Correction for dispersion distortions of frequency response of wideband HF radio channel with the use of the deconvolution method

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Abstract

Studies address to the propagation of wideband wave packets over the ionospheric HF radio channel. We tackled the problem of deconvolution of a wideband HF signal with frequency hopping spread spectrum, corrupted by the frequency dispersion due to the propagation over the channel with a 1 MHz bandwidth from the single-mode propagation range. We assumed that errors in dispersion correction can occur during signal processing. That errors are caused by the noise variations in the channel. Errors cause losses in the data transfer rate. A method of training adaptive dispersion corrector with the use of the data on sounding a wideband channel is presented. Corrector implements the deconvolution function. Based on the experimental data gathered on the radio propagation path Cyprus-to-Yoshkar-Ola, we obtained the dependence of the signal-to-noise ratio on the error value in a wideband channel of 1 MHz bandwidth with a fading depth of up to 20 dB. Considering losses due to the inverse filtering, we estimated the ultimate data transfer rates of HF modems and gain in the covertness of the wideband HF communication system.

1 Introduction

Currently, HF communication is rapidly developing due to increasing capabilities in the signal synthesis and processing by digital methods. In particular, recent studies have being carried out most actively into the use of wideband signals [1-3] for communication with a bandwidth smaller than the coherence bandwidth of the ionospheric radio channel, when dispersion distortions can be neglected. A new impetus for research into the wideband signals with a bandwidth sufficiently exceeding the channel coherence bandwidth have been emerged. However, in a wideband channel the negative effect of dispersion distortions is severe and should be definitely considered [4].

It is known that a signal transmitted over an ionospheric radio link $u_T(t)$ and a received signal $u_R(\tau,t)$ are related by the convolution operator:

$$u_R(\tau,t) = u_T(t) \otimes h(\tau,t) \qquad (1)$$

where $h(\tau,t)$ - channel impulse response, τ – fast time (signal delay), t – slow time (geophysical time).

Deconvolution (inversion) in this case is the inverse problem, that is manifested in finding the function $u_T(t)$ by the functions $u_R(\tau,t)$ and $h(\tau,t)$ with the use of the convolution operator (1). We shall note that deconvolution has wide application in many fields of science related to measurements. Especially, it is widely used in digital processing of seismic data and image processing [5].

The solution for inversion is obtained by conversion into the frequency domain from the time domain. As a result, (1) is represented as follows:

$$U_R(j\omega,t) = H(j\omega,t)\cdot U_T(j\omega) \qquad (2)$$

where $U_{T,R}$ - spectra of the transmitted and received signals, respectively; $H(j\omega,t)$ - channel frequency response.

Here, to perform inversion through the spectral representation (in frequency domain) there is the following equation:

$$\begin{aligned} u_T(t) &= F^{-1}\left[U_R(j\omega,t)/H(j\omega,t)\right] = \\ &= F^{-1}\left[U_R(j\omega,t)\cdot H^{-1}(j\omega,t)\right]. \end{aligned} \qquad (3)$$

Mathematical operation under square brackets is referred to as inverse filtering, and the function $H^{-1}(j\omega,t)$ is the transfer function (frequency response) of the inverse filter.

Propagating in the ionosphere, HF signal with a bandwidth greater than the coherence bandwidth [6, 7] suffers shape distortions (amplitude-frequency response (AFR) and phase-frequency response (PFR)) due to the influence of frequency dispersion. Therefore, in our problem, the deconvolution method is used to correct for frequency dispersion of the ionosphere. The challenges in overcoming the frequency dispersion are the multimode propagation of the transmitted signal, the variability of the medium and the presence of varying narrowband and fluctuating additive interferences [4, 8-10]. The use of the state-of-the-art software defined radio (SDR) technology allowed to adequately implement the method of correction for dispersion distortions of wideband signals propagating in the ionosphere.

The aim of the research was to elaborate and experimentally verify the deconvolution method for solving the problem of correction for dispersion distortions of communication signals in wideband ionospheric HF radio channels.

