ADS-B Reception at Airport Airside Areas using TDL-based Channel Modeling

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Abstract

In this paper we introduce an approach to reception and processing of the ADS-B extended squitter signals provided by aircrafts and other vehicles on the airport airside area. The paper presents a method for use channel modelling based on TDL model for purposes of ADS-B signal processing enhancement. The model tests are based on real data measurements at Prague airport. The method for application of this approach and verification tests are presented as well.

Keywords: ADS-B; channel impulse response; TDL model; signal processing

Introduction

The air traffic density is constantly increasing throughout the time and the most critical situation is naturally around airports the nodes of air transport network. Besides controlling position of aircrafts, air traffic control has to have information about true position of other moving subjects within area of airport, no matter whether in air or on the ground. The evaluation of the availability of the position information of the objects at the airport airside area (which is crucial for a safety of the air traffic) is based on a reception and processing of signals that carry themselves such position information or their source and behavior provides information to estimate such position. Typical signal is for example ADS-B extended squitter signal. ADS-B (Automatic Dependent Surveillance – Broadcast) is technology (RTCA DO-242, 2002) that replaces or extends a surveillance based on classical radar detection and tracking. Each vehicle (aircraft, helicopter, car, truck) provides via ADS-B signal its position, vertical and horizontal speed, altitude to air traffic control center and also to the vehicles in its vicinity. To obtain data for provision of such information, the aircraft is equipped by other instruments, e.g. GNSS receiver (at present usually based on combination of GPS and SBAS), altimeter, airspeed indicator, etc.

The transmission of signals above is realized by a transponder of secondary surveillance radar (SSR) in mode S with function “extended squitting”(RTCA DO-260B, 2009). The squitting means periodical broadcast of aircraft data using mode S SSR transponder without request (poll) from control center. (in opposite to classical response “squawk”) The term “extended” represents increased number of transmitted parameters (up to 49) in comparison to common mode S response (7 parameters). The ADS-B message has for extended squitter version duration of 120 microseconds, where first 8 microseconds form preamble consisting of four pulses of 0.5 microseconds each, following by 112 bits of data together with parity check (Fig. 1). The ADS-B broadcast uses frequency 1090 Mhz, same as SSR mode S reponse. The data are modulated through pulse position modulation (PPM), where data symbol 1 is represented by high value in first half of symbol duration interval and low value in second half. The symbol 0 uses swapped levels in comparison to symbol 1. The signal propagation in free space is usually without strong disturbances and interference and the reception of such signal in the air is not complicated. However, the signal propagation at the ground is affected by various effects (reflections from other objects, buildings, diffraction on edges, etc. – Fig.2). Moreover, the signals at airport airside area are received within high dynamic range based mainly on uneven distance between receiver and various transmitters. Therefore the successful reception and processing of the ADS-B signals in such environment is a challenging task (Harman et al., 1998)(Pei et al., 2013). The reception can be further enhanced by using some knowledge about radio channel parameters. One of them is channel impulse response that describes behaviour of the signal in the time domain and enables radio channel modelling for reception enhancement.

Since ADS-B extended squitter transmitters provide regular repeatable signal source with known parts of the data, its reception and processing can be used for estimation of channel impulse response. Such knowledge can be then further used for design of advanced processing algorithms of ADS-B signals at the ground area of the airport and thus enhance these signals' reception and decoding.

Determination of Channel Model

In this section, we introduce an approach to determine parameters of radio channel model based on uniformly spaced TDL model. This model will be derived for typical environment at airport airside area, where dominant source of interference is a multipath propagation with constant number of discrete components.

