the transmitter Olšanská. The second detection corresponds to Ládví, and finally, the last one is transmitter Novodvorská. If we look at real measurement in figure 27c it is again very different from simulation, but the interesting is that one similarity is present. The two proximate detections are at the $\tau = -0.003$ km and $\tau = 0.135$ km. This means that possible offset between the transmitters Ládví and Novodvorská could be minimal. If it is true the only offset in this SFN is added by transmitter Olašanská. The last detection at $\tau = -12.575$ km is further from the maximal detection than half of the pilot signal correlation length. The alias closer to the maximal detection is used even if it is not detected, utilizing the same trick as previously. However in this measurement is even possible to see this alias at $\tau = 9.800$ km, unlike in the previous measurement. This value is used for evaluation of the offsets.

The last simulation was performed with boosted power of the transmitter Novodvorská in simulator, to be even detectable. The power was boosted by 6 dB. This problem was predicted in the paragraph describing chosen places. The simulation output is shown by figure 27f. Again, the simulation differs from real measurement displayed in figure 27e, because of the transmitter time offsets. The highest detection in measured data is always shifted to center. By CA-CFAR algorithm it was detected at $\tau = -0.009$ km. The second largest detection is at $\tau = -14.913$ km, but again for the estimation of the time offsets in SFN is used alias closer to the maximal detection. This alias is detected at $\tau = 7.459$ km. The last detection which should correspond to signal propagated from transmitter Novodvorská was not automatically detected, but it is possible to guess that peak at $\tau = 1.909$ km. It may seem odd, that in measurement is this peak visible although it should have not according to simulation. This can be caused by the directivity of the individual transmitters antennas. The actual antennas radiation patterns are not known to the author. It is very likely that azimuthal directivity is not constant and it is possible, that directivity of the antenna on transmitter Novodvorská has higher gain in azimuth toward the receiver than Olšanská. This theory is supported by the fact that in simulation the Ládví signal level is 15.5 dB under Olšanská and in received data it is only 7.5 dB lower.

Now, when we have all necessary parameters τ, it is possible to apply SFN Time Offset Estimation algorithm from section 4.3.2 to evaluate the offsets. First, the coordinates in ellipsoidal coordinate system WGS84, places in table 1 are transformed into the position in the Cartesian ECEF frame. The next step is to evaluate individual distances between the transmitters and receivers, which is simple in the Cartesian coordinate system (it is the size of the difference vector). The distances can compose the matrix $\mathbf{t}$ and be used to generate the matrix $\mathbf{T}$ according to equation (43). The relative time of detections in table 2, obtained from measuring, are values of matrix $\boldsymbol{\tau}$, which is used to evaluate the matrix $\mathbf{D}$ using equation (42). Then $\mathbf{D}$ is expanded to the next dimension k containing all permutations of the transmitter order. And finally, the matrix $\mathbf{O}$ is evaluated using equation (47). In tables 3a, 3b and 3c values of the SFN time offsets are evaluated for all permutations of the transmitter reordering for measuring points Suchdol, Strahov, Parukářka, respectively. However, only one permutation gives correct offset values. The permutation present in all measurements contains the offset values as described in section 4.3.2. Values in the correct permutation are not exactly the same for all measurements, because of the measurement uncertainty. One permutation, which is the most similar with permutations in other measurements, is picked from matrix $\mathbf{O}$. The average of picked permutations is evaluated to increase the accuracy of the measured offsets. In the performed measurement the second line from every sub-matrix $\mathbf{O_n}$ was picked and the estimated relative offsets are 41.8775 μs, 0.0898 μs and 0 μs in order of transmitter Olšanská, Ládví and Novodvorská.

Table 1: The coordinates used for estimation of the transmitters time offset.

(a) The table of transmitter coordinates.

Name	Latitude°	Longitude°	Altitude [ma.s.l.]
Ládví	50.136422	14.465282	359
Olšanská	50.083529	14.469104	250
Novodvorská	50.016389	14.451111	305

(b) The table of receiver coordinates.

Name	Latitude°	Longitude°	Altitude [ma.s.l.]
Suchdol	50.13175	14.38581	275
Strahov	50.08048	14.39566	330
Parukářka	50.08510	14.46022	300

Table 2: The relative time of detections (τ_{no}) obtained from measured data.

Name (n)	τ_{n1} [m]	τ_{n2} [m]	τ_{n3} [m]
Suchdol (1)	-7947.91	-14.98	6892.76
Strahov (2)	-3.00	134.86	9800.03
Parukářka (3)	-8.99	1909.06	7459.41

Table 3: Values in μs of the offset sub-matrices $\mathbf{O_n}$ evaluated from measured data on defined positions.

(a) The sub-matrix $\mathbf{O}_1$ (Suchdol).

0	1.0440	42.3264
0	0.1240	41.8664
0	10.0764	33.2940
0	9.4924	32.1261
0	8.5724	31.6661
0	9.1564	32.8340

(b) The sub-matrix $\mathbf{O}_2$ (Strahov).

0	52.9787	68.3320
0	0.0387	41.8620
0	45.2828	76.0279
0	18.7741	23.0106
0	30.7064	34.1659
0	7.6572	57.2151

(c) The sub-matrix $\mathbf{O}_3$ (Parukářka).

0	12.9066	48.3040
0	0.1066	41.9040
0	29.7840	31.4266
0	18.4134	23.2774
0	10.4774	12.0134
0	16.9840	25.0266

6.3 Measurement of the Receiver Position

The estimated transmitter offsets in the measured DVB-T channel number 42 were used for correcting the detections obtained from experimental measurement in order to evaluate position using terrestrial TV broadcasting service. The method described in section 4.3 was used for positioning. The input of function $PosEval.m$ is a vector of detections, GPS coordinates of the last known position and vector of SFN offsets obtained in section 6.2. As a last known position was used known GPS coordinates of the measuring point from table 1b distorted with a random position error of standard deviation equal to 50 m. The positioning algorithm uses the last known position and SFN offsets for the cell identification necessary to suppress ambiguities caused by incorrectly assigned detection to corresponding transmitters. When the assignment is correctly performed, the offsets are added to the corresponding detections and position can be estimated using the iterative solver.

The positions obtained from the experimental measurement with offset correction applied are shown in the table 4. The first note is that altitude cannot be assumed because the algorithm is only in 2D mode, at least three independent time differences would be needed able evaluation of the correct height. The second note is that position at ČVUT FEL was not possible to evaluate due to dynamic of measurement the beam from transmitter Novodvorská was not detectable. The evaluated position from the measurement performed in Suchdol have the lowest error (7 m), the position on Strahov is 22 m from the actual position and in park Parukářka is this error 9 m. When the line of sight was shadowed the dynamic was insufficient, and the corresponding beam was not detectable. The example is measurement carried out on the roof of ČVUT FEL, where the signal from Novodvorská is shadowed by terrain.

Table 4: The evaluated position obtained from measured data using the time offset correction.

Name	Latitude°	Longitude°
Suchdol	50.13181	14.38584
Strahov	50.08033	14.39587
Parukářka	50.08508	14.46009
ČVUT FEL	-	-

7 Conclusion

The aim of this work was to discuss the Signals of Opportunity (SoO) shortly and to target mainly on the system used for TV broadcast, Digital Video Broadcasting-Terrestrial (DVB-T). For this reason, the Global System for Mobile Communications (GSM) was shortly described, and the signal Positioning Reference Signal was mentioned as one of the possibility how to utilize the GSM signal for positioning. Another possibility can be receiver based on filtration matched to synchronization signals Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS). This can lead to the similar architecture of the receiver like the one designed for DVB-T as described in this work.

The second system marked as SoO is the subject of this thesis and it is DVB-T. This system was described in more detail in section 3.2.1, because for simulations and experiments it was necessary to replicate its signal structure. Its wideband modulation and synchronous operation of the system called SFN predetermines it to be used for positioning via Time Difference of Arrival TDoA method.

