Interference-to-noise ratio estimation in long-term evolution passive radar based on cyclic auto-correlation

Haitao Wang,1 Xiaoyong Lyu,2,10 and Liping Zhong1

1School of Information and Communication, Guilin University of Electronic Technology, Guilin, China
2School of Information Engineering, Zhengzhou University, Zhengzhou, China

Correspondence
X. Lyu, School of Information Engineering, Zhengzhou University, Zhengzhou, 450001, China.
Email: iexyl@zzu.edu.cn

This letter considers the interference-to-noise ratio (INR) estimation problem in long-term evolution (LTE)-based passive bistatic radar. The INR is of great importance in the evaluation of interference level, the prediction of the target detection capability and the target parameter estimation. Traditional passive radar uses the cross-correlation function between the reference and surveillance signals to estimate the INR. This is not applicable to LTE-based passive radar due to the uncorrelation between the interference and reference signals in LTE-based passive radar. In this letter, we propose a cyclic auto-correlation method to estimate the INR. Simulation results show the effectiveness of the proposed method.

Introduction: Recently, passive radars have received renewed interest [1, 2]. The long-term evolution (LTE) signal provides remarkable advantages when used as the illuminator of opportunity (IoO) of the passive radars, including the broad bandwidth and wide coverage [3–5]. Therefore, particular attention has been paid to the LTE-based passive radars. In LTE communication systems, there usually exist multiple base stations (BSs) sharing the same frequency band owing to the frequency reuse mechanism. The interference signals in LTE-based passive radar include not only the direct and multipath signals (DMS) from the BS that is used as the IoO (BS-IoO) but also the co-channel interference (CI) from the co-channel BS (CC-BS) that work in the same channel as the BS-IoO. In order to remove the interference from CC-BS, cascaded cancellation method [6, 7], which is similar to the CLEAN cancellation method [8], is usually used. In cascaded cancellation method, the INR should be evaluated after each cancellation stage to show whether all the CIs have been suppressed adequately. Then, according to the INR of the remaining signal, the algorithm determines whether the cancellation procedure stops. Additionally, the INR also plays significant roles in other aspects of passive radar. For example, we can predict the target detection capability with the knowledge of the interference level indicated by the INR. Meanwhile, some target parameter estimation methods based on the maximum likelihood assume that the covariance of the additive interference is known a priori, which can be easily estimated if the INR is known [9]. So the estimation of the INR is necessary for LTE-based passive radar.

The traditional passive radars calculate the range-Doppler cross-correlation function (RDCF) between the reference and surveillance signals and take the peak-to-noise floor ratio in the RDCF surface as an approximate estimate of the INR [10, 11]. This, however, can only be used to estimate the INR of the DMS, but cannot estimate that of the CI, because the waveforms of the CIs from different CC-BSs are different and they are not correlated with the reference signal. In this letter, we propose a cyclic auto-correlation (CAC) method for estimating the INR in LTE-based passive radar according to the cyclostationarity of the LTE signal.

Signal model: The LTE-based passive radar is shown schematically in Figure 1.

As can be seen from Figure 1, one BS is selected as the BS-IoO, and several CC-BSs are sited around the BS-IoO. The surveillance signals received by the radar receiver can be represented as

\[ s[n] = I[n] + z[n] + I[n] \quad n = 1, \ldots, N \] (1)

where \( I[n] \) and \( z[n] \) are the target echo and thermal noise. \( N \) is the total number of signal samples. \( I[n] \) is the interference signal from the BS-IoO and CC-BSs and can be written as

\[ I[n] = \sum_{l=1}^{N_l} \sum_{m=1}^{N_s} a_l[m] d_l[n - \tau_{l,m}] \] (2)

where \( d_l[n] \) is the direct signal from the \( l \)th BS, \( a_l[m] \) and \( \tau_{l,m} \) are the complex amplitude and delay of the \( m \)th multipath signal, \( N_l \) is the number of the multipath signals from each BS, \( N_s \) is the number of the CC-BSs plus the BS-IoO. Usually, the interference signals from different BSs have different waveforms and they are not correlated with each other. Therefore, the INR cannot be estimated using the RDCCF between the reference and interference signals. In the following, we develop a CAC method to estimate the power ratio of the interference signal to noise according to the cyclostationarity of the LTE signal.

estimation: It is quite general in passive radar that the target echo before integration is far weaker than the interference signal and noise (usually 60–100 dB weaker than the interference signal and can be at least 10 dB weaker than the noise [12]); thus, the target echo can be neglected when estimating the INR. Then, Equation (1) can be rewritten as

\[ \tilde{s}[n] = I[n] + z[n] \quad n = 1, \ldots, N \] (3)

The LTE signal adopts the orthogonal frequency division multiplexing (OFDM) modulation [4]. The frame structure of the signal is shown schematically in Figure 2.