LS Estimation of Channel Impulse Response

The discrete channel output can be expressed by general discrete convolution of input signal and impulse response. For real situation we can assume that the impulse response is finite in time, i.e. it can be considered zero or negligible outside time interval <0,m_{max}>. Then the convolution will run through finite interval and can be expressed as

$$\tilde{y}(k) = \sum_{m=0}^{m_{\max}} \tilde{x}(k-m)\boldsymbol{h}(m)$$

where $\tilde{x}(k)$ are samples of input (transmitted) signal, $\tilde{y}(k-m)$ are samples of output (received) signal, and **h**(m) is a channel impulse response. The symbol ~ denotes lowpass-equivalent form (complex envelope) of affected signals. The K samples of output signal can be obtained using matrix operation of K+m_{max} samples of input signal, m_{max} samples of impulse response and noise

$$\mathbf{y} = \mathbf{M}\mathbf{h}+\mathbf{n} \qquad (2)$$

where **y** = $\tilde{y}(0),\ldots,\tilde{y}(K)$ are K evaluated samples of received signal, **M** represents matrix K to m_{max} of samples of transmitted signal $\tilde{x}(-m_{max}),\ldots,\tilde{x}(K-m_{max})$, **h** = h(0),…, h($m_{max}$) and **n** = n(0),…, n($m_{max}$) is noise, all in a form

$$\begin{bmatrix} \tilde{y}_0 \\ \tilde{y}_1 \\ \vdots \\ \tilde{y}_K \end{bmatrix} = \begin{bmatrix} \tilde{x}_0 & \tilde{x}_{-1} & \cdots & \tilde{x}_{-m_{\max}} \\ \tilde{x}_1 & \tilde{x}_0 & \cdots & \tilde{x}_{1-m_{\max}} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_K & \tilde{x}_{K-1} & \cdots & \tilde{x}_{K-m_{\max}} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{h}_0 \\ \boldsymbol{h}_1 \\ \vdots \\ \boldsymbol{h}_{m_{\max}} \end{bmatrix} + \begin{bmatrix} n_0 \\ n_1 \\ \vdots \\ n_{m_{\max}} \end{bmatrix}$$

From this term we can obtain LS (least squares) estimate of the desired channel impulse response by

$$\mathbf{h}_{est} = (\mathbf{M}^T\mathbf{M})^{-1}\mathbf{M}^T\mathbf{y}$$

The estimate of impulse response would provide the best results for Dirac pulse as an input signal. The input signal in the real situation is band limited, therefore the obtained channel impulse response estimate will represent band limited channel of ADS-B system with impact of band limitation caused by processing bandwidth of receiver used for obtaining the received signal. As we focus on the processing of the ADS-B signals only, this limitation will cause no significant error.

TDL Model of the Radio Channel

Because of the band limitation described above and multipath propagation as a dominant source of interference in channel we can describe such radio channel by discrete version of a band limited multipath channel model (Proakis, 2000). The general time–variant model has variable tap gains a_k, variable tap delays τ_k, and variable number of taps K. The equivalent lowpass-equivalent impulse response of such discrete multipath channel is given

$$\tilde{h}(\tau,t) = \sum_{k=1}^{K(t)} \tilde{a}_k\left(\tau_k(t),t\right)\delta\left(\tau - \tau_k(t)\right)$$

where δ(t) is Dirac delta function and symbol ~ denotes lowpass-equivalent form of related parameter. For such outdoor multipath channel evaluated in time limited interval, we can assume approximation based on considered constant number of discrete components and negligible variation of delay values. The model then simplifies to

$$\tilde{h}(\tau,t)=\sum_{k=1}^{K}\tilde{a}_k(t)\delta(\tau-\tau_k)$$

and corresponding lowpass-equivalent output is

$$\tilde{y}(t)=\sum_{k=1}^{K}\tilde{a}_k(t)\tilde{s}(t-\tau_k)$$

where $\tilde{s}(t)$ is lowpass-equivalent input signal to the radio channel.
Such band limited channel then can be described by output of the tapped delay line (TDL) system with corresponding structure shown at Fig. 3. The output is given

$$\tilde{y}(t)=\sum_{n=-N}^{N}\tilde{s}(t-nT)\tilde{g}_n(t)$$

where $g_n(t)$ are TDL tap gains in its lowpass-equivalent form

$$\tilde{g}_n(t)=\sum_{k=1}^{K}\tilde{a}_k(t)\alpha(k,n)$$

for total number of 2N taps from interval n= –N,…,N , where

$$\alpha(k,n)=\mathrm{sinc}\left[\frac{\tau_k}{T}-n\right]$$

and T=1/B is a sampling period.

For WSSUS channel we can further consider both tap gains $a_k(t)$ and related TDL tap gains $g_n(t)$ to be substituted by time invariant values a_k, g_n, respectively.

