Int. J. Electron. Commun. (AEÜ) 86 (2018) 86–91

Contents lists available at ScienceDirect

Int. J. Electron. Commun. (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Regular paper

Signal enhancement techniques for through-the-earth communication based on multiple references and beamforming

Yu-zhong Jiang[a], Peng Zhao[a,*], Qi Zhai[a], Wen-wei Ying[a], Qiao-lin Hu[b]

[a] *College of Electronic Engineering, Naval University of Engineering, Wuhan 430033, China*
[b] *Department Five, Air Force Early Warning Academy, Wuhan 430019, China*

ARTICLE INFO

Keywords:
Downlink signal reception
Signal enhancement
MVDR beamformer
Through-the-earth communication

ABSTRACT

Through-the-Earth Communication (TEC) is very vulnerable to electromagnetic interference (EMI) and the conventional signal enhancement techniques employing local primary and remote reference antennas are unfeasible for downlink signal reception due to the limited space and complicated terrain on the receiving sites. In this paper, a novel magnetic field sensing system for downlink reception, in which multiple reference sensors are deployed locally and orthogonally with the primary receiving sensor, is introduced and the signal model is constructed from a perspective of array reception. A modified minimum variance distortionless response (MVDR) beamformer is designed by exploiting the TEC operating conditions for suppressing the EMIs and enhancing the signal. Real tests with power line harmonic interferences (PLHIs) from household wiring in laboratory and an additional wideband jamming demonstrated a great reduction of the EMIs and thus reliable downlink signal reception could be obtained.

1. Introduction

Through-the-Earth Communication (TEC), which is operated in the frequency range of 10 Hz to 10 kHz, have much more advantages in communications from surface to underground and underwater and vice versa, such as the in-tunnel communications and cave rescue, trapped-miner communication and location, as well as the remote control of the Unmanned Underwater Vehicles (UUVs) [1–3]. In such applications, the received signal is generally contaminated with strong electromagnetic interference (EMI), e.g. the atmospheric noise and man-made EMIs. Besides, the signal level is very low due to the poor efficiency of the transmitting antennas. Thereby the signal-to-noise ratio (SNR) at the receiving terminals can be a few decibels lower than zero.

Great challenges faced by TEC include the signal reception and interference suppression [1]. Classical methods for ridding TEC signals of the effects of EMIs mainly consist of the adaptive filtering, such as adaptive clipper combined with direct matrix inversion [4] and adaptive noise cancellation combined with nonlinear processing [5]. The signal-to-interference ratio gain (SIRG) could be -2 to $+12$ dB and 10–24 dB respectively.

Generally for TEC, the receiving system is built through spatially separated antennas for up-link (from underground or underwater to surface) signal reception. However, in these situations where downlink signals need to be received, the receiving sites underground and underwater are usually provided with limited space and complicated terrain, such as in the underground mine sites. So it is unfeasible to deploy remote reference sensors. Thus a novel magnetic field sensing system which employs local multiple reference sensors orthogonal with the primary receiving antenna, was proposed in [6] for downlink signal reception for TEC. Both the primary and reference sensors are made up of the ferromagnetic-cored search coil magnetometers (SCMs), which feature high sensitivity and small size. Take the cancellation of PLHIs as example, the average 36 dB of SIRG and 18 dB of SINRG (signal to interference-plus-noise ratio gain) could be obtained through multichannel recursive least squares (MRLS) algorithm. Whereas the receiving system is much more compact and the whole volume is as little as $10^{-2}\,\mathrm{m}^3$.

The adaptive filtering algorithms are correlation dependent, and namely the uncorrelated noise between reference channels such as the background white noise, could be superposed to the output of the noise canceller. So the corresponding SINRG could be much smaller than the SIRG. This may be severe when the uncorrelated noise between reference input is in a high level.