The Channel Impulse Response Based Receiver described in section 4.1 was designed. This method suffers the same problems as the previous design used in previous research in [10]. The biggest issue was the receiver complexity and high hardware requirements. This architecture was further simplified in order to omit all unnecessary algorithms delaying position evaluation and enabling to create an implementable system with commonly available hardware. The first step was to omit payload data from computations using only pilot signals contained in DVB-T stream enabling to significantly reduce the number of mathematical operations without influence on distance resolution. This leads only to shortening the correlation length of the signal with the pilot sequence, as was described in section 4.1.4 and shown in figure 9. The next improvement reducing the computation complexity is a possibility to skip calculation of the radio channel model along the frequency axis. This was possible thanks to low transmitter carrier frequency and constrained velocity. In section 4.1.4 was shown, that Doppler effect causes maximal attenuation of the detection lower than 0.06 dB if the receiver velocity is lower than 130 km/h and can be neglected.

Further simplifications lead to changing the receiver type to the Matched Filter Based Receiver described in section 4.2. This type allows to omit necessity of finding the beginning of OFDM symbol, even allows to work if the guard interval duration is not known, but this would need several adjustments to be able to perform averaging over more OFDM symbols. Another advantage of matched filtration is a possibility to use general ADC with integer MSps sampling rate as described in section 4.2.1. The impulse response of the matched filter is generated with respect to the sampling rate, and it is also filtered in order to suppress the excessive side lobes in the temporal domain. Details of the mismatched filter are described in section 4.2.2.

According to basic of detection theory, outlined in section 4.3.1, the optimal type of detector based on correlative properties was applied. The detection algorithm is using non-coherent averaging. This causes processing loss, but because it is not realizable phase synchronization of all beams propagated from the individual transmitters simultaneously the coherent integration is not possible. The size of loss depending on the type of integrator can be found in [14].

The positioning and the influence of the phenomena occurring in the radio channel were simulated using the DVB-T Positioning System Simulator described in section 5. It can be used to simulate measurement in numerous points defined in Google Earth .kml file. It was used to optimize coefficients used in CA-CFAR detector, to confirm precision constraints given by signal structure, sampling rate and Dilution of Precision (DoP). The study of wrong cell identification provided an optimal solution how to suppress this ambiguity using information about the last known position rather than using the difference of position given by IMU.

The experimental measurements showed that the individual transmitters in DVB-T channel 42 work synchronously, but there is a nonzero time offset in this SFN network. The algorithm providing the offset values is described in section 4.3.2. The experimental measurement was performed to estimate them. For this reason, the optimal positions were picked. The requirement was to ensure line of sight to all transmitters at the same time and perform measurement at least at two posts. For this reason, the locations at Suchdol, Strahov, and Parukářka were chosen, and measurement was conducted. After processing of the measured data, the offsets were calculated. It was estimated that transmitters Olšanská and Ládví are delayed 41.8775 μs and 0.0898 μs against the transmitter Novodvorská.

The TDoA positioning method is outlined in section 2.2, but the implementation of the iterative algorithm is described in section 4.3.4. This approach was presented in [5]. The cell identification algorithm based on last known position and SFN offset cancellation was added into position evaluation algorithm.

And finally, the position of the measuring points was evaluated. The error of estimated positions confirms simulations performed with the DVB-T Positioning System Simulator. Specifically, the error was 7 m for the measurement conducted in Suchdol, 22 m on Strahov and finally 9 m in park Parukářka. The measurement carried out on the ČVUT FEL roof failed because of insufficient strength of the signal from transmitter Novodvorská.

In this work, DVB-T signal was successfully received with designed experimental hardware and used as SoO to evaluate the position of the receiver. The performed simulations and measurements show that this system is relatively fragile and its functionality depends highly on balance between the received power from the individual transmitters. Even using averaging, this system provides only approximately 24 dB power range where all received beams must lie. The possible solution for this problem can be filtering payload data from received signal before next processing. This would increase computation complexity but theoretically, can improve power range up to 40 dB as can be shown from the autocorrelation function shown in figure 10. It is autocorrelation of the pilot replica, which is the same as DVB-T signal without payload data. The restriction is given by correlation properties of the Pseudo-Random Binary Sequence (PRBS) which is used for pilot signal modulation.