Measurement of the Source Data for Impulse Response Estimation

As we needed to provide estimation algorithm with relevant input data, we organized measurement campaign focused on obtaining signal records for the evaluation of impulse response of the radio channel dedicated to signal of ADS-B extended squitter transmitted on frequency 1090 MHz. The measurement in the first phase used existing set of MLAT (multilateration) transponders that were installed at the Vaclav Havel Airport Prague to provide stable source of known signal. The measured locations were chosen to cover all typical cases of combinations of source, receiver, and obstacles to be able to evaluate both LOS (line of sight) and NLOS (non line of sight) cases of reception. Moreover, the effect of distance of possible obstacles for producing multipath components of the received signal was taken into account during choice of measurement points. The map of airport that shows measurement points and evaluated sources is at Fig.4.

These transponders periodically broadcast ADS-B extended squitter signals at the frequency 1090 MHz. The incoming signal was received by specially designed WNav receiver (Jakubov et al., 2010) equipped by suitable ADS-B antenna and selective preamplifier (Fig.5) installed in laptop via PCI-E interface. The position of the measurement points was obtained from GPS receiver with antenna placed together with ADS-B antenna on the roof of the measuring vehicle. Each measurement consisted of several records, each of them with one second duration. The received signal was sampled with sampling frequency of 20 MHz in the form of complex envelope. Appropriate signal samples for both inphase and quadrature part of complex envelope (lowpass-equivalent signal) were then stored in laptop and external drive for further post processing. Each record of data consists of 20 million of complex samples related to the duration of measurement of 1 second. The size of such record was more than 200 MiB. This file has to be for post processing purposes split to 50 milliseconds parts (Fig. 6).

Measured Data Processing

The focus was aimed to search ADS-B extended squitter data, thus responses in modes A/C and S without extended data had to be excluded from processing. This was done by the search for a pattern equal to mode S. Then the length was checked to exclude “short” responses without extended squitter data. The result was then processed for obtaining the impulse response estimate.

Since we could test the algorithm on known data provided by MLAT transponders, we could generate proper replicas. The problem for further processing was residual carrier wave distortion of PPM modulated data which had to be removed to obtain suitable PPM constellation (Fig. 7). This constellation can be processed in the same manner as simple On-Off Keying (OOK) or amplitude shift keying (ASK) modulation with double data rate where is present unknown residual carrier frequency and unknown phase shift. Such residual carrier distortion was caused by allowed variance of transmitter's carrier wave frequency as specified in (RTCA DO-260B, 2009). There can be seen spreading of received symbols around mean value caused by noise and rotation of the constellation caused by phase shift of the carrier wave. Such phase shift will not affect decoding of data and can be compensated prior data de modulation. There was used a simple atan function detector with evaluation of the mean value of phase shift.

Moreover, ADS-B response received from landing or taxiing airplane can be affected also by Doppler shift of the transmitted signal. The caused shift for typical speed of 160 knots is for the 1090 MHz signal in the order of kHz and therefore several orders bellow allowed variance of the carrier wave of the transmitter (1000 ppm) (RTCA DO-260B, 2009). The other objects at the airport ground (support, guidance and airport authority vehicles), they move with even lower speed. Thus, for current set of signal sources the Doppler spread and its impact to channel coherence time caused by movement could be considered negligible. After obtaining PPM modulated data samples, we were able to generate reconstructed replica of the ADS-B signal. This reconstructed replica was together with the received signal samples the source for impulse response estimation according to the approach described above using (4). Due to the limited dynamic range of the receiver, several records were affected by recorded signal levels saturation. This occurred in the cases of a simultaneous presence of strong and weak responses in one record (near-far effect). Some strong signals were even out of dynamic range of the receiver and could not be processed.