As is shown in Figure 2, the LTE signal consists of a sequence of OFDM symbols. Each symbol consists of an OFDM useful signal and cyclic prefix (CP). We denote the lengths of the OFDM useful signal and CP by \( T \) and \( L \), respectively. The CP is the copy of one segment of the OFDM useful signal. Owing to this frame structure, the LTE signal has the cyclostationarity [13]. That is, the auto-correlation function of the signal has periodical peaks, and the period by which the peaks occur is equal to the length of the OFDM useful signal, that is, \( T \).
The CAC of the signal $\delta[n]$ is defined as

$$y_{\text{cac}}[k] = \sum_{n=1}^{N} \delta(n) s^\dagger(n + k) \quad k = 1, \ldots, K$$

\((4)\)

where $^\dagger$ is the conjugate operator. The CAC result of a simulated LTE signal is shown in Figure 3.

In the simulation, the sampling frequency is set to 30.72 MHz, the sample number of the OFDM useful signal is 2048, and the sample number of the CP is 144. The simulation setups are selected according to the specifications of the LTE protocol. It can be seen from Figure 3 that there are two apparent peaks in the CAC surface. The peak at $k = 0$ is due to the perfect match of the OFDM symbol. The peak at $k = 2048$ corresponds to the cyclostationarity of the LTE signal; it is caused by the match of the CP.

In the following, we will exploit the cyclostationarity of the LTE signal to estimate the INR. Combining Equations (3) and (4), the CAC $y_{\text{cac}}[k]$ at $k = 0$ can be written as

$$y_{\text{cac}}[0] = \sum_{n=1}^{N} I(n) I^\dagger(n) + \sum_{n=1}^{N} z(n) z^\dagger(n)$$

\((5)\)

$$+ \sum_{n=1}^{N} I(n) z^\dagger(n) + \sum_{n=1}^{N} z(n) I^\dagger(n) z(n)$$

Without loss of generality, we assume that the interference is independent of the thermal noise; then, Equation (5) can be manipulated as

$$y_{\text{cac}}[0] = \sum_{n=1}^{N} I(n) I^\dagger(n) + \sum_{n=1}^{N} z(n) z^\dagger(n)$$

\((6)\)

where $\sum_{n=1}^{N} I(n) I^\dagger(n)$ is the energy of the interference, and $\sum_{n=1}^{N} z(n) z^\dagger(n)$ is the energy of the thermal noise. Denoted by $\text{INR}$, the energy ratio between the interference and noise in Equation (6) can be rewritten as

$$y_{\text{cac}}[0] = \left(1 + \frac{1}{\text{INR}}\right) \sum_{n=1}^{N} I(n) I^\dagger(n)$$

\((7)\)

The CAC $y_{\text{cac}}[k]$ at $k = T$ is represented as

$$y_{\text{cac}}[T] = \sum_{n=1}^{N} I(n) I^\dagger(n + T) + \sum_{n=1}^{N} z(n) z^\dagger(n + T)$$

\((8)\)

$$+ \sum_{n=1}^{N} I(n) z^\dagger(n + T) + \sum_{n=1}^{N} z(n) I^\dagger(n + T)$$

Since the thermal noise has no cyclostationarity and the interference signal is independent of the noise, then Equation (8) can be approximated as

$$y_{\text{cac}}[T] = \sum_{n=1}^{N} I(n) I^\dagger(n + T)$$

\((9)\)

Combining Equations (7) and (9) we can get

$$\frac{y_{\text{cac}}[0]}{y_{\text{cac}}[T]} = \left(1 + \frac{1}{\text{INR}}\right) \frac{\sum_{n=1}^{N} I(n) I^\dagger(n)}{\sum_{n=1}^{N} I(n) I^\dagger(n + T)}$$

\((10)\)

Recall that $\sum_{n=1}^{N} I(n) I^\dagger(n)$ represents the perfect match of the signal. Suppose that the signal contains $M$ OFDM symbols. The integration gain of perfect term can be expressed as $M \times (T + L) \times E$, where $E$ denotes the average power of the signal. Furthermore, we know from the frame structure of the LTE signal shown in Figure 2 that in $\sum_{n=1}^{N} I(n) I^\dagger(n + T)$, only the signal corresponds to the CP matches. So the intensity of this term can be expressed as $M \times L \times E$. Consequently, we have

$$\frac{\sum_{n=1}^{N} I(n) I^\dagger(n)}{\sum_{n=1}^{N} I(n) I^\dagger(n + T)} \approx \frac{(T + L)}{L}$$

\((11)\)

Equation (11) can be verified through the simulation result in Figure 3. It can be seen from Figure 3 that the intensity of the peak at $k = 0$ is 24.97 dB, and the intensity of the peak at $k = 2048$ is equal to 1.272 dB. The intensity ratio between the two peaks can be calculated as 23.698 dB, which is very close to the result calculated by $(T + L)/L = 23.65$ dB.

