Blind Source Separation for Satellite Communication Anti-jamming

Hua Yang[1], Hang Zhang[1(✉)], Jiang Zhang[2], Liu Yang[1], and Pengfei Wang[1]

[1] College of Communication and Engineering, Army Engineering University of PLA, Nanjing 210007, Jiangsu, China
zhanghangnj@126.com

[2] 63rd Research Institute, National University of Defense Technology, Nanjing 210007, Jiangsu, China

Abstract. In this paper, the feasibility of applying blind source separation (BSS) to satellite communication (SatCom) anti-jamming is studied. And an EASI-based BSS method is introduced for anti-jamming processing for SatCom system. This method achieves the elimination of jamming signal by separation. Meanwhile, the anti-jamming ability of this method is completely dissected herein. Experimental simulations are conducted to demonstrate the availability of the EASI-based anti-jamming processing method. Simulation results show that the EASI-based method can effectively separate the jamming signal. And, after EASI-based anti-jamming processing, the signal-to-jamming-plus-noise ratio nearly approximates the signal-to-noise ratio and the available transmission rate of SatCom system approaches the theory rate.

Keywords: Satellite communication anti-jamming · Blind source separation · EASI · Transmission rate

1 Introduction

Contrasted to conventional ground communication, satellite communication (SatCom) [1–3] can cover larger area and connect longer distance due to its inherent height advantage. Especially, in some rough terrains (e.g., high mountain, canyon and ocean, etc.) that can't build the base station for ground communication, the function of SatCom is irreplaceable. Therefore, not surprisingly, SatCom plays a very important role in both of civilian and military communication fields. For modern warfare, military SatCom even serves as a multiplier role for the winning of warfare, as it can significantly enhance the capacity of cross-regional command, control and cooperation, e.g., in the C^4ISR systems [4,5].

However, as communication satellite exposes in the space and its orbit is relatively stationary (e.g., the geostationary orbit), it is easy to be jammed by

Supported by National Natural Science Foundation of China under Grant 61671475.

M. Jia et al. (Eds.): WiSATS 2019, LNICST 280, pp. 717–726, 2019.
https://doi.org/10.1007/978-3-030-19153-5_70

hostile jammer no matter in uplink or downlink. There are many jamming styles, including single or multi-tone jamming, barrage or full band jamming [6], etc. When communication satellite is jammed, the quality of communication signal will be badly deteriorated that leads to the degradation of communication quality even communication outage. It would be fatal for the communication parties in the warfare, if without effective anti-jamming countermeasures. To cope with jamming signal, many methods can be employed, e.g., spread spectrum, adaptive antenna, and post anti-jamming signal processing [7], etc. Among these, post anti-jamming signal processing method is preferred, as it has lower complexity and higher transferability. It can be flexibly implemented in uplink or downlink.

Blind source separation (BSS) [8,9] is viewed as a powerful anti-jamming or interference cancellation method, due to its capacity of separating mixture of signals that are non-Gaussian and mutually statistically independent. Because the preconditions are easy to be satisfied, BSS can cope with various jamming or interference patterns. As in [10], a BSS-based radar anti-jamming approach is proposed to improve the tracking ability of radar systems. In [11], BSS is employed to cancel the jamming signal in frequency hopping communication system. In [12] and [13], BSS is used to deal with the self-interference problem for full-duplex communication systems. For BSS-based SatCom anti-jamming, there are also many literatures. As in [7], BSS is applied to eliminate the jamming signal encountering in the uplink of satellite communication systems. In [14], an adjacent satellite interference cancellation method based on BSS is introduced. A satellite communication system that removes unwanted in-band interference by BSS technology is investigated in [15]. Although, many literatures have studied the application of BSS to SatCom anti-jamming. However, they only concentrate on the separation of communication signal and jamming signal and lack comprehensive analysis of the anti-jamming ability of BSS-based method.

In this paper, we will fully analyze the anti-jamming ability of BSS-based method, and an EASI-based anti-jamming processing method is correspondingly introduced. In addition, experimental simulations are conducted to verify the analysis, including the anti-jamming ability and available transmission rate of the EASI-based method are evaluated.