Model Parameters

The channel impulse response estimates could be classified into two main groups: a cases with direct path transmitter–receiver (LOS) and cases with obstructed direct path between the transmitter and the receiver (NLOS). For these cases we made estimations of channel impulse responses. These channels are described by their power delay profiles (PDP) obtained by simulations based on estimated samples of channel impulse response (Fig. 8, Fig. 9). The obtained impulse response for both dominant groups (LOS, NLOS) was source for determination of lowpass-equivalent complex values of multiplicative coefficients a_k and from them we have obtained TDL model taps g_n for proposed channel model. The separation of delays of the rays $\Delta\tau = \tau_{i+1}-\tau_i$ obtained from estimated power delay profiles is much lower than ADS-B data symbol duration T_S, here $\Delta\tau/T_S = 0.05$ for T_S equal to 1 microsecond. According to (Van Trees, 1968) we can then consider the channel to be frequency-nonselective. With the using the power delay profile according (Jeruchim et al., 2000) the TDL model was determined for 7 taps because higher taps can be considered negligible (Li et al., 2013). The resulting mean tap gains for TDL model for both cases are for one evaluated mutual position of transmitter and receiver in the Table 1. There can be used either mean values of ADS-B groung channel model or we can estimate these TDL model tap gains for various mutual positions of transmitter and receiver and then apply them jointly on the received signal from unknown position at the airport. To verify the model conformity with the real environment, we did comparison of characteristics of the signal obtained by simulations using the model and the signal obtained by the measurements. The comparison of autocorrelation functions of both signals for one case of chosen transmitter is shown at Fig. 10.

The applicationof the model to signal detection and demodulation was then tested. We used signals generated by processing known replica (consisting of preamble and DF, CA, and ICAO code parameters representing 40 microseconds of known signal) with TDL channel model for LOS and NLOS cases and their result was then applied to received signal for detection by cross-correlation function evaluation. According to the result of cross-correlation, appropriate model and its generated impulse response were used for adjustment of matched filter for application to full length of received signal (Kay, 1998). The output was then provided to symbols decoding algorithm. The block scheme of operations can be seen at Fig.11. The TDL models for another jointly evaluated configurations of transmitter-receiver pair will be then represented by adding another TDL blocks and multiplicattion/integration branches for the cross-correlation maximum evaluation block. The example of a received signal and the signal corrected by using ADS-B channel model together with decoded data symbols can be seen at Fig. 12 and Fig. 13.

Conclusions

We have proposed a model of the ADS-B extended squitter radio channel for ground area of airport based on TDL model. The parameters of the model were set up according to estimates of channel impulse response taken from on-site measurements. The model shows good conformity with data obtained by measurements for WSSUS type of channel and can be used for correction of distorted received signal for data demodulation enhancement. Further work is aimed to the non-WSSUS cases expansion and to the hardware and software enhancement of processing signals with high dynamic range that can be typically present at airport airside areas.

Acknowledgment

The work on presented topic was supported by project CTU SGS14/149/OHK3/2T/13. We would like to thank to Air Navigation Services of CR (RLP CR) for support during measurements at the Prague airport.

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Table 1 : Tap Gains for TDL Channel Model

tap	LOS	NLOS
1	-0.1646 - 0.0128i	0.4089 - 0.0028i
2	0.2433 + 0.0196i	-0.6021 + 0.0041i
3	-0.4665 - 0.0407i	1.1423 - 0.0070i
4	6.3647 + 7.7408i	-9.2771 - 0.7803i
5	0.5611 + 0.0307i	-1.4438 + 0.0130i
6	-0.2667 - 0.0172i	0.6765 - 0.0055i
7	0.1750 + 0.0118i	-0.4418 + 0.0035i