2 General approach to solving the problem of deconvolution of a wideband HF signal

Let us generally consider wideband communication systems operating over a varying ionospheric radio channel, that can be modeled by a linear system with the following frequency response [4]:

$$H(j\omega,t)=\begin{cases}H(\omega,t)\cdot\exp[-j\varphi(\omega,t)],\\ if\ \omega\in\left[\omega_c-\Omega_{ch}/2,\,\omega_c+\Omega_{ch}/2\right]\\ 0,\ if\ \omega\notin\left[\omega_c-\Omega_{ch}/2,\,\omega_c+\Omega_{ch}/2\right]\end{cases} \quad (4)$$

where ω - angular frequency, ω_c - channel mid-band frequency, Ω_{ch} - channel bandwidth, $H(\omega,t)$ - channel AFR and $\varphi(\omega,t)$ - channel PFR, t - slow (geophysical) time.

Employed wideband spread spectrum signals can be represented in the frequency domain as follows:

$$U_T(j\omega)=U(\omega)\cdot\exp j\phi(\omega)\cdot\hat{U}_T(\omega) \quad (5)$$

where $U(\omega)$ - AFR and $\phi(\omega)$ - PFR of a communication signal, $\hat{U}_T(\omega)$ - carrier spectrum.

It is clear that the signal spectrum at the receiver input is as follows:

$$\begin{gathered}U_R(j\omega,t)=H(\omega,t)\cdot\exp[-j\varphi(\omega,t)]\cdot\\ \cdot U(\omega)\cdot\exp j\phi(\omega)\cdot\hat{U}_T(\omega)\end{gathered}. \quad (6)$$

We shall note that for the communication systems in (6) it is required to extract the component carrying data. Therefore, for communication systems, it is crucial to filter both the channel components and the carrier signal, since they corrupt the information signal. The problem can be solved by applying deconvolution as inverse filtering together with the matched filtering. So, that operation is represented as follows:

$$\begin{gathered}U_R(j\omega,t)\cdot\frac{\exp[j\varphi(\omega,t)]}{H(\omega,t)}\cdot\hat{U}_T^*(j\omega)=\\ =U(\omega)\cdot\exp j\phi(\omega)\cdot|\hat{U}_T(\omega)|^2\end{gathered}. \quad (7)$$

Typically, noise that corrupts the signal is δ -correlated. Therefore, after a short time interval, it significantly changes. This influences the results of signal deconvolution. Let us consider that problem.

Let say that the measured frequency response is as follows:

$$\begin{aligned}H(j\omega,t)&=(I_H(\omega,t)+x(\omega,t))+\\ &+j(Q_H(\omega,t)+y(\omega,t))=\\ &=\tilde{I}_H(\omega,t)+j\tilde{Q}_H(\omega,t)\end{aligned} \quad (8)$$

where $x(\omega,t)$; $y(\omega,t)$ - quadrature noise components.

We assumed that the noise changes rapidly over time and noise samples are different at time instants $t=t_1$ and $t=t_2$. Therefore, if the measurement was done at a time instant $t=t_1$, it is reasonable to denote time index accordingly $H(j\omega,t=t_1)=H(j\omega,t_1)$ in (8). In that case, the frequency response of the inverse filter can be represented as follows:

$$\begin{aligned}K(j\omega,t_1)&=\frac{1}{H(j\omega,t_1)}=\frac{H^*(j\omega,t_1)}{H^2(\omega,t_1)}=\\ &=\frac{\tilde{I}_{1H}(\omega,t_1)-j\tilde{Q}_{1H}(\omega,t_1)}{\tilde{I}_{1H}{}^2+\tilde{Q}_{1H}{}^2}\end{aligned}. \quad (9)$$

That inverse FR completely compensates for the channel FR $H(j\omega,t_1)$ with noise. At the next time instant $t=t_2$, the frequency response changes only due the change in the noise samples, taking on the role of an error. Therefore, FR can be represented as follows:

$$\begin{aligned}H(j\omega,t_2)&=(I_{1H}+x(\omega,t_1)+x(\omega,t_2))+\\ &+j(Q_{1H}+y(\omega,t_1)+y(\omega,t_2))=\\ &=H(j\omega,t_1)+(x(\omega,t_2)+jy(\omega,t_2))\end{aligned}. \quad (10)$$

Let us analyze the effect of the inverse filter on a new sample of the frequency response:

$$\begin{aligned}K(j\omega,t_1)\cdot H(j\omega,t_2)&=\frac{H(j\omega,t_2)}{H(j\omega,t_1)}=\\ &=1+\frac{(x(\omega,t_2)+jy(\omega,t_2))}{H(j\omega,t_1)}=\\ &=1+M_0K(j\omega,t_1)\cdot[\frac{x(\omega,t_2)}{M_0}+j\frac{y(\omega,t_2)}{M_0}]\end{aligned} \quad (11)$$

where $M_0=\left\langle\sqrt{I_H{}^2+Q_H{}^2}\right\rangle|_\omega$ is averaged over frequency.