2 System Model

Assume that there are deployed with two receiving antennas in the communication satellite or ground receiver, then the baseband received signal model under jammed environment at a sampling time can be formulated as

$$\mathbf{x} = \mathbf{H}\mathbf{s} + \mathbf{n} \tag{1}$$

where $\mathbf{x} = [x_1, x_2]^T$ denotes the received signal vector, $\mathbf{s} = [s_1, s_2]^T$ represents the transmitted signal vector with s_1 being the communication signal and s_2 being the jamming signal, $\mathbf{H} \in \mathbb{C}^{2\times 2}$ is the channel coefficient matrix and is assumed to be flat fading, and $\mathbf{n} \in \mathbb{C}^{2\times 1}$ is the additive white Gaussian noise vector with zero mean and σ_n^2 variance.

The jamming signal s_2 badly deteriorates the quality of communication signal s_1. And signal-to-jamming-plus-noise ratio (SJNR) is used to measure the quality of communication signal, that is

$$SJNR_i = \frac{|h_{i1}s_1|^2}{|h_{i2}s_2|^2 + \sigma_n^2},\ i\ =\ 1,\ 2 \tag{2}$$

where h_{ij} is the (i, j) th element of $\mathbf{H}$. Without effective jamming elimination or suppression, the SJNR condition would be very low as jamming signal usually has stronger power level than communication signal, which leads to the degradation of communication quality (i.e., symbol error ratio (SER) increasing) even communication outage when SER increasing to an intolerable level. For military communication, it would be fatal. Therefore, it is vital to resort to corresponding anti-jamming processing method to deal with possible encountered jamming signal.

3 BSS for Anti-jamming

As communication signal and jamming signal come from different transmitters, naturally, they can be treated as mutually statistically independent source signals. Meanwhile, they are also non-Gaussian. These make it feasible to utilize BSS [8,9] to separate the mixture of communication signal and jamming signal.

BSS can estimate a separating matrix $\mathbf{W} \in \mathbb{C}^{2\times 2}$ to separate the received signal vector $\mathbf{x}$ (i.e., the mixture of communication signal and jamming signal) and then make the elements among the separated signal vector $\mathbf{y}$ (defined as $\mathbf{y} = \mathbf{W}\mathbf{x}$) be mutually statistically independent signals. In fact, BSS procedure renders the product of separating matrix $\mathbf{W}$ and channel matrix $\mathbf{H}$ be equivalent to a generalized permutation matrix (i.e., there is only one non-zero element in each row and column). In that case, the separated signal vector $\mathbf{y}$ is a valid estimation of the transmitted signal vector $\mathbf{s}$. There are up to an ambiguity of order and scaling (amplitude and phase), and some noise disturbance between the two signal vectors. That is

$$\mathbf{y} = \mathbf{W}\mathbf{x} = \mathbf{W}\mathbf{H}\mathbf{s} + \mathbf{W}\mathbf{n} = \mathbf{G}\mathbf{s} + \tilde{\mathbf{n}} \tag{3}$$

where $\mathbf{G}$ denotes the generalized permutation matrix, and $\tilde{\mathbf{n}} = \mathbf{W}\mathbf{n}$ is the noise disturbance. In other words, communication signal and jamming signal are no longer mixed together in the separated signal vector $\mathbf{y}$. The negative effect of jamming signal on communication signal is eliminated, and then the anti-jamming purpose is achieved.

3.1 EASI-Based Anti-jamming Processing Method

Many effective BSS algorithms can be employed to implement the separation of communication signal and jamming signal for the target of SatCom anti-jamming, including EASI [16], JADE [17] and FastICA [18]. In this paper, we will primarily introduce an EASI-based anti-jamming processing method.

The iterative equation of separating matrix $\mathbf{W}$ of EASI algorithm is formulated as

$$\mathbf{W}[k+1] = \mathbf{W}[k] - \mu\left(\mathbf{y}[k]\mathbf{y}^H[k] - \mathbf{I} + \boldsymbol{\varphi}\left(\mathbf{y}[k]\right)\mathbf{y}^H[k] - \mathbf{y}[k]\boldsymbol{\varphi}^H\left(\mathbf{y}[k]\right)\right)\mathbf{W}[k] \tag{4}$$

where k denotes the sampling time index, $\mu \in (0, 1]$ represents the step size, $\boldsymbol{\varphi}(\mathbf{y}) = [\varphi_y(y_1), \varphi_y(y_2), \ldots, \varphi_y(y_N)]^T$ with $\varphi_y(y_i)$ being the nonlinear kernel function (NKF) of the i th element y_i of $\mathbf{y}$ and N being the number of source signals, superscript ^{H} is the conjugate transpose operator, and $\mathbf{I} \in \mathbb{R}^{N\times N}$ is the identity matrix.