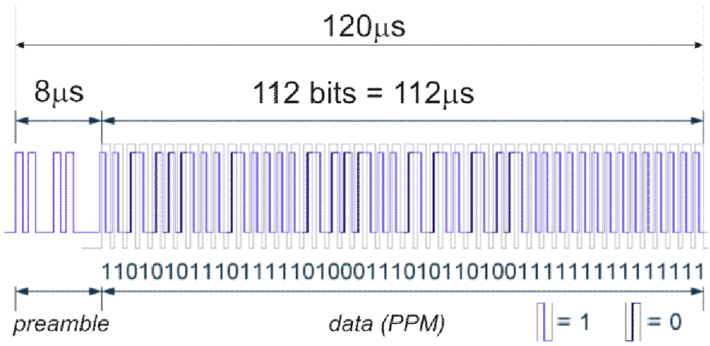

Figure 1: ADS-B Message Format

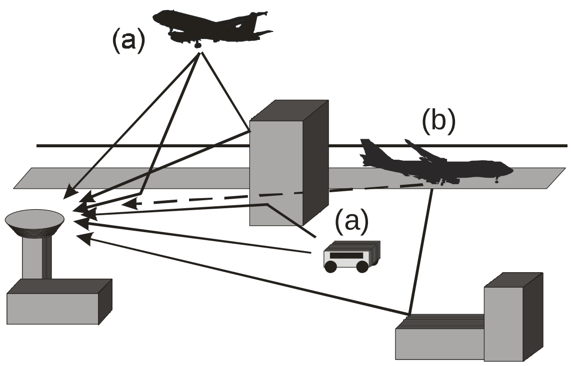

Figure 2: Typical Airport Airside Area Propagation Environment with Examples of LOS – Line-of-Sight Signal Propagation (a) and NLOS – Non-Line-of-Sight Signal Propagation (b)

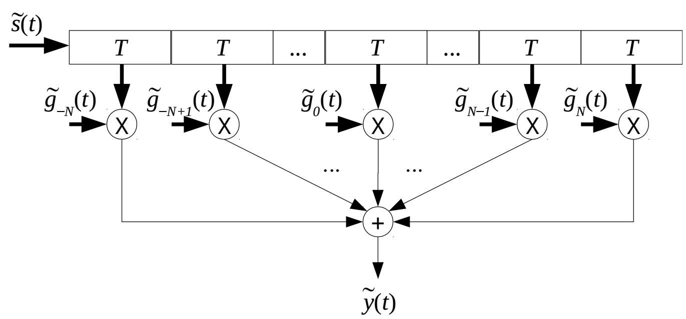

Figure 3: Uniformly Spaced TDL Model for Band Limited Discrete Multipath Channel

Figure 4: Situation Plan of the Prague Vaclav Havel Airport with view to Positions of Transmitters (TXAxx) and Measured Points (00x) (Shown on Map Layer of OSM maps)

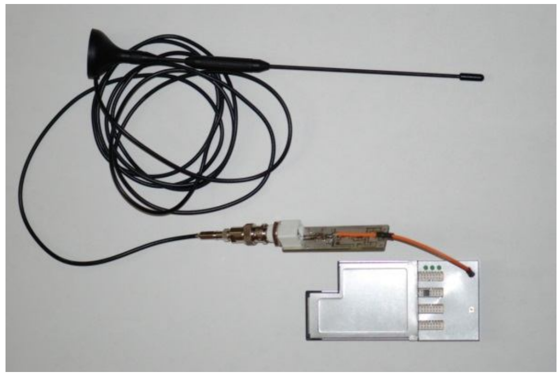

Figure 5: Set of Measuring Receiver WNav with ADS-B antenna and Selective LNA

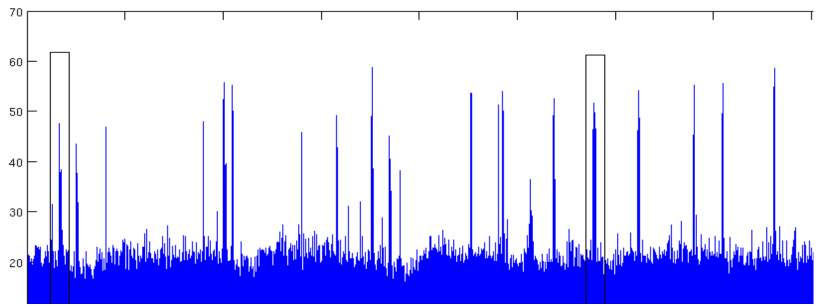

Figure 6: 50 Milliseconds (Abscissa) Record of SSR Responses (Mode C, mode S, ADS-B) in form of Magnitude of the Complex Envelope (Ordinate). The Rectangles Mark Responses from the Same Source