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Attachments

```
% positioning system using DVB-T signal received via Software Defined Radio
% author: Rostislav Karasek
close all; clear all;
Fc=642e6; %Fc=674e6;
DecimFact=10;
OFDMNum=10;
FileName='CH42';
%FileName='CH46';
LKPos=[50.129545 14.381039 318.16];
DecimFact=round(DecimFact);
if DecimFact<4
    DecimFact=4;
    display('Minimal DecimFact is 4.');
end
OFDMNum=round(OFDMNum);
if OFDMNum<6
    OFDMNum=6;
    display('Minimal OFDMNum is 6.');
end
 % DVB-T signal parameters
DVB.Fsa = 100e6/DecimFact;  % Sampling frequency of the received signal
DVB.prn=PRBSgenerator;      % pseudo random noise used for pilot modulation
DVB.Tsym=896e-6;            % duration of OFDM symbol [s]
DVB.DatNos=6817;            % number of nonzero carriers in 8k mod
DVB.Carrier=8192;           % number of carriers in 8k mod
DVB.BWsym=1/DVB.Tsym;       % carrier spacing
DVB.delMax = 1/4;           % maximal size of the guard interval in DVB-T
DVB.delMin = 1/32;          % minimal size of the guard interval in DVB-T
DVB.K=DVB.Fsa*DVB.Tsym;     % number of sampled carriers
DVB.k0=DVB.K/2-6816/2+1;    % first data subcarrier
DVB.nATM=1+325e-6;          % refractivity index of air near surface
DVB.c=1/sqrt(8.8541878176e-12*4*pi*1e-7)/DVB.nATM; % Speed of light
DVB.DistStep=DVB.c/DVB.Fsa; % length correspondig one sample period [m]
                            % coefficients of the CP subcarriers
DVB.CP=[0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 ...
    636 714 759 765 780 804 873 888 918 939 942 969 984 1050 1101 1107  ...
    1110 1137 1140 1146 1206 1269 1323 1377 1491 1683 1704 1752 1758    ...
    1791 1845 1860 1896 1905 1959 1983 1986 2037 2136 2154 2187 2229    ...
    2235 2322 2340 2418 2463 2469 2484 2508 2577 2592 2622 2643 2646    ...
    2673 2688 2754 2805 2811 2814 2841 2844 2850 2910 2973 3027 3081    ...
    3195 3387 3408 3456 3462 3495 3549 3564 3600 3609 3663 3687 3690    ...
    3741 3840 3858 3891 3933 3939 4026 4044 4122 4167 4173 4188 4212    ...
    4281 4296 4326 4347 4350 4377 4392 4458 4509 4515 4518 4545 4548    ...
    4554 4614 4677 4731 4785 4899 5091 5112 5160 5166 5199 5253 5268    ...
    5304 5313 5367 5391 5394 5445 5544 5562 5595 5637 5643 5730 5748    ...
    5826 5871 5877 5892 5916 5985 6000 6030 6051 6054 6081 6096 6162    ...
    6213 6219 6222 6249 6252 6258 6318 6381 6435 6489 6603 6795 6816];
                            % coefficients of the TPS subcarriers
DVB.TPS=[34 50 209 346 413 569 595 688 790 901 1073 1219 1262 1286 1469 ...
    1594 1687 1738 1754 1913 2050 2117 2273 2299 2392 2494 2605 2777    ...
    2923 2966 2990 3173 3298 3391 3442 3458 3617 3754 3821 3977 4003    ...
    4096 4198 4309 4481 4627 4670 4694 4877 5002 5095 5146 5162 5321    ...
    5458 5525 5681 5707 5800 5902 6013 6185 6331 6374 6398 6581 6706 6799];
% If we have A priori information aboute Tx delays use TxOff
TxOff=[41.8775 0.0898 0]*1e-6*DVB.c; % TxOff=[Olšanská Ládví Novodvorská];
PilotSignal = GeneratePilotReplica(DVB.K);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
MeasNum=1;
while (MeasNum<240) % Number of mesurements
% Sa...number of samples (n*8192 samples)
```

```
Sa=ceil((OFDMNum*(1+DVB.delMax)*DVB.Tsym*DVB.Fsa)/8192)*8192;
Time=clock;
SFileName=['Data\',num2str(Time(1)),'_',num2str(Time(2)),'_',...
            num2str(Time(3)),'_',num2str(Time(4)),'_',num2str(Time(5)),...
            '_',num2str(Time(6)),'_',FileName,'_',num2str(MeasNum),'.mat'];
RxData = Rx(Fc,DecimFact,Sa);
save(SFileName,'RxData');
RxData=ifft(fftshift(fft(RxData)));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% finding the guard interval duration, time and frequency offset
DVB.del = EstTdel(RxData(1:(DVB.K*(1+2/4)*2)),DVB);
DVB.Tdel=(DVB.del)*DVB.Tsym;       % duration of guard interval \Delta [s]
DVB.Nd=int64(DVB.Tdel*DVB.Fsa);    % number of samples of the CP
DVB.Nu=int64(DVB.Tsym*DVB.Fsa);    % number of samples of the OFDM symbol
Rm=zeros(1,DVB.Nu+DVB.Nd);
    m=0;
while m<DVB.Nu+DVB.Nd              % Searched time interval
Rm(m+1)=Rm(m+1)+sum(RxData(m+1:DVB.Nd+m)...
             .*conj(RxData(DVB.Nu+1+m:DVB.Nd+m+DVB.Nu)));
m=m+1;
end
[MaxRm, maxRm]=max(Rm);
Toff=maxRm+2;                                          % time offset
Foff=angle(Rm(maxRm))*DVB.Fsa/(2*pi*double(DVB.Nu)); % frequency offset Hz
RxData=RxData(Toff:length(RxData));
RxData=RxData.*(exp(1j*2*pi*(0:1:length(RxData)-1)/DVB.Fsa*Foff));
GShft=-64;
RxData=RxData(DVB.Nd-GShft:length(RxData));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Finding delayed DVB-T signals corresponding to transmitters
InterpFact=10;
   WinL = 10*ceil(DVB.K/DVB.Carrier)*InterpFact;
   WinR = 15*ceil(DVB.K/DVB.Carrier)*InterpFact;
   SaveC = 2*ceil(DVB.K/DVB.Carrier)*InterpFact;
   ThreshMul=3;
ComprimeIn=(filter(conj(fliplr(PilotSignal)),1,RxData));
ComprimeOut=zeros(1,(DVB.Nu+DVB.Nd));
for i=1:OFDMNum-3
ComprimeOut=ComprimeOut...
           +abs(ComprimeIn(i*(DVB.Nu+DVB.Nd)+1:(i+1)*(DVB.Nu+DVB.Nd)));
end
MaxDiff=24e3; % maximal possible distance difference in [m]
              % maximal distance between the most distant transmitters
WIN=floor(MaxDiff/2/DVB.DistStep);
[~, CenterWIN]=max(ComprimeOut);
ComprimeOut=circshift(ComprimeOut,[0,(length(ComprimeOut)/2-CenterWIN)]);
DataOut=interp(ComprimeOut(length(ComprimeOut)/2-WIN...
        :length(ComprimeOut)/2+WIN)/max(ComprimeOut),InterpFact);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    figure
    [DetMax, argDetMax]  = CA_CFAR(DataOut,WinL,WinR,SaveC,ThreshMul,...
                               DVB.DistStep/InterpFact);
% sort by value of maxim (big to small) by bubble sort
    [DetMax,argDetMax] = BublSort(DetMax,argDetMax,1);
% sort by distant to receiver (small to big) by bubble sort
    [argDetMax,DetMax] = BublSort(argDetMax,DetMax,-1);
     if length(DetMax)>2
    DetMax = DetMax(1:3);
    argDetMax = argDetMax(1:3);
[EstLLH, ~] = PosEval(argDetMax,LKPos,TxOff);
```

```
formatSpec = 'Position is: %2.9f°N %2.9f°E %2.9fmnm\n';
fprintf(formatSpec,EstLLH)
PathLonO(MeasNum) = EstLLH(2);
PathLatO(MeasNum) = EstLLH(1);
PathAltO(MeasNum) = EstLLH(3);
     else
PathLonO(MeasNum) = 0;
PathLatO(MeasNum) = 0;
PathAltO(MeasNum) = 0;
    display('Insufficient number of visible transmitters')
     end
display(MeasNum);
MeasNum=MeasNum+1;
pause(6*60);
end
OutputPos = ge_point(PathLonO, PathLatO, PathAltO);
ge_output('GenPaths\OutputPos.kml',OutputPos);
```

```
% positioning system using DVB-T signal sampled and saved in file
% author: Rostislav Karasek
close all; clear all;