Another effective signal enhancement technique for multiple sensors is the beamforming. Beamformers are spatio-temporal filters, which enhance the signal with a specific spatial properties while suppress the noise and interference thereof. The statistically optimal beamformers, which require the statistical knowledge of the desired

---

[*] Corresponding author.
E-mail addresses: zhaopeng@cug.edu.cn (P. Zhao), huqiaolin@nudt.edu.cn (Q.-l. Hu).

https://doi.org/10.1016/j.aeue.2018.01.014
Received 29 August 2017; Accepted 16 January 2018

and interference signals, can be designed by several criteria, such as maximum signal-to-noise ratio (MSNR), minimum mean-squared error (MMSE) and linearly constrained minimum variance (LCMV) [7,8]. Among the LCMV beamformers, one of the most well-known case is the minimum variance distortionless response (MVDR) beamformer [9,10], also known as Capon beamformer [11], which features high resolution and is useful especially in multiple source context [12]. However, for general TEC downlink receptions, the wavelengths of interference and desired signal are usually much greater than the sensor spacing and thus the relative phase shift between the sensor output is very little. So the common MVDR beamformer may not work effectively for the TEC downlink signal enhancement.

In this paper, we propose a modified MVDR beamformer which is designed by exploiting the structure of the receiving system in [6] and real TEC operating conditions. Firstly a brief introduction of the sensing system proposed in [6] is presented. The received signal is modeled from a perspective of array reception in the time and frequency domain. Then, the MVDR beamformer is introduced and modified specially for the signal propagation model. Finally, real tests with EMIs consisting of PLHIs plus an additional wideband jamming, are conducted to examine the interference reduction performances. The experimental procedure and results are presented in detail.

2. Introduction of the receiving system and its signal model

2.1. Brief introduction of the receiving system

The noise and EMIs in the frequency range where TEC is operated are high-level and non-stationary. Although lots of statistical models have been proposed [13], it is usually difficult to predict and suppress them by conventional fixed-parameter filters. So a more enlightening way is acquiring them in real time and suppressing them by adaptive algorithms.

Thus a magnetic sensing system with multiple vector sensors was proposed in [6] for TEC downlink signal reception. The top view of this sensing system is shown as Fig. 1. N ($N \geq 1$) pairs of reference SCMs (Coil 1 to $2N$) are deployed uniformly along the primary SCM (Coil 0) core axis by considerable distance. Both the two SCMs of each pair are orthogonal mutually and are orthogonal with the primary SCM too, so the structure of three-axial magnetic field sensor is obtained. All the SCMs are deployed locally to make the whole system compact and small in size so that it can be set underground and underwater more easily.

In Fig. 1, Coil 0 refers to the primary SCM, whose core axis is parallel to the x axis. Coil 1, 3, …, 2N − 1 and Coil 2, 4, …, 2N denote the reference SCMs which are parallel to the y axis and z axis respectively. Coil 0 is wrapped with an aluminum cavity for electric filed shielding.

All of the bandwidths, resonant frequencies, sensitivity thresholds and volumes of the SCMs were finely tuned and optimized to meet the demands of TEC downlink reception and EMI suppression.

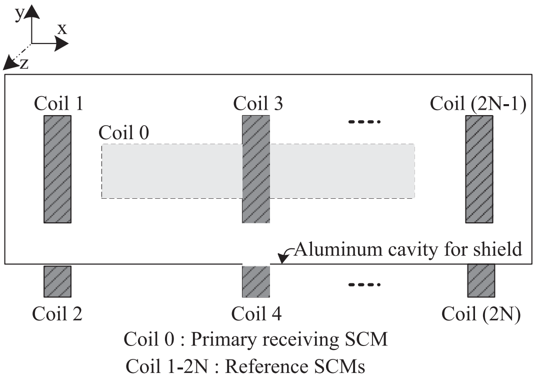

Fig. 1. Top view of TEC receiving system.

2.2. Signal model

In this section, we first construct the signal model from a perspective of array reception. Then, the signal model is extended to the situation of TEC reception.

Consider an array of $2N + 1$ sensors which is shown in Fig. 1. The signal s is emitted through a transmitting antenna which is oriented in the same direction as that of the primary receiving SCM. Propagation of the signal to the sensors is modeled in the time domain as

$$\begin{aligned} x_n(k) &= \boldsymbol{f}_n(k) \otimes \boldsymbol{s}(k) + g_n(k) \\ &= f_{n,0}(k) \otimes s(k) + \textstyle\sum_{u=1}^{U} f_{n,u}(k) \otimes i_u(k) + g_n(k) \end{aligned} \tag{1}$$

where $x_n(k)$ denotes the output of nth sensor, $\boldsymbol{s}(k) = [s(k), i_1(k), \dots, i_U(k)]$ is the source vector, $U \geq 1$. $\boldsymbol{f}_n(k) = [f_{n,0}(k), f_{n,1}(k), \dots, f_{n,U}(k)]$ denotes the impulse response vector, $f_{n,0}(k)$ and $f_{n,u}(k)$ denote the impulse response from the desired source s and uth interferer i_u to the nth sensor respectively, u, $n \in \mathrm{N}^+$ and $1 \leq u \leq U$, $0 \leq n \leq 2N$. $g_n(k)$ denotes the additive Gaussian noise. k is the discrete time index. $\otimes$ denotes convolution.