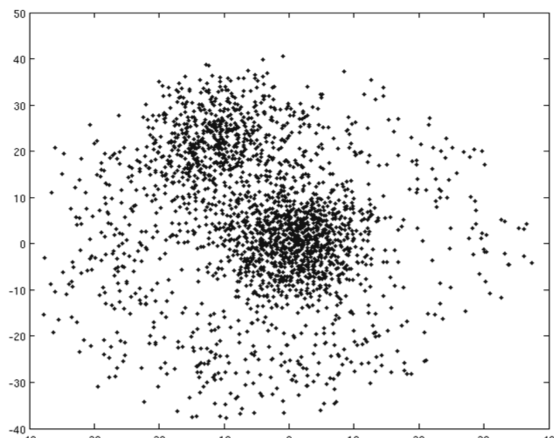

Figure 7: Constellation of Received OOK(ASK) Modulated ADS-B Symbols (Axes Description: Abscissa – Values of Inphase Component of Complex Envelope, Ordinate – Values of Quadrature Component of Complex Envelope)

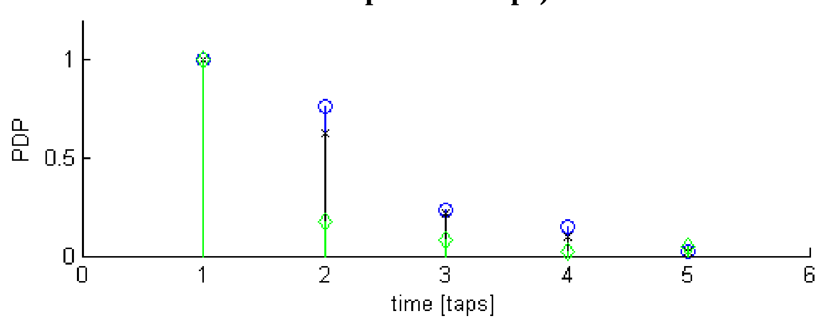

Figure 8: Example of PDPs for LOS Case, with Various Distance of Obstacles Relative to Line of Sight – Less (Diamonds,Green), Equal (Circle, Blue, and Cross, Black).

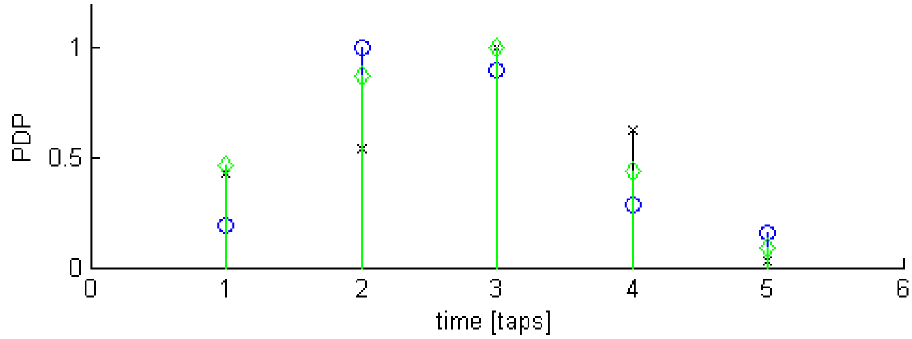

Figure 9: Example of PDPs for NLOS case for Various Positions of Receiver with Respect to the Same Transmitter

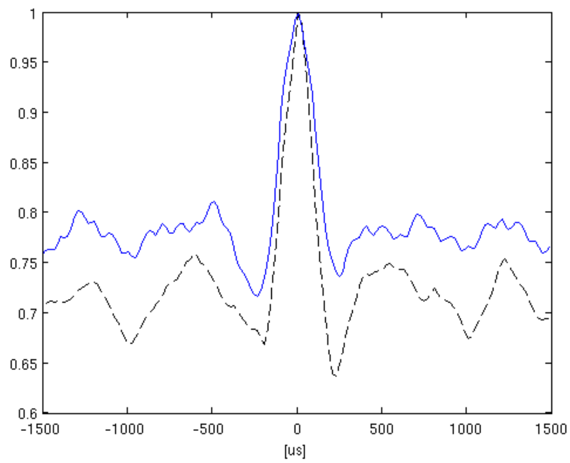

Figure 10: Autocorrelation Function of Signal Obtained by Simulation (Dashed Line) and Signal Obtained by Measurement (Solid Line)