The frequency dependence of $M_0K(j\omega,t_1)$ is derived from experimental data. The values x and y are specified relatively M_0 (in fractions of that value) and defined by the signal-to-noise ratio in the channel. We assumed that they have a normal distribution with the same standard deviations ($\sigma_x/M_0=\sigma_y/M_0$), but they do not correlate with each other, i.e. the samples are independent. Let us denote $\xi = -20\log(\sigma_x / M_0) = -20\log(\sigma_y / M_0)$.

Rapidly changing noise will influence IR of the corrected channel:

$$h(\tau,t_1) = \int_{\omega_1}^{\omega_2} K(j\omega,t_1)\cdot H(j\omega,t_1)\cdot \exp j\omega\tau \frac{d\omega}{2\pi}, \qquad (12)$$

$$h(\tau,t_2) = \int_{\omega_1}^{\omega_2} K(j\omega,t_1)\cdot H(j\omega,t_2)\cdot \exp j\omega\tau \frac{d\omega}{2\pi} =$$

$$= h(\tau,t_1) +$$

$$+\int_{\omega_1}^{\omega_2} \left[M_0 K(j\omega,t_1)\cdot\left(\frac{x(\omega,t_2)}{M_0} + j\frac{y(\omega,t_2)}{M_0}\right)\right]\cdot \exp j\omega\tau \frac{d\omega}{2\pi} = \qquad (13)$$

$$= h(\tau,t_1) + u_N(\tau,t_2)$$

where $\Omega_{ch} = \omega_2 - \omega_1$ - channel bandwidth, $u_N(\tau,t_2)$ - noise at $t = t_2$ time instant, $x(\omega,t_2)$ and $y(\omega,t_2)$ - difference between the noise samples at time instants $t = t_1$ and $t = t_2$.

In actual conditions, the correction function is derived from sounding data and contains an error due to the additive noise in the channel. Therefore, the functions $h(\tau,t_1)$ and $h(\tau,t_2)$ will also be corrupted with these errors. Derived equations allowed to numerically calculate these integrals and determine the signal-to-noise ratio in the first SNR_1 [dB] and second SNR_2 [dB] cases. They were used to estimate the losses due to inverse filtering when measurements are corrupted with errors and noise:

$$\eta_{loss} = SNR_1 - SNR_2 . \qquad (14)$$

3 Experimental estimation of losses in data transfer rate and gain in covertness of communication

The experiments on sounding ionosphere and wideband (1 MHz) radio channels were carried out on the mid-latitude radio path Cyprus-to-Yoshkar-Ola of the length of 2600 km. The characteristics of wideband radio channels of the 1 MHz bandwidth were measured by means of the developed software implementing SDR technology on the USRP platform [4, 10]. Studies focused on the radio channels from the single-mode propagation range (SMPR), determined by the real-time data on panoramic (across the entire HF range) sounding of the experimental radio link by FMCW signal. Receive terminal maintaining and digital signal processing were performed by the computer in accordance with the schedule specified by the software. Frequency sweep rate of the sounding signal was 100 kHz/sec. In experiments we performed correction of the frequency response by the inverse filtering method without error and with artificially added error. Figure 1 presents the IR of the 1 MHz radio channel before and after correction without error. Experimentally measured non-corrected impulse response of the wideband channel had broadening of roughly 20 µs. After applying inverse filtering without error, IR broadening decreased to 1 µs.