Transposing to the frequency domain, (1) can be rewritten as

$$X_n(j\Omega) = |F_{n,0}(j\Omega)|S(j\Omega)e^{-j\Omega\tau_{n,0}} + \sum_{u=1}^{U} |F_{n,u}(j\Omega)|I_u(j\Omega)e^{-j\Omega\tau_{n,u}} + G_n(j\Omega), \tag{2}$$

where $\tau_{n,m}$ is the time delay, which includes the propagation delay from the mth source to the nth sensor and the additional delay from the sensor response, $m = 0, 1, \dots, U$. Ω represents the discrete frequency.

Note that, as the sensors are not omnidirectional and each sensor would induce one of the three Cartesian components of the magnetic field, so a projection coefficient should be taken into account. Thus the signal model can be rewritten as

$$\begin{aligned} X_n(j\Omega) &= \beta_{n,0}|F_{n,0}(j\Omega)|S(j\Omega)e^{-j\Omega\tau_{n,0}} \\ &+ \sum_{u=1}^{U} \beta_{n,u}|F_{n,u}(j\Omega)|I_u(j\Omega)e^{-j\Omega\tau_{n,u}} + G_n(j\Omega), \end{aligned} \tag{3}$$

where $\beta_{n,m}$ denotes the orthogonal projection coefficient from the mth incident magnetic field to the nth sensor.

The signal model is better summarized in a vector notation as

$$\begin{aligned} \mathbf{X}(j\Omega) &= \mathbf{D}\cdot\mathbf{S}(j\Omega) + \mathbf{G}(j\omega) \\ &= S(j\Omega)\mathbf{d}_0(j\Omega) + \textstyle\sum_{u=1}^{U} I_u(j\Omega)\mathbf{d}_u(j\Omega) + \mathbf{G}(j\Omega) \end{aligned} \tag{4}$$

where $\mathbf{X}(j\Omega) = [X_0(j\Omega), X_1(j\Omega), \dots, X_{2N}(j\Omega)]^T$, $\mathbf{S}(j\Omega) = [S(j\Omega), I_1(j\Omega), \dots, I_U(j\Omega)]^T$, $\mathbf{G}(j\Omega) = [G_0(j\Omega), G_1(j\Omega), \dots, G_{2N}(j\Omega)]^T$. $\mathbf{D}$ represents the propagation matrix,

$$\mathbf{D} = [\mathbf{d}_0(j\Omega), \mathbf{d}_1(j\Omega), \cdots, \mathbf{d}_U(j\Omega)] \tag{5}$$

$$\mathbf{d}_m(j\Omega) = \left[\beta_{0,m}|F_{0,m}\left(j\Omega\right)|e^{-j\Omega\tau_{0,m}}, \beta_{1,m}|F_{1,m}\left(j\Omega\right)|e^{-j\Omega\tau_{1,m}}, \cdots, \beta_{2N,m}|F_{2N,m}\left(j\Omega\right)|e^{-j\Omega\tau_{2N,m}}\right]^T \tag{6}$$

where $\mathbf{d}_m \in \mathrm{C}^{(2N+1)\times 1}$denotes the steering vector of mth source, superscript ^{T} denotes transpose operation.

It is important to note that the clearance distance between the SCMs are usually much more smaller than the wavelength in the TEC frequency range, so the propagation delays between these sensors can be neglected, namely $\tau_{n,m} = \tau_m$ as a constant for all $n = 0, 1, \dots, 2N$. Thus the steering vector can be rewritten as

$$\mathbf{d}_m(j\Omega) = e^{-j\Omega\tau_m}[\beta_{0,m}|F_{0,m}(j\Omega)|, \beta_{1,m}|F_{1,m}(j\Omega)|, \cdots, \beta_{2N,m}|F_{2N,m}(j\Omega)|]^T \tag{7}$$