For the stability of algorithm, there is a normalized version, that is

$$\mathbf{W}[k+1] = \mathbf{W}[k] - \mu\left(\frac{\mathbf{y}[k]\mathbf{y}^H[k] - \mathbf{I}}{1+\mu\mathbf{y}^H[k]\mathbf{y}[k]} + \frac{\boldsymbol{\varphi}\left(\mathbf{y}[k]\right)\mathbf{y}^H[k] - \mathbf{y}[k]\boldsymbol{\varphi}^H\left(\mathbf{y}[k]\right)}{1+\mu\left|\mathbf{y}^H[k]\boldsymbol{\varphi}\left(\mathbf{y}[k]\right)\right|}\right)\mathbf{W}[k] \tag{5}$$

After separating matrix $\mathbf{W}$ is well estimated, the anti-jamming processing can be implemented as in (3). Certainly, subsequent extraction and phase recovery for the communication signal are necessary, however, we don't intend to elaborate as these are out the scope of this paper.

And the SJNR after EASI-based anti-jamming processing can be expressed as

$$SJNR_{\text{EASI}} = \frac{\max\limits_i \left\{\left|g_{i1}s_1\right|^2\right\}}{\left|g_{i2}s_2\right|^2 + \sigma_n^2\|\mathbf{w}_i\|^2} \tag{6}$$

where g_{ij} denotes the (i, j) th entry of $\mathbf{G}$, and $\mathbf{w}_i$ is the i th row of $\mathbf{W}$. As $\mathbf{G}$ is equivalent to a generalized permutation matrix, $g_{i2} \approx 0$, the jamming item $\left|g_{i2}s_2\right|^2$ approaches zero. In addition, the noise power may be enhanced, however, its effect is little or negligible. Then, the SJNR is improved.

3.2 Anti-jamming Ability Analysis

As only requiring source signals to be mutually statistically independent, EASI algorithm can adapt to various jamming patterns, including single or multi tone jamming, barrage or full band jamming, etc. And, not constrained in SatCom anti-jamming, EASI algorithm can also be applied to unintentional interference cancellation, e.g., co-channel interference cancellation in MIMO system, and self-interference cancellation in full-duplex communication system [12,13].

In addition, EASI algorithm is capable of countering strong jamming signal. Essentially, when the iteration of separating matrix $\mathbf{W}$ arrives a stationary point, the update term in (4) would be zero, that is

$$\mathrm{E}\left\{\mathbf{y}\mathbf{y}^H - \mathbf{I} + \boldsymbol{\varphi}(\mathbf{y})\mathbf{y}^H - \mathbf{y}\boldsymbol{\varphi}^H(\mathbf{y})\right\} = \mathbf{0} \tag{7}$$

where $\mathrm{E}\left\{\cdot\right\}$ denotes the expectation operator, and $\mathbf{0}$ represents the zero matrix. And Eq. (7) can be decomposed into symmetric and skew-symmetric parts, namely

$$\mathrm{E}\left\{\mathbf{y}\mathbf{y}^H - \mathbf{I}\right\} = \mathbf{0} \tag{8}$$

$$\mathrm{E}\left\{\boldsymbol{\varphi}(\mathbf{y})\mathbf{y}^H - \mathbf{y}\boldsymbol{\varphi}^H(\mathbf{y})\right\} = \mathbf{0} \tag{9}$$

Equation (8) ensures the separated signal vector $\mathbf{y}$ being spatially white, and (9) guarantees the components among the separated signal vector $\mathbf{y}$ being mutually statistically independent. Seemingly, there are nothing special. However, in the anti-jamming context, these characteristics make a big difference. The mutually statistically independent condition makes the communication signal and jamming signal no longer be mixed together, then the negative effect of jamming signal on communication signal is eliminated. And the spatially white condition makes the separated communication signal and jamming signal be unit variance. What it means? The separated jamming signal would be suppressed to the same power level as communication signal no matter how strong the emitted jamming signal is, which makes EASI algorithm be capable of countering strong jamming signal. Therefore, we can conclude that EASI algorithm is a powerful anti-jamming processing method.