Fc=642e6;
DecimFact=10;
OFDMNum=10;
FileName='CH42';
LKPos=[50.084740, 14.458877 200];
DecimFact=round(DecimFact);
if DecimFact<4
    DecimFact=4;
    display('Minimal DecimFact is 4.');
end
OFDMNum=round(OFDMNum);
if OFDMNum<6
    OFDMNum=6;
    display('Minimal OFDMNum is 6.');
end
 % DVB-T signal parameters
DVB.Fsa = 100e6/DecimFact;  % Sampling frequency of the received signal
DVB.prn=PRBSgenerator;      % pseudo random noise used for pilot modulation
DVB.Tsym=896e-6;            % duration of OFDM symbol [s]
DVB.DatNos=6817;            % number of nonzero carriers in 8k mod
DVB.Carrier=8192;           % number of carriers in 8k mod
DVB.BWsym=1/DVB.Tsym;       % carrier spacing
DVB.delMax = 1/4;           % maximal size of the guard interval in DVB-T
DVB.delMin = 1/32;          % minimal size of the guard interval in DVB-T
DVB.K=DVB.Fsa*DVB.Tsym;     % number of sampled carriers
DVB.k0=DVB.K/2-6816/2+1;    % first data subcarrier
DVB.nATM=1+325e-6;          % refractivity index of air near surface
DVB.c=1/sqrt(8.8541878176e-12*4*pi*1e-7)/DVB.nATM; % Speed of light
DVB.DistStep=DVB.c/DVB.Fsa; % length correspondig one sample period [m]
                            % coefficients of the CP subcarriers
DVB.CP=[0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 ...
    636 714 759 765 780 804 873 888 918 939 942 969 984 1050 1101 1107  ...
    1110 1137 1140 1146 1206 1269 1323 1377 1491 1683 1704 1752 1758    ...
    1791 1845 1860 1896 1905 1959 1983 1986 2037 2136 2154 2187 2229    ...
    2235 2322 2340 2418 2463 2469 2484 2508 2577 2592 2622 2643 2646    ...
    2673 2688 2754 2805 2811 2814 2841 2844 2850 2910 2973 3027 3081    ...
    3195 3387 3408 3456 3462 3495 3549 3564 3600 3609 3663 3687 3690    ...
    3741 3840 3858 3891 3933 3939 4026 4044 4122 4167 4173 4188 4212    ...
    4281 4296 4326 4347 4350 4377 4392 4458 4509 4515 4518 4545 4548    ...
    4554 4614 4677 4731 4785 4899 5091 5112 5160 5166 5199 5253 5268    ...
    5304 5313 5367 5391 5394 5445 5544 5562 5595 5637 5643 5730 5748    ...
    5826 5871 5877 5892 5916 5985 6000 6030 6051 6054 6081 6096 6162    ...
    6213 6219 6222 6249 6252 6258 6318 6381 6435 6489 6603 6795 6816];
                            % coefficients of the TPS subcarriers
DVB.TPS=[34 50 209 346 413 569 595 688 790 901 1073 1219 1262 1286 1469 ...
    1594 1687 1738 1754 1913 2050 2117 2273 2299 2392 2494 2605 2777    ...
    2923 2966 2990 3173 3298 3391 3442 3458 3617 3754 3821 3977 4003    ...
    4096 4198 4309 4481 4627 4670 4694 4877 5002 5095 5146 5162 5321    ...
    5458 5525 5681 5707 5800 5902 6013 6185 6331 6374 6398 6581 6706 6799];
% If we have A priori information aboute Tx delays use TxOff
TxOff=[41.8775 0.0898 0]*1e-6*DVB.c; % TxOff=[Olšanská Ládví Novodvorská];
PilotSignal = GeneratePilotReplica(DVB.K);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
uiopen(); % open .m file with saved RxData signal
RxData=ifft(fftshift(fft(RxData)));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% finding the guard interval duration, time and frequency offset
```

```
DVB.del = EstTdel(RxData(1:(DVB.K*(1+2/4)*2)),DVB);
DVB.Tdel=(DVB.del)*DVB.Tsym;        % duration of guard interval \Delta [s]
DVB.Nd=int64(DVB.Tdel*DVB.Fsa);     % number of samples of the CP
DVB.Nu=int64(DVB.Tsym*DVB.Fsa);     % number of samples of the OFDM symbol
Rm=zeros(1,DVB.Nu+DVB.Nd);
    m=0;
while m<DVB.Nu+DVB.Nd               % Searched time interval
Rm(m+1)=Rm(m+1)+sum(RxData(m+1:DVB.Nd+m)...
             .*conj(RxData(DVB.Nu+1+m:DVB.Nd+m+DVB.Nu)));
m=m+1;
end
[MaxRm, maxRm]=max(Rm);
Toff=maxRm+2;                                          % time offset
Foff=angle(Rm(maxRm))*DVB.Fsa/(2*pi*double(DVB.Nu)); % frequency offset Hz
RxData=RxData(Toff:length(RxData));
RxData=RxData.*(exp(1j*2*pi*(0:1:length(RxData)-1)/DVB.Fsa*Foff));
GShft=-64;
RxData=RxData(DVB.Nd-GShft:length(RxData));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Finding delayed DVB-T signals corresponding to transmitters
InterpFact=10;
   WinL = 10*ceil(DVB.K/DVB.Carrier)*InterpFact;
   WinR = 15*ceil(DVB.K/DVB.Carrier)*InterpFact;
   SaveC = 2*ceil(DVB.K/DVB.Carrier)*InterpFact;
   ThreshMul=2;
ComprimeIn=(filter(conj(fliplr(PilotSignal)),1,RxData));
ComprimeOut=zeros(1,(DVB.Nu+DVB.Nd));
for i=1:OFDMNum-3
ComprimeOut=ComprimeOut...
           +abs(ComprimeIn(i*(DVB.Nu+DVB.Nd)+1:(i+1)*(DVB.Nu+DVB.Nd)));
end
MaxDiff=24e3; % maximal possible distance difference in [m]
              % maximal distance between the most distant transmitters
WIN=floor(MaxDiff/2/DVB.DistStep);
[~, CenterWIN]=max(ComprimeOut);
ComprimeOut=circshift(ComprimeOut,[0,(length(ComprimeOut)/2-CenterWIN)]);
DataOut=interp(ComprimeOut(length(ComprimeOut)/2-WIN...
        :length(ComprimeOut)/2+WIN)/max(ComprimeOut),InterpFact);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    figure
    [DetMax, argDetMax]  = CA_CFAR(DataOut,WinL,WinR,SaveC,ThreshMul,...
                               DVB.DistStep/InterpFact);
% sort by value of maxim (big to small) by bubble sort
    [DetMax,argDetMax] = BublSort(DetMax,argDetMax,1);
     if length(DetMax)>2
    DetMax = DetMax(1:3);
    argDetMax = argDetMax(1:3);
% sort by distant to receiver (small to big) by bubble sort
    [argDetMax,~] = BublSort(argDetMax,DetMax,-1);
argDetMax = DVB.DistStep/InterpFact*(argDetMax);
[EstLLH, ~] = PosEval(argDetMax,LKPos,TxOff);
formatSpec = 'Position is: %2.9f°N %2.9f°E %2.9fmnm\n';
fprintf(formatSpec,EstLLH)
PathLonO = EstLLH(2);
PathLatO = EstLLH(1);
PathAltO = EstLLH(3);
     else
    display('Insufficient number of visible transmitters')
     end
```

```
% estimation of the guard interval duration
% author: Rostislav Karasek
function del = EstTdel(sigt,DVB)
Nu=DVB.K; Nd=DVB.K/4;
Rml=((Nu+2*Nd));
sigconj=conj(sigt);
Rm=zeros(1,Rml); m=0;
    while m<Rml
      Rm(int64(m+1))=abs(sum(sigt(1+m:int64(1+Nd+m))...
                   .*sigconj(Nu+1+m:int64(1+Nd+m+Nu))));
       m=m+1;
    end
    [N,D] =rat(DVB.K/8192);
RmN=resample(Rm/max(Rm),D,N);
h(1:8192/32)=32/8192; % impulse response for LPF with minimal possible Nd
diffRm=filter(h,1,diff(RmN));
% maximal value corresponds to the guard interval duration
maxRm=max(diffRm);
if maxRm>1/4096 && maxRm<3/4096
    del=1/4;
end
if maxRm>3/4096 && maxRm<6/4096
    del=1/8;
end
if maxRm>6/4096 && maxRm<10/4096
    del=1/16;
end
if maxRm>10/4096 && maxRm<22/4096
    del=1/32;
end
end
```

```
% pilot signal generator
% frequency coefficience weighted with Taylor window to supress sidelobes
% Author: Rostislav Karasek
function PilotSig = GeneratePilotReplica(K)
