INFORMATION-THEORETIC ESTIMATIONS OF COVER DISTORTION BY ADAPTIVE MESSAGE EMBEDDING

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Abstract: *Counteraction to confidential information leakage in commercial and public communication systems is topical problem today. There is taken special interest on early detection of messages that are embedded in widespread digital media, such as audio, images, videos etc. One of the most complex cases is connected with situation of limitation or even absence of a priory information of embedding method's features. Detection of hidden messages (stego files) requires search of cover parameters (features) that is sensitive to cover's weak alteration during message hiding. As such features we propose to use the information-theoretic based estimation of the cover elements distribution distortion, such as Kullback-Leibler divergence, Hellinger distance etc. The paper is devoted to performance analysis of these estimations usage for revealing the stego files, formed according to advanced embedding method, such UNIWARD, MG and MiPOD algorithms. It is shown that taking into account special-purpose information-theoretic indices, such as spectrum of Renyi divergences, allows us reliably detection of weak alteration the cover files even in case of low cover payload (less than 10%).*

Keywords: *digital images steganalysis, adaptive embedding methods, cover distortion.*

ITHEA Keywords: *K.6.5 Management of computing and information systems. Security and Protection; I.4.10 Image processing and computer vision. Image representation.*

Introduction

One of the traditional ways to reveal the unauthorized (hidden) transmission of confidential data is usage of stegdetector [Fridrich, 2009]. These modules are based on usage a statistical model of cover file, for instance digital image. Any differences of image parameters from mentioned model can be used for classification the file as containing the embedding message (stego file). Based on such approach there are developed a range of high-effective stegdetectors for reliable detection the wide set of steganographic (embedding) methods, such as OutGuess, nsF5, HUGO, WOW etc.

High accuracy of stego image detection requires preliminary tuning of stegdetector, namely optimization of cover model, based on steganographic method's features. It makes stegdetectors unsuitable for revealing a stego images, formed according to a priory unknown embedding method. Therefore it is needed development of universal (blind) stegdetector that allows reliably detection of stego files even in case of limitation or absence the information of used embedding method features.

There are proposed various approaches for design a blind stegdetector, based on generalization of cover model [Fridrich and Kodovský, 2012b; Progonov, 2017], usage of calibration function [Kodovsky, 2009] or applying of artificial neural network for automatization the cover model construction [Chen, 2017]. Important characteristic of these methods is approach of feature selection that will be used for subsequent files classifications as cover or stego. For one side, such features should be quite "common" for revealing wide range of known embedding methods. On the other hand, these features should be "sensitive" enough for revealing weak alteration of cover image caused by message hiding. Therefore determination of such cover parameters is non-trivial and complicated problem.

For solving mentioned problem we propose to use the information-theoretic indices of differences between cover and stego elements distributions. These indices allow distinguishing small distortion of cover elements distribution and can be used for processing any type of cover files. The paper is devoted to performance analysis of usage the common and special-purpose information-theoretic indices for revealing the cover image distortion case by adaptive message hiding.

Related works

Revealing and estimation of cover image parameters distortions due to message (stegodata) hiding play important role in digital steganalysis. In most practical cases detection of cover parameters alteration required creation a statistical models of cover image [Fridrich, 2009]. These models are taking into account various parameters of cover images, such as statistical characteristics (e.g. parameters of pixels brightness distributions), correlation of adjacency pixels brightness and fractal parameters [Progonov and Kushch, 2014a; Progonov and Kushch, 2014b]. For improving the stego image detection accuracy several models can be merged into the rich models. Well-known examples of rich models are:

- SRM model [Fridrich and Kodovský, 2012a] – is based on usage the Markov property of digital images (closeness of adjacency pixels brightness). The image residuals, computing using high-pass filters, are used for increasing the model's performance.
- CC-JRM model [Fridrich and Kodovský, 2012b] – one of the first models to reveal a stegodata that are embedded on JPEG-doain. For suppressing artifacts (image distortions) caused by JPEG-compression, there is used image calibration method, proposed by Jessica Fridrich [Kodovsky, 2009