Combining Equations (10) and (11) we can get

$$\frac{y_{\text{cac}}[0]}{y_{\text{cac}}[T]} \approx \left(1 + \frac{1}{\text{INR}}\right) \frac{(T + L)}{L}$$

\((12)\)

Then, the INR is estimated as

$$\text{INR} \approx \frac{\frac{y_{\text{cac}}[0]}{y_{\text{cac}}[T]} - (T + L) \frac{y_{\text{cac}}[0]}{y_{\text{cac}}[T]}}{L}$$

\((13)\)

**Simulation:** In this section, we test the CAC method through simulations. We take the simulated LTE signal as the IoS. According to the LTE protocol from the 3rd Generation Partnership Project (3GPP) [14], the length of the OFDM useful signal $T$ is set to 2048, and the length $L$ of the CP is set to 144. The sampling frequency is set to 30.72 MHz. In the simulation scenario, we set one BS-IoS, six CC-IoSS and one target.

We first calculate the RDCCF between the reference and surveillance signals and display it in Figure 4. As shown in Figure 4, the peak at the zero-Doppler slice of the RDCCF indicates that there are strong DMS in the surveillance signals. The target is masked below the interference floor. We use the cancellation method in [10] to suppress the DMS. The RDCCF after DMS cancellation is shown in Figure 5. It can be seen from Figure 5 that the peak at the zero-Doppler slice diminish, which indicates that the DMS has been cancelled. However, the target is still masked below the interference floor. This is due to the presence of the CIs. Since the waveform of the CIs is not correlated with the reference signal, there are no integrated peaks in the RDCCF at the positions of the CIs. Therefore, the RDCCF cannot indicate anything about the CIs. The interference level of the CIs, that is, the INR, can be estimated by the proposed method in this letter. With this information, one can determine whether extra effort is needed to further cancel the interference.

In the following, we test the INR estimation performance. We verify Equation (12) under a variety of real INRs. We use $R - LF$ to represent the left side of (12), that is,

$$R - LF = \frac{y_{\text{cac}}[0]}{y_{\text{cac}}[T]}$$

\((14)\)
The letter investigates the INR estimation problem in LTE-based passive radar. A CAC method is proposed for estimating the INR by using the cyclostationarity of the LTE signal. The method is tested through simulations. The results show that the proposed method can obtain good estimation of the INR in the LTE-based passive radar. The estimated INR provides significant information about the interference level remaining in the surveillance signal. With this information, decisions about whether further cancellation effort is needed can be made.

Acknowledgements: This work is partially supported by Guangxi Key Laboratory of Wireless Wideband Communication and Signal Processing and Ministry of Education Key Lab. of Cognitive Radio and Information Processing.

© 2021 The Authors. Electronics Letters published by John Wiley & Sons Ltd on behalf of The Institution of Engineering and Technology

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Received: 9 December 2020 Accepted: 9 February 2021
doi: 10.1049/el.12.12130

References
1 Karthik, A.K., Blum, R.S.: Improved detection performance for passive radars exploiting known communication signal form. IEEE Signal Process. Lett. 25(11), 1625–1629 (2018)
2 Gao, Y., Li, H., Himed, B.: Joint transmit and receive beamforming for hybrid active–passive radar. IEEE Signal Process Lett. 24(6), 779–783 (2017)
3 Evers, A., Jackson, J.A.: Cross-ambiguity characterization of communication waveform features for passive radar. IEEE Trans. Aerosp. Electron. Syst. 51(4), 3440–3455 (2015)
4 Salah, A.A., et al.: Experimental study of LTE signals as illuminators of opportunity for passive bistatic radar applications. Electron. Lett. 50(7), 545–547 (2014)
5 Abdullah, R.S., et al.: Experimental investigation on target detection and tracking in passive radar using long-term evolution signal. IET Radar Sonar Navig. 10(3), 577–585 (2016)
6 Xiaode, L.Ü., et al.: Research on co-channel base station interference suppression method of passive radar based on LTE signal. J. Electron. Inf. Technol. 41(9), 2123–2130 (2019)
7 Pingyu, L.I.U., et al.: Research on co-channel interference suppression method for passive radar based on the joint processing of primary and reference channels. J Radars (2020, in press)
8 Kulpa, K.: The CLEAN type algorithms for radar signal processing. In: 2008 Microwaves, Radar and Remote Sensing Symposium, Kiev, Ukraine, pp 152–157 (2008)
9 Zhang, X., et al.: Joint delay and Doppler estimation for passive sensing with direct-path interference. IEEE Trans. Signal Process. 64(3), 630–640 (2015)
10 Colone, F., et al.: A multistage processing algorithm for disturbance removal and target detection in passive bistatic radar. IEEE Trans. Aerosp. Electron. Syst. 45(2), 698–722 (2009)
11 Garry, J.L., Baker, C.J., Smith, G.E.: Evaluation of direct signal suppression for passive radar. IEEE Trans. Geosci. Remote Sens. 55(7), 3786–3799 (2017)
12 Willis, N.J., Griffiths, H.D.: Advances in Bistatic Radar, vol. 2. SciTech Publishing, Raleigh, NC (2007)
13 Gardner, W.A., Napolitano, A., Lastra, L.: Cyclostationarity: Half a century of research. Signal Process. 86(4), 639–697 (2016)
14 3GPP TS 36.211 V13.2.0. Physical channels and modulation. (2016)