4 Experimental Simulations

In this section, EASI algorithm is experimentally employed to perform the anti-jamming processing for SatCom system in the downlink. In the simulations, we assume that quadrature amplitude modulation (QAM) is adopted as the modulation scheme for communication signal, and the jamming pattern is single tone jamming. The channel is assumed to be block flat, its coefficients are randomly generated complex variables with absolute value belonging to $(0, 1)$, and the length of symbol block is set to 1000. In addition, the symbol rate is set to 2.4 kHz, the roll-off factor of shaping filter is set to 0.35, the jamming frequency point in baseband is set to 800 Hz, and the baseband signal sampling frequency Fs is set to 19.2 kHz. For EASI algorithm, the step size μ is set to 0.002, and the NKF is set to $\varphi_y(y_i) = y_i|y_i|^2$.

4.1 Anti-jamming Ability

First, we evaluate the anti-jamming ability of EASI algorithm. The waveform (only the real part) and spectrum of the communication signal (4QAM), jamming signal, and received signal are illustrated in Fig. 1. The signal-to-noise ratio (SNR) is 20 dB, and the jamming-to-signal ratio (JSR) equals 50 dB. And in Fig. 2, the waveform and spectrum of the separated communication signal and jamming signal are plotted. Although the jamming signal is overwhelming to the communication signal in the received signal as shown in Fig. 1, we can note that the communication signal and jamming signal are effectively separated both in waveform and spectrum from Fig. 2. And, the separated jamming signal nearly has the same power level as the separated communication signal. These prove the separation and suppression abilities of EASI algorithm to strong jamming signal.

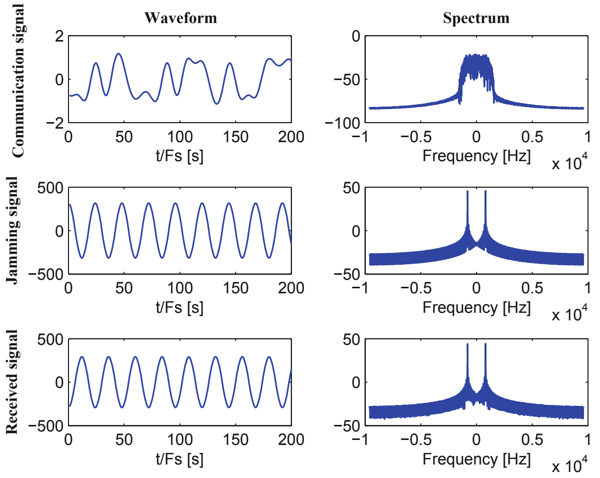

Fig. 1. Waveform and spectrum of the communication signal, jamming signal, and received signal. SNR = 20 dB, and JSR = 50 dB.

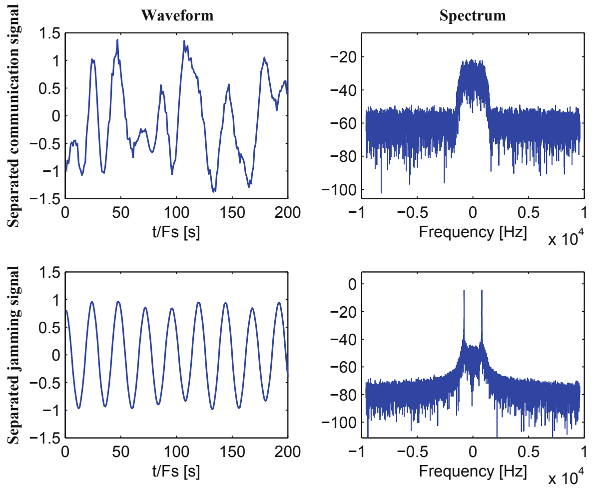

Fig. 2. Waveform and spectrum of the separated communication signal and jamming signal.

In Fig. 3, the constellations of the received signals, separated communication signal and separated jamming signal are shown. We can observe that the communication signal is submerged by the strong jamming signal in the received signals. However, after BSS-based anti-jamming processing, the constellation of communication signal is effectively recovered. And there is a phase offset due to the inherent ambiguity of BSS procedure.