% RxGPS.... GPS coordinates of the receiver
% TxDel.... Delays of individual transmitters
% OFDMNum.. Number of the generated OFDM symbols
% MPnum.... Maximal number of MultiPaths
prn=PRBSgenerator;
k0=K/2-6816/2+1;
kMax=k0+6816;   % last nonzero subcarrier
CP=[0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 ...
    636 714 759 765 780 804 873 888 918 939 942 969 984 1050 1101 1107 ...
    1110 1137 1140 1146 1206 1269 1323 1377 1491 1683 1704 1752 1758   ...
    1791 1845 1860 1896 1905 1959 1983 1986 2037 2136 2154 2187 2229   ...
    2235 2322 2340 2418 2463 2469 2484 2508 2577 2592 2622 2643 2646   ...
    2673 2688 2754 2805 2811 2814 2841 2844 2850 2910 2973 3027 3081   ...
    3195 3387 3408 3456 3462 3495 3549 3564 3600 3609 3663 3687 3690   ...
    3741 3840 3858 3891 3933 3939 4026 4044 4122 4167 4173 4188 4212   ...
    4281 4296 4326 4347 4350 4377 4392 4458 4509 4515 4518 4545 4548   ...
    4554 4614 4677 4731 4785 4899 5091 5112 5160 5166 5199 5253 5268   ...
    5304 5313 5367 5391 5394 5445 5544 5562 5595 5637 5643 5730 5748   ...
    5826 5871 5877 5892 5916 5985 6000 6030 6051 6054 6081 6096 6162   ...
    6213 6219 6222 6249 6252 6258 6318 6381 6435 6489 6603 6795 6816];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% generate pilot signal with SP and CP sequence
S=zeros(1,K);
Win=taylorwin(6817,2,-23).';
S(k0:3:kMax)=prn(1:3:end)*sqrt(42)*4/3.*Win(1:3:end); % add SP
S(CP+k0)=prn(CP+1)*sqrt(42)*4/3.*Win(CP+1); % add SP
PilotSig=ifft(S);
end
```

```
% adaptive detection algorithm CA-CFAR
% author: Karásek Rostislav
% WinL ... length of left window
% WinL ... length of right window
% saveC ... number of save cells (odd number)
% TresMul ... treshold level multiplying constant
% DistStep ... distance between two data sequence samples in meters
function [DetMax, argDetMax] = CA_CFAR(data,WinL,WinR,saveC,ThresMul,DistStep)
if mod(saveC,2)==0
    saveC=saveC+1;
end
h(1:WinL+WinR+saveC)=1/(WinL+WinR); h(WinL+1:WinL+saveC)=0;
Threshold=filter(h,1,data)*ThresMul;
Threshold=circshift(Threshold(length(h)+1:end),[0,-(WinL+(saveC-1)/2)]);
data=data(length(h)+1:end);
Actual=0; Previous=0; MaxNum=1; Begin=0; End=0;
for m=1:length(Threshold)  % finding maximal values of detections:
   if Threshold(m)<data(m) % actual point of data bigger than treshold?
       Actual=1;
   else                    % previous point of data bigger than treshold
       Actual=0;
   end
   if Actual>Previous        % begin of detection?
      Begin = m;
   elseif  Actual<Previous   % end of detection?
       End = m;
   end
   if End>0
       DataWin=zeros(1,length(data));
       DataWin(Begin:End)=data(Begin:End);
      [DetMax(MaxNum), argDetMax(MaxNum)] = max(DataWin);
      MaxNum=MaxNum+1; End=0;
   end
   Previous=Actual;
end
xaxe=(-(length(Threshold)/2-length(h)/2):...
       length(Threshold)/2-1+length(h)/2)*DistStep/1000;
  set(gcf,'PaperUnits','centimeters','PaperPosition',[0,0,17,10])
  set(gca,'FontSize',12,'FontName','Times New Roman')
  plot(xaxe,10*log10(Threshold.^2),'b',...
       xaxe,10*log10(data.^2),'r','LineWidth',1)
  Xlab=xlabel('$\tau / \mathrm{km} $','Interpreter','latex');
  Ylab=ylabel('r[dB], treshold[dB]','Interpreter','latex');
  h_legend=legend('treshold','filtered data');
  set(h_legend,'FontSize',12,'FontName','Times New Roman');
  set(Xlab,'FontSize',12,'FontName','Times New Roman');
  set(Ylab,'FontSize',12,'FontName','Times New Roman');
  set(gca,'YLim',[-30 0],'YTick',(-30:3:0));
  set(gca,'XLim',[-20 20],'XTick',(-20:4:20)); drawnow;
end
```

```
% function for possition estimation in DVB-T channel 42
% authors: Rostislav Karasek & Vaclav Navratil
function [EstLLH, H] = PosEval(argDetMax,LKPos,TxOff)
if nargin == 2;
    TxOff = [0 0 0];
end
o=[50.083529 14.469104 250]; % coordinates of the transmitter Olšanská
l=[50.136422 14.465282 359]; % coordinates of the transmitter Ládví
n=[50.016389 14.451111 305]; % coordinates of the transmitter Novodvorská
TxO=[1 2 3]; % Order of transmitters: [Olšanská Ládví Novodvorská]
radv = [pi/180 pi/180 1];
% 'k' - ECEF Cartesian coordinate system
ok=wgs842xyz(o.*radv);
lk=wgs842xyz(l.*radv);
nk=wgs842xyz(n.*radv);
% finding the right order of transmitters-> Cell Identification
LKPosk=wgs842xyz(LKPos.*radv);
TxDist = [sqrt((ok-LKPosk)*(ok-LKPosk)') ...
          sqrt((lk-LKPosk)*(lk-LKPosk)') ...
          sqrt((nk-LKPosk)*(nk-LKPosk)')]+TxOff;
% sort by distance (small to big) and the same way rearrange TxO
[TxDist,TxO] = BublSort(TxDist,TxO,-1);
% sort by TxO (small to big) and the same way rearrange argDetMax
[TxO,argDetMax] = BublSort(TxO,argDetMax,-1);
% detections now reordered: argDetMax=[Olšanská Ládví Novodvorská]
argDetMax=argDetMax-TxOff;
midxyz=(ok+nk+lk)./3;
midwgs=xyz2wgs84(midxyz,1e-3);
midwgs(3)=0;
midxyz=wgs842xyz(midwgs); % Shiftet to the surface of the wgs84
% 'f' - East North Up coordinate system with zero in midxyz
nr=(nk)';
or=(ok)';
lr=(lk)';
nf =  xyz2enu(nr, midxyz, 1e-6);
of =  xyz2enu(or, midxyz, 1e-6);
lf =  xyz2enu(lr, midxyz, 1e-6);
% diference = first - second
% diff_num = [Olšanská-Ládví;Olšanská-Novodvorská;Ládví-Novodvorská];
  DiffNum = [1,2;1,3;2,3]; % DiffNum = [1,2;1,3];
  BasePos = [of(1:2)';lf(1:2)';nf(1:2)'];
  DiffVal = [argDetMax(1)-argDetMax(2) ;...
             argDetMax(1)-argDetMax(3) ;...
             argDetMax(2)-argDetMax(3)];
  InitPos = [-5 -10] ;
% position estimation using Newton-Raphson iterative solver
[EstPos, PCorrNorm, G, Iters] = ...
    NewtonRaphson(DiffNum, BasePos, DiffVal, InitPos(1:2), .1);
 EstECEF = enu2xyz([EstPos(1,1:2),0]',midxyz,1e-6);
 EstLLH = xyz2wgs84(EstECEF,1e-3)./radv;
 H=inv(G'*G);
end
```

```
% Newton-Raphson PVT method
% authors: Vaclav Navratil & Rostislav Karasek
% Inputs
%   sat_num - vector of satellite numbers
%   sat_pos - matrix ov satellite positions (XYZ-coordinates as row)
%   prange - pseudorange measurements to according satellites
%   init_pos - search initial position (row vector)
%   tol - minimal iteration size
% Outputs
%   est_pos - estimated position (row vector)
%   pcorr_norm - norm of last iteration correction
%   G - geometry matrix
%   iters - iteration log
function [est_pos, pcorr_norm, G, iters] = ...
    NewtonRaphson(diff_num, base_pos, diff_val, init_pos, tol)
% editted for TDoA positioning method
% iteration pos alloc
iters = zeros (100,3);
% change norm variable and iteration counter allocation
pcorr_norm = inf; cntr = 0;
ndiff = size(diff_num,1); % diff count
nbase = size(base_pos,1);
% TDOA differrence alloc
d_diff = zeros(ndiff,1);
% stretching matrix