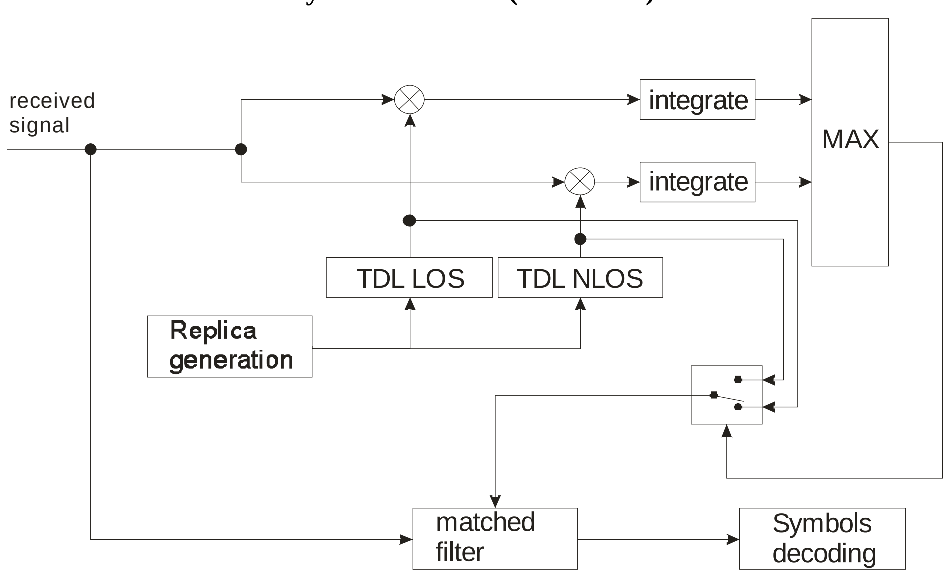

Figure 11: Block Scheme of Signal Detection and Demodulation Enhancement Using ADS-B Channel Modelling

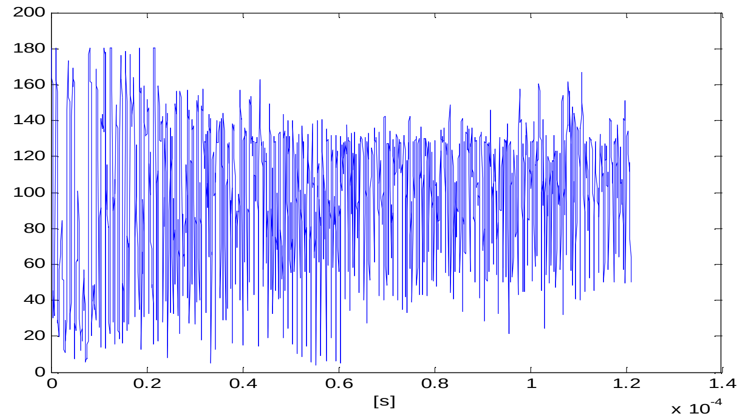

Figure 12: Example of Received Signal Complex Envelope Prior to Correction by Channel Model

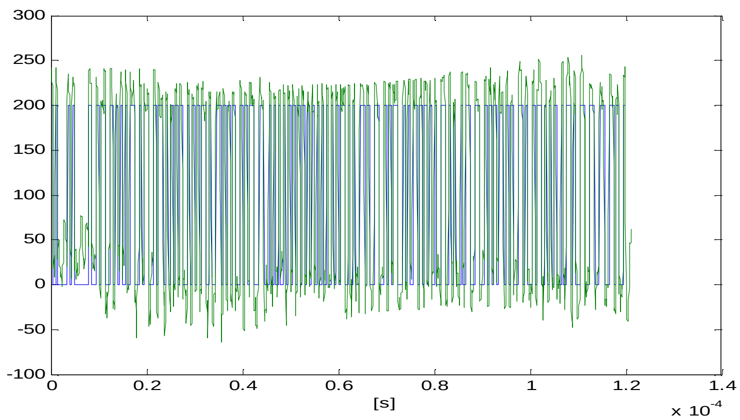

Figure 13: Example of Received Signal Complex Envelope after the Correction Using the Channel Model and Related Sequence of Decoded Data Symbols