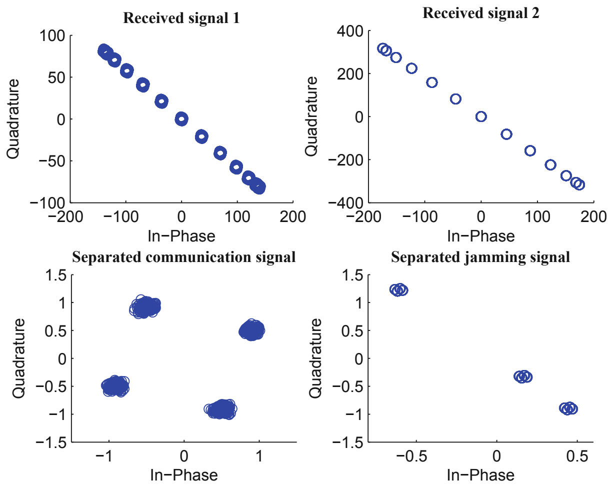

Fig. 3. Constellations of the received signals, separated communication signal and separated jamming signal.

In Fig. 4, the symbol SJNR curves in different JSR conditions are shown. The SJNR_NJC means the no jamming cancellation case (NJC), and the SJNR_EASI means the EASI-based anti-jamming processing case. We can note that the symbol SJNR curve with EASI-based anti-jamming processing almost approximates the SNR condition and is unaffected by the JSR condition. It also demonstrates the strong anti-jamming ability of EASI algorithm.

4.2 Available Transmission Rate

Secondly, we theoretically assess the available transmission rate for the SatCom system with EASI-based anti-jamming processing. And the transmission rate is calculated as [19]

$$R = \log_2(M) * (1 - SER(M, SJNR)) \text{ [bps/Hz]} \tag{10}$$

with

$$SER(M, SJNR) = 1 - \left[1 - \left(1 - \frac{1}{\sqrt{M}}\right) * \operatorname{erfc}\left(\sqrt{\frac{1.5 * SJNR}{M-1}}\right)\right]^2 \tag{11}$$

where M denotes the modulation order, $SER(\cdot)$ is the symbol error ratio function, and $\operatorname{erfc}(\cdot)$ is the complementary error function.

From Fig. 5, we can know that the available transmission rates with EASI-based anti-jamming processing approximate the theory value in different modulation order, and the NJC cases drop fast when JSR increasing. It indicates that the quality of communication can be effectively ensured with EASI-based anti-jamming processing.

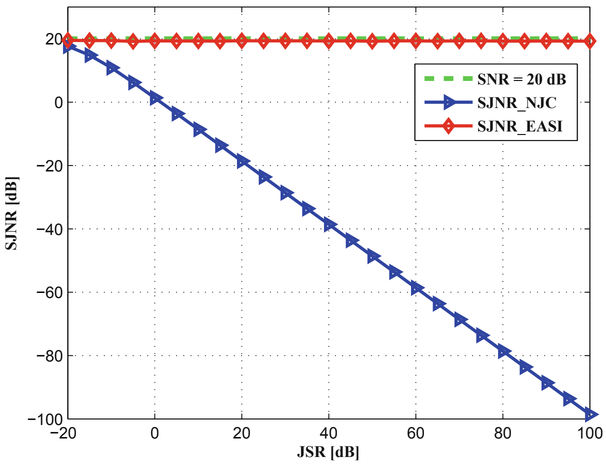

Fig. 4. Symbol SJNR versus JSR.

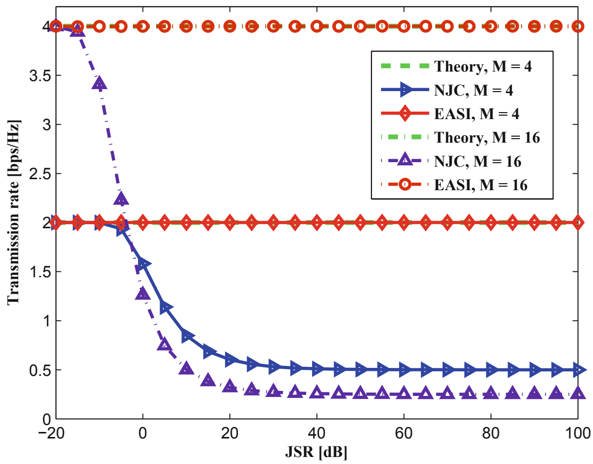

Fig. 5. Transmission rate versus JSR.