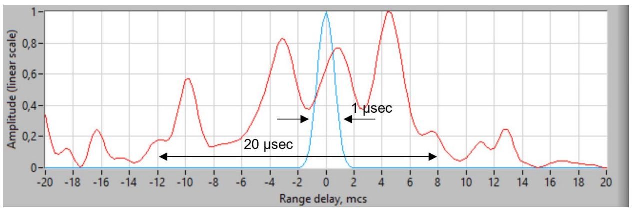

Figure 1. IR of the 1 MHz radio channel before and after correction without error

Errors were introduced by adding white noise to the frequency response. The noise had a normal distribution with a zero mathematical expectation. We employed the previously derived equations with $\xi \in \{-4,-2,0,..,30\}$. Losses were estimated for the worst case of the operation of a communication system when the fading depth reaches 20 dB. There were calculated SNR_1 for the case of correction without error and SNR_2 for the case with error. Figure 2 presents the obtained experimental data. Findings showed that losses due to inverse filtering in a 1 MHz channel with a fading depth of up to 20 dB are $\eta_{loss} = 5$ dB.

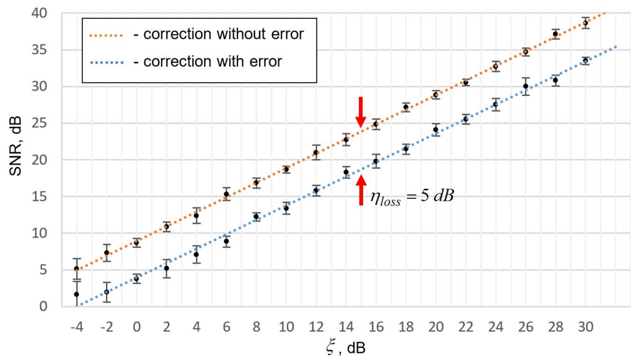

Figure 2. Dependence of the signal-to-noise ratio in the wideband megahertz-bandwidth channel on ξ

A decrease in the signal-to-noise ratio will lead to losses in the data transfer rate of spread spectrum communications. Let us assume that the communication system ensures the data transfer rate R. At transmission, information signal bandwidth is spread by frequency hopping up to 1 MHz, and at the receiver, the spread spectrum is compressed to the information signal bandwidth. We also assumed that the generated modulating signal satisfies the requirements of STANAG 4539 and MIL-STD-188-110B standards. Typically, in single-mode channels, delay spread and Doppler spread satisfy these requirements and the vital parameter that defines the data transfer rate is SNR. So, if the transmitter operates with a constant power over the wideband channel with fading depth of up to 20 dB, there will be losses in the signal-to-noise ratio of up to 5 dB. According to the STANAG 4539 and MIL-STD-188-110B standards, 5 dB losses result in a decrease in the data transfer rate by 2 ... 4 times if the signal-to-noise ratio in the corrected channel do not exceed 18 dB.

In the framework of that model, the gain in the covertness due to spreading the signal bandwidth is defined by the ratio of the spectral energy density contained in the information bandwidth to that contained in the spread spectrum bandwidth. This assumption is adequate if the power and duration of the bit carried by the signal with the information bandwidth are equal to the power and duration of the bit carried by the spread spectrum signal. In fact, the energy per bit equals $E_b = P \cdot T_b = P / R$, and the spectral energy density is E_b / b_s for a narrowband signal, and E_b / B_s for a spread spectrum one. The bit occupies the bandwidth $b_s = R = 1/T_b$. Hence, the gain in the covertness increases by the value $G = 10\log(B_s / b_s) = 10\log(B_s / R) = 10\log(B_s T_b)$.

For instance, a channel with bandwidth of 1 MHz for a 100 bps data stream would provide the processing gain of 40 dB.

4 Conclusions

It was shown that deconvolution, employed to correct for frequency dispersion when the noise rapidly changes, results in deterioration of the signal-to-noise ratio in the corrected channel due to the errors in measuring frequency response. Experimental studies of this effect were carried out on the mid-latitude radio path Cyprus-to-Yoshkar-Ola. Findings showed that losses due to signal deconvolution reaches up to 5 dB in a 1 MHz bandwidth single-mode channel with fading depth of up to 20 dB (the worst case of the operation of a communication system). These losses cause a decrease in the data transfer rate of spread spectrum communication systems by 2 ... 4 times, if the signal-to-noise ratio in the corrected channel do not exceed 18 dB. Since the gain in covertness of spread spectrum communications is defined by the product of bandwidth and data rate, a 1 MHz bandwidth channel for a 100 bps data stream would provide the processing gain of up to 40 dB. The reserve in covertness can be used to increase the transmitted power and to compensate the losses in the data rate.

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