est_pos = repmat(init_pos,nbase,1);
% Line-of-Sight Vector Alloc
los_uvect = zeros(size(base_pos));
% DIFFERENCED Line-of-Sight Vector Alloc
dlos_uvect = zeros(ndiff,2);
while (pcorr_norm>tol && cntr < 20);
    % LOS unit vector estimation
    % LOS non-unit vect
    los_uvect = (est_pos(:,1:2)-base_pos);
    for i = 1:nbase ;
        % LOS vector norm
        los_norm(i,1) = norm(los_uvect(i,:));
        % LOS unit vector (direction vector)
        los_uvect(i,:) = los_uvect(i,:)./los_norm(i,1);
    end;
    for i=1:ndiff
        % PseudoRange differrence: measured PR - geometryestimated PR
        d_diff(i) = diff_val(i)- ...
                    (los_norm(diff_num(i,1))-los_norm(diff_num(i,2)));
        %unit vector difference
        dlos_uvect(i,:) =   los_uvect(diff_num(i,1),:) - ...
                            los_uvect(diff_num(i,2),:);
    end
    % Geometry matrix
    G = [dlos_uvect];
    est_corr = (G'*G)\G'*d_diff;
    pcorr_norm = norm(est_corr(1:2));
    est_corr = repmat((est_corr)',length(base_pos),1);
    est_pos = est_pos+est_corr;
    cntr=cntr+1;
    iters(cntr,:) = [est_pos(1,:) pcorr_norm];
end;
iters = iters(1:cntr,:);
```

```
% simulator of the positioning using DVB-T chnnel 42 in Prague.
% author: Rostislav Karasek
% program reads path from the Google Earth .kml
% DVB-T distorted according possitions from the .kml file
% works with arbitrary oversampled signal, Fsa = n*1MHz || Fsa > 9 MHz
clear all; close all;
OFDMNum = 10;
% DVB-T signal parameters
DVB.Fsa = 25e6;            % Sampling frequency in whole MHz > 9 MHz
DVB.prn=PRBSgenerator;     % pseudo random noise used for pilot modulation
DVB.Tsym=896e-6;           % duration of OFDM symbol [s]
DVB.DatNos=6817;           % number of nonzero carriers in 8k mod
DVB.Carrier=8192;          % number of carriers in 8k mod
DVB.BWsym=1/DVB.Tsym;      % carrier spacing
DVB.delMax = 1/4;          % maximal size of the guard interval in DVB-T
DVB.delMin = 1/32;         % minimal size of the guard interval in DVB-T
DVB.K=DVB.Fsa*DVB.Tsym;    % number of sampled carriers
DVB.k0=DVB.K/2-6816/2+1;   % first data subcarrier
DVB.nATM=1+325e-6;         % refractivity index of air near surface
DVB.c=1/sqrt(8.8541878176e-12*4*pi*1e-7)/DVB.nATM; % Speed of light
DVB.DistStep=DVB.c/DVB.Fsa;% length correspondig one sample period [m]
                           % coefficients of the CP subcarriers
DVB.CP=[0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 ...
    636 714 759 765 780 804 873 888 918 939 942 969 984 1050 1101 1107  ...
    1110 1137 1140 1146 1206 1269 1323 1377 1491 1683 1704 1752 1758    ...
    1791 1845 1860 1896 1905 1959 1983 1986 2037 2136 2154 2187 2229    ...
    2235 2322 2340 2418 2463 2469 2484 2508 2577 2592 2622 2643 2646    ...
    2673 2688 2754 2805 2811 2814 2841 2844 2850 2910 2973 3027 3081    ...
    3195 3387 3408 3456 3462 3495 3549 3564 3600 3609 3663 3687 3690    ...
    3741 3840 3858 3891 3933 3939 4026 4044 4122 4167 4173 4188 4212    ...
    4281 4296 4326 4347 4350 4377 4392 4458 4509 4515 4518 4545 4548    ...
    4554 4614 4677 4731 4785 4899 5091 5112 5160 5166 5199 5253 5268    ...
    5304 5313 5367 5391 5394 5445 5544 5562 5595 5637 5643 5730 5748    ...
    5826 5871 5877 5892 5916 5985 6000 6030 6051 6054 6081 6096 6162    ...
    6213 6219 6222 6249 6252 6258 6318 6381 6435 6489 6603 6795 6816];
                            % coefficients of the TPS subcarriers
DVB.TPS=[34 50 209 346 413 569 595 688 790 901 1073 1219 1262 1286 1469 ...
    1594 1687 1738 1754 1913 2050 2117 2273 2299 2392 2494 2605 2777    ...
    2923 2966 2990 3173 3298 3391 3442 3458 3617 3754 3821 3977 4003    ...
    4096 4198 4309 4481 4627 4670 4694 4877 5002 5095 5146 5162 5321    ...
    5458 5525 5681 5707 5800 5902 6013 6185 6331 6374 6398 6581 6706 6799];
% If we have A priori information aboute Tx delays use TxOff
TxOff=[41.8775 0.0898 0]*1e-6*DVB.c; % TxOff=[Olšanská Ládví Novodvorská];
PilotSignal = GeneratePilotReplica(DVB.K);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%  read_kml reads coordinates from google earth .kml format
[PathLon, PathLat, PathAlt]=read_kml('GenPaths\05measuredpoints.kml');
for PathPoint=1:length(PathLon)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Generating distorted DVB-T signal according Rx position
RxGPS = [PathLat(PathPoint), PathLon(PathPoint), PathAlt(PathPoint)];
TxDel = [ 41.8775 0    0.0898]*1e-6; % [Olšanská Ládví Novodvorská];
MPnum = 0;
RxData = GenerateDVBT(RxGPS,TxDel,OFDMNum,MPnum,DVB.K,DVB.k0);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
exp1 = exp(-1j*pi*(0:1:length(RxData)-1));
RxData=RxData.*exp1;
LPF=zeros(1,length(RxData));
LPF(round(length(LPF)/2-length(LPF)/(DVB.Fsa*DVB.Tsym)*(4096-512))...
    :round(length(LPF)/2+length(LPF)/(DVB.Fsa*DVB.Tsym)*(4096-512)))=1;
```

```
RxData=ifft(fft(RxData).*LPF);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% finding the guard interval duration, time and frequency offset
DVB.del = EstTdel(RxData(1:(DVB.K*(1+2/4)*2)),DVB);
DVB.Tdel=(DVB.del)*DVB.Tsym;       % duration of guard interval \Delta [s]
DVB.Nd=int64(DVB.Tdel*DVB.Fsa);    % number of samples of the CP
DVB.Nu=int64(DVB.Tsym*DVB.Fsa);    % number of samples of the OFDM symbol
Rm=zeros(1,DVB.Nu+DVB.Nd);
    m=0;
while m<DVB.Nu+DVB.Nd               % Searched time interval
Rm(m+1)=Rm(m+1)+sum(RxData(m+1:DVB.Nd+m)...
             .*conj(RxData(DVB.Nu+1+m:DVB.Nd+m+DVB.Nu)));
m=m+1;
end
[MaxRm, maxRm]=max(Rm);
Toff=maxRm+2;                                         % time offset
Foff=angle(Rm(maxRm))*DVB.Fsa/(2*pi*double(DVB.Nu)); % frequency offset Hz
RxData=RxData(Toff:length(RxData));
RxData=RxData.*(exp(1j*2*pi*(0:1:length(RxData)-1)/DVB.Fsa*Foff));
GShft=-64;
RxData=RxData(DVB.Nd-GShft:length(RxData));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Finding delayed DVB-T signals corresponding to transmitters
InterpFact=10;
   WinL = 10*ceil(DVB.K/DVB.Carrier)*InterpFact;
   WinR = 15*ceil(DVB.K/DVB.Carrier)*InterpFact;
   SaveC = 2*ceil(DVB.K/DVB.Carrier)*InterpFact;
   ThreshMul=3;
ComprimeIn=(filter(conj(fliplr(PilotSignal)),1,RxData));
ComprimeOut=zeros(1,(DVB.Nu+DVB.Nd));
for i=1:OFDMNum-3
ComprimeOut=ComprimeOut...
           +abs(ComprimeIn(i*(DVB.Nu+DVB.Nd)+1:(i+1)*(DVB.Nu+DVB.Nd)));
end
MaxDiff=24e3; % maximal possible distance difference in [m]
              % maximal distance between the most distant transmitters
WIN=floor(MaxDiff/2/DVB.DistStep);
[~, CenterWIN]=max(ComprimeOut);
ComprimeOut=circshift(ComprimeOut,[0,(length(ComprimeOut)/2-CenterWIN)]);