5 Conclusions

In this paper, the issue that employing BSS to SatCom anti-jamming is investigated, and an EASI-based anti-jamming processing method is introduced. By separating the received signal basing on the independence between communication signal and jamming signal, this method is capable of eliminating the negative effect of jamming signal on communication signal. Meanwhile, from the perspective of algorithm, the anti-jamming ability of this method is fully analyzed herein. Experimental simulations are carried out to prove the availability of the EASI-based anti-jamming processing method. The simulation results show that the EASI-based method can effectively separate the mixture of communication signal and jamming signal. And, with EASI-based anti-jamming processing, the SJNR nearly approximates the SNR condition and the available transmission rate approaches the theory rate.

References

1. Matin, M.A.: Satellite communication systems. In: Communication Systems for Electrical Engineers. SECE, pp. 107–124. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-70129-5_7
2. Elbert, B.R.: The Satellite Communication Applications Handbook. (Artech House Space Applications Series). Artech House Inc., Norwood (2003)
3. Fritz, D.A., Doshi, B.T., Oak, A.C., et al.: Military satellite communications: Space-based communications for the global information grid. Johns Hopkins APL Tech. Dig. **27**(1), 32–40 (2006)
4. Jinfeng, Z., Chen, Z., Songhua, H., et al.: An effects analysis method for C4ISR system structure based on information flow. In: 2017 36th Chinese Control Conference (CCC), pp. 10149–10154. IEEE (2017)
5. Zhou, F., Ding, R., Yi, K.: The research of C4ISR system design and modeling method based on model. In: Proceedings of the 2017 The 7th International Conference on Computer Engineering and Networks, CENet2017, 22–23 July 2017 Shanghai, China (2017)
6. Rao, G.K., Rao, R.S.H.: Status study on sustainability of satellite communication systems under hostile jamming environment. In: 2011 Annual IEEE India Conference on (INDICON), pp. 1–7. IEEE (2011)
7. Lin, B., Zhang, B.N., Guo, D.S.: Blind source separation in noisy environment and applications in satellite communication anti-jamming. In: Asia-Pacific Conference on Computational Intelligence and Industrial Applications, PACIIA 2009, pp. 96-99. IEEE (2009)
8. Naik, G.R., Wang, W.: Blind Source Separation. Springer, Heidelberg (2014). https://doi.org/10.1007/978-3-642-55016-4
9. Comon, P., Jutten, C.: Handbook of Blind Source Separation: Independent Component Analysis and Applications. Academic Press, Cambridge (2010)
10. Huang, G.M., Yang, L.X., Su, G.Q., Blind source separation used for radar anti-jamming. In Proceedings of 2003 International Conference on Neural Networks and Signals Processing (2003)
11. Zhu, X., Liu, Y., Zhang, X.: A blind source separation-based anti-jamming method by space pre-whitening. In: 2016 7th IEEE International Conference on Software Engineering and Service Science (ICSESS), pp. 454–457. IEEE (2016)
12. Li, J., Zhang, H., Fan, M.: Digital self-interference cancellation based on independent component analysis for co-time co-frequency full-duplex communication systems. IEEE Access **PP**(99), 1 (2017)
13. Yang, H., Zhang, H., Zhang, J., et al.: Digital self-interference cancellation based on blind source separation and spectral efficiency analysis for the full-duplex communication systems. IEEE Access **6**, 43946–43955 (2018)
14. Li, C., Zhu, L., Zhang, Z.: Underdetermined blind separation of adjacent satellite interference in modern satellite communication systems (2017)
15. Downey, M.L., Chu, J.C.: System for and method of removing unwanted inband signals from a received communication signal: U.S. Patent 9,537,521, 3 January 2017

16. Cardoso, J.F., Laheld, B.H.: Equivariant adaptive source separation. IEEE Trans. Sig. Process. **44**(12), 3017–3030 (1996)
17. Nordhausen, K., Cardoso, J.F., Miettinen, J., et al.: JADE: Blind source separation methods based on joint diagonalization and some BSS performance criteria. J. Stat. Softw. **76**, 1–31 (2017)
18. Hyvärinen, A., Oja, E.: A fast fixed-point algorithm for independent component analysis. Neural Comput. **9**, 1483–1492 (1997)
19. Catreux, S., Driessen, P.F., Greenstein, L.J.: Data throughputs using multiple-input multiple-output (MIMO) techniques in a noise-limited cellular environment. IEEE Trans. Wirel. Commun. **1**(2), 226–235 (2002)