DataOut=interp(ComprimeOut(length(ComprimeOut)/2-WIN...
        :length(ComprimeOut)/2+WIN)/max(ComprimeOut),InterpFact);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    figure
    [DetMax, argDetMax]  = CA_CFAR(DataOut,WinL,WinR,SaveC,ThreshMul,...
                                DVB.DistStep/InterpFact);
% sort by value of maxim (big to small) by bubble sort
    [DetMax,argDetMax] = BublSort(DetMax,argDetMax,1);
     if length(DetMax)>2
    DetMax = DetMax(1:3);
    argDetMax = argDetMax(1:3);
% sort by distant to receiver (small to big) by bubble sort
    [argDetMax,DetMax] = BublSort(argDetMax,DetMax,-1);
argDetMax = DVB.DistStep/InterpFact*(argDetMax);
LKPos = [PathLat(PathPoint), PathLon(PathPoint), PathAlt(PathPoint)];
[EstLLH, H] = PosEval(argDetMax,LKPos,TxOff);
     end
% Evaluate difference from the Last Known Possition to null the influence
% of the transmitters offset.
if PathPoint==1
    PathDiff=LKPos-EstLLH;
```

```
end
formatSpec = 'Position is: %2.6f°N %2.6f°E %2.5fmnm\n';
fprintf(formatSpec,EstLLH)
PathLonO(PathPoint) = EstLLH(2);
PathLatO(PathPoint) = EstLLH(1);
PathAltO(PathPoint) = EstLLH(3);
DiffPathLonO(PathPoint) = EstLLH(2)+PathDiff(2);
DiffPathLatO(PathPoint) = EstLLH(1)+PathDiff(1);
DiffPathAltO(PathPoint) = EstLLH(3)+PathDiff(3);
end
Exact=[PathLat, PathLon, PathAlt];
Eval= [PathLatO.', PathLonO.', PathAltO.'];
[E, var]=MeanVar(Eval,Exact);
fprintf('mean value of the possition deviance is (%2.3f',E(1));
fprintf(',%2.3f',E(2));
fprintf(',%2.3f)m',E(3));
fprintf( '\n');
fprintf('Standard deviation of the possition is %2.3f m',sqrt(var));
fprintf( '\n');
InputPos = ge_point(PathLon, PathLat, PathAlt);
ge_output('GenPaths\InputPos.kml',InputPos);
OutputPos = ge_point(PathLonO, PathLatO, PathAltO);
ge_output('GenPaths\OutputPos.kml',OutputPos);
CorrOutputPos = ge_point(DiffPathLonO, DiffPathLatO, DiffPathAltO);
ge_output('GenPaths\CorrOutputPos.kml',CorrOutputPos);
```

```
% function generating signal according DVB-T Positioning System Simulator
% author: Rostislav Karasek
% creating signal paths from transmitters, multipaths and propagation FSL
% random number of multipath uniformly distributed.
% independent number of multipaths & propagation time delay
% maximal number of multipaths for every transmitter is MPnum
function RxData = GenerateDVBT(RxGPS,TxDel,OFDMNum,MPnum,K,k0)
% RxGPS.... GPS coordinates of the receiver
% TxDel.... Delays of individual transmitters
% OFDMNum.. Number of the generated OFDM symbols
% MPnum.... Maximal number of MultiPaths
prn=PRBSgenerator;
Tu=896e-6;      % Duration of the OFDM symbol in seconds
del=1/8;        % Guard interval
kMax=k0+6816;   % Last nonzero subcarrier
SNR=40;         % AWGN is added to final generated signal
nATM=1+325e-6;  % refractivity index of air near surface
c=1/sqrt(8.8541878176e-12*4*pi*1e-7)/nATM; % Speed of light in vacuum/nATM
[TxToP, TxE]=PropagationModel(RxGPS,c);
TxTpD = TxToP+TxDel;    % propagation time & delay of the transmitter time
TxTpD=TxTpD-min(TxTpD);
TxN=length(TxTpD);      % number of transmitters
CP=[0 48 54 87 141 156 192 201 255 279 282 333 432 450 483 525 531 618 ...
    636 714 759 765 780 804 873 888 918 939 942 969 984 1050 1101 1107 ...
    1110 1137 1140 1146 1206 1269 1323 1377 1491 1683 1704 1752 1758  ...
    1791 1845 1860 1896 1905 1959 1983 1986 2037 2136 2154 2187 2229  ...
    2235 2322 2340 2418 2463 2469 2484 2508 2577 2592 2622 2643 2646  ...
    2673 2688 2754 2805 2811 2814 2841 2844 2850 2910 2973 3027 3081  ...
    3195 3387 3408 3456 3462 3495 3549 3564 3600 3609 3663 3687 3690  ...
    3741 3840 3858 3891 3933 3939 4026 4044 4122 4167 4173 4188 4212  ...
    4281 4296 4326 4347 4350 4377 4392 4458 4509 4515 4518 4545 4548  ...
    4554 4614 4677 4731 4785 4899 5091 5112 5160 5166 5199 5253 5268  ...
    5304 5313 5367 5391 5394 5445 5544 5562 5595 5637 5643 5730 5748  ...
    5826 5871 5877 5892 5916 5985 6000 6030 6051 6054 6081 6096 6162  ...
    6213 6219 6222 6249 6252 6258 6318 6381 6435 6489 6603 6795 6816];
% generating random data and creating ideal DVB-T signal with SP and CP
for i=0:OFDMNum-1;
S=zeros(1,K);
S(k0:kMax)=randi(8,1,6817)*2-9+1j*(randi(8,1,6817)*2-9);
S(k0+3*mod(i,4):12:kMax)=prn(1+3*mod(i,4):12:6817)*sqrt(42)*4/3; % add SP
S(k0+CP)=prn(CP+1)*sqrt(42)*4/3;                                 % add CP
r(K*del+1:K*del+K)=ifft(fftshift(S));
r(1:K*del)=r(K+1:K*(del+1));
s(1,((i)*length(r))+1:((i+1)*length(r)))=r;
end
if MPnum>0
    % Number of multipaths for individual transmitters
    beams(2:1+TxN)=randi(MPnum,1,TxN);
end
beams(1)=0;
% time delay of the individual signal paths
tau=zeros(1,TxN+sum(beams));
tau(1:TxN)=TxTpD;
% amplitude of the individual signal paths without random phase
A=zeros(1,TxN+sum(beams));
A(1:TxN)=TxE;
% generating multipaths for every single transmitter
if MPnum>0
for i=2:TxN+1
  tau(TxN+sum(beams(1:i-1))+1:TxN+sum(beams(1:i)))...
```

```
        =abs(normrnd(TxTpD(i-1),1e-7,1,beams(i)));
  A(TxN+sum(beams(1:i-1))+1:TxN+sum(beams(1:i)))...
        =abs(normrnd(TxE(i-1),1,1,beams(i)));
end
end
Tau=(round(tau*(K/Tu)))+1;
FIR(Tau)=A;
RxDat=filter(FIR,1,s);
RxDat=awgn(RxDat,SNR,'measured'); % add AWGN into the signal
RxData=RxDat(randi(4096):end);
end
```

```
% implementation of the propagation model of the DVB-T channel 42
% author: Rostislav Karasek
function [TxToP, TxE] = PropagationModel (RxGPS,c)
fc42=642e6;
% Order of transmitters: [Olšanská Ládví Novodvorská]
TxEch42=sqrt([10 20 5]*1e3); % ERP of transmitter of the channel 42 [W]
o=[50.083529 14.469104 250]; % coordinates of the transmitter Olšanská
l=[50.136422 14.465282 359]; % coordinates of the transmitter Ládví
n=[50.016389 14.451111 305]; % coordinates of the transmitter Novodvorská
radv = [pi/180 pi/180 1];
% 'k' means coordinates in Cartesian system
ok=wgs842xyz(o.*radv);
lk=wgs842xyz(l.*radv);
nk=wgs842xyz(n.*radv);
RxGPSk=wgs842xyz(RxGPS.*radv);
% line of sight distances from Tx_i to Rx
TxDist = [sqrt((ok-RxGPSk)*(ok-RxGPSk)') ...
          sqrt((lk-RxGPSk)*(lk-RxGPSk)') ...
          sqrt((nk-RxGPSk)*(nk-RxGPSk)')];
TxToP = TxDist/c; % [us]
TxL=c./(TxDist*4*pi*fc42);
% Free Space Loss: E=E0*TxL
TxE=TxEch42.*TxL;
end
```

```
% return estimates of the distance error mean value and variance value
% Author: Rostislav Karasek
function [E, var]=MeanVar(Eval,Exact)
% Eval  ... evaluated possitions in WGS84
% Exact ... correct values of the possitions in WGS84
radv = [pi/180 pi/180 1];
for i=1:size(Eval,1)
   EvalXYZ(i,1:3) = wgs842xyz(Eval(i,:).*radv);
   ExactXYZ(i,1:3) = wgs842xyz(Exact(i,:).*radv);
   Deviation(i,:)=EvalXYZ(i,:)-ExactXYZ(i,:);
   Distance(i) = ((EvalXYZ(i,:)-ExactXYZ(i,:))*...
                  (EvalXYZ(i,:)-ExactXYZ(i,:))');
end
E=sum(Deviation)/length(Deviation);
var=sum(Distance)/length(Distance);
end
```

```
% implementation of the SFN offset estimator using measured data
% author: Rostislav Karasek
clear all;close all;clc;
nATM=1+325e-6;             % refractivity index of air near surface
c=1/sqrt(8.8541878176e-12*4*pi*1e-7)/nATM; % Speed of light in vacuum/nATM
radv = [pi/180 pi/180 1];
% Coordinates of the transmitter Olšanská
ol=wgs842xyz([50.083529 14.469104 250].*radv);
% Coordinates of the transmitter Ládví
lad=wgs842xyz([50.136422 14.465282 359].*radv);
% Coordinates of the transmitter Novodvorská
nov=wgs842xyz([50.016389 14.451111 305].*radv);
% Coordinates of the measured points
strahov=wgs842xyz([50.0804 14.3956 330].*radv);
suchdol=wgs842xyz([50.1317 14.3858 275].*radv);
parukarka=wgs842xyz([50.0851 14.4602 300].*radv);
% tau obtained from CA-CFAR detection algorithm
tauSuchdol=[-7947.91 -14.98 -15485.24+22378]/c;
tauStrahov=[-3.00 134.86 9800.03]/c;
tauParukarka=[-8.99 1909.06 7459.41]/c;
% matrix of transmitters coordinates
Tx=[ol; lad; nov ];
% matrix of receivers coordinates
Rx=[strahov; suchdol;  parukarka];
% matrix of relative time detections
tau=[tauStrahov; tauSuchdol;  tauParukarka];
nMax=size(Rx,1);oMax=size(Tx,1);pMax=size(Tx,1);
% implementation of the SFN Time Offsets Estimation algorithm
for n=1:nMax
   for p=1:pMax
      for o=1:oMax
         t(n,o)=sqrt((Rx(n,:)-Tx(o,:))*(Rx(n,:)-Tx(o,:)).')/c;
         T(n,p,o)=t(n,p)-t(n,o);
      end
   end
   t(n,:)=t(n,:)-min(t(n,:));
   h(n,:)=sort(tau(n,:),2)-min(tau(n,:));
   Perm(n,:,:)=perms(h(n,:));
end
T=-1*T;
for n=1:nMax
    for k=1:factorial(oMax)
   O(k,:,n)=Perm(n,k,:)-T(n,1,:);
   O(k,:,n)=O(k,:,n)-min(O(k,:,n));
   end
end
O=1e6*sort(O,2); display(O); % offset matrix O displayed in us
```

```matlab
% control function for the ETTUS N210
% author: Rostislav Karasek
% Fc: channel 42 -> 642 MHz, channel 46 -> 674 MHz
function RxData=Rx(Fc,DecimFact,Sa)
FrameLength=512;     % Length of the frame in samples
hRx = comm.SDRuReceiver('192.168.10.2', ...
              'CenterFrequency', Fc, ...
              'DecimationFactor', DecimFact, 'Gain',15, 'OverrunOutputPort',1, ...
              'FrameLength', FrameLength);
frames=ceil(Sa/FrameLength);
i = 1;
while(1)
    [Y, LEN] = step(hRx);
    if LEN==FrameLength
        R(1,(i-1)*FrameLength+1:i*FrameLength)=Y;
        i=i+1;
    end
    if i ==(frames+1)
        break;
    end
end
release(hRx)
display('Stop')
RxData=double(R(1:Sa));
end
```

```
% generator of Pseudo-Random Binary Sequence used in DVB-T
% author: Rostislav Karasek
function prn=PRBSgenerator()
pol= true(1,12);
pol(1)=false;
numE=6817;
prn=zeros(1,numE);
num=1;
while num<numE+1
  prn(num)=int8(((-pol(12))+0.5)*2);
  pol=circshift(pol,[0,1]);
  pol(1)=xor(pol(10),pol(12));
  num=num+1;
end
end
```

```
% Bubble sort by the value of variable Seq2Sort and the same adjustments
% are applied on the dependent sequence (DepSeq)
% author: Rostislav Karasek
%Dir =  1 sort big-->small
%Dir = -1 sort small-->big
function [Seq2Sort,DepSeq] = BublSort(Seq2Sort,DepSeq,Dir)
switch Dir
case 1 % %sort by value of maxim (big to small) by bubble sort
    for i=1:length(Seq2Sort)
       for j=1:length(Seq2Sort)-i
           if Seq2Sort(j)<Seq2Sort(j+1)
               Mem=[Seq2Sort(j) DepSeq(j)];
               Seq2Sort(j)=Seq2Sort(j+1); DepSeq(j)=DepSeq(j+1);
               Seq2Sort(j+1)=Mem(1); DepSeq(j+1)=Mem(2);
           end
       end
    end
 case -1 % sort by distant to receiver (small to big) by bubble sort
    for i=1:length(Seq2Sort)
       for j=1:length(Seq2Sort)-i
           if Seq2Sort(j)>Seq2Sort(j+1)
               Mem=[Seq2Sort(j) DepSeq(j)];
               Seq2Sort(j)=Seq2Sort(j+1); DepSeq(j)=DepSeq(j+1);
               Seq2Sort(j+1)=Mem(1); DepSeq(j+1)=Mem(2);
           end
       end
    end
    otherwise
        disp('use Dir = 1 or Dir = -1')
end
end
```

```
% initialization for the Golden Section Search algorithm using CP
% Author: Rostislav Karasek
function [Toff]=GSSinitCP(s,prn,CP,k0)
S=fft(s);
S=S*length(S)/(sum(abs(S)));
    Toff=0;
    xaxa=500;
    stepdiv=896/8192/10; % 10 steps equals shift by one sample
    P=zeros(1,2*xaxa+1);
for m=-xaxa:xaxa
    e=Toff+m*stepdiv;    % time offset in \mu s
 % fine time shift is achieved by multiplying by exp() in frequency domain
 Pp=S(CP+k0).*prn(CP+1).*exp(-1j*2*pi*(CP/896)*e);
 P(m+xaxa+1)=sum(Pp);
end
absP=abs(P);
[~, cor]=max(absP);
Toff=(cor-xaxa-1)*stepdiv;
end
```

```
% initialization for the Golden Section Search algorithm using SP
% Author: Rostislav Karasek
function [Toff]=GSSinitSP(s,prn,k_SP)
S=fft(s);
S=S*length(S)/(sum(abs(S)));
    Toff=0;
    xaxa=100;
    stepdiv=1/2;
    P=zeros(1,2*xaxa+1);
for m=-xaxa:xaxa
    e1=Toff+m*stepdiv;
% fine time shift is achieved by multiplying by exp() in frequency domain
Pp=S(k_SP+689).*prn(k_SP+1).*exp(1j*(k_SP)*(e1/length(S)));
P(m+xaxa+1)=sum(Pp);
end
absP=abs(P);
[~, cor]=max(absP);
 Toff=(cor-xaxa-1)*stepdiv;
end
```

```matlab
% implementation of the Time Offset Estimation
% Author: Rostislav Karasek
% optimalization using Golden Section Search algorithm
function [Toff]=GSSToff(s,prn,k_SP,Toff)
S=fft(s);
S=S*length(S)/(sum(abs(S)));
    g=(sqrt(5)-1)/2;     % golden ratio
    xL=-896/8192;
    xU=+896/8192;
    delta=xU-xL;
    x1=delta*g+xL;
    x2=delta*(1-g)+xL;

    X1=abs(sum(S(k_SP+689).*prn(k_SP+1)...
       .*exp(-1j*2*pi*(k_SP/896)*((Toff+x1)))));
    X2=abs(sum(S(k_SP+689).*prn(k_SP+1)...
       .*exp(-1j*2*pi*(k_SP/896)*((Toff+x2)))));
    i=1;
    while delta>896/8192/4
        i=i+1;
    if X2>X1  % upper bound is moved into x1
        xU=x1;
        delta=abs(xU-xL);
        x1=x2;
        x2=delta*(1-g)+xL;
        X1=X2;
        X2=abs(sum(S(k_SP+689).*prn(k_SP+1)...
           .*exp(-1j*2*pi*(k_SP/896)*((Toff+x2)))));
    elseif X2<X1 % lower bound is moved into x2
        xL=x2;
        delta=abs(xU-xL);
        x2=x1;
        x1=delta*g+xL;
        X2=X1;
        X1=abs(sum(S(k_SP+689).*prn(k_SP+1)...
            .*exp(-1j*2*pi*(k_SP/896)*((Toff+x1)))));
    elseif X1==X2 % both bounds are moved
        xL=x2; xU=x1;
        delta=abs(xU-xL);
        x1=delta*g+xL;
        x2=delta*(1-g)+xL;
        X1=abs(sum(S(k_SP+689).*prn(k_SP+1)...
           .*exp(-1j*2*pi*(k_SP/896)*((Toff+x1)))));
        X2=abs(sum(S(k_SP+689).*prn(k_SP+1)...
           .*exp(-1j*2*pi*(k_SP/896)*((Toff+x2)))));
    end
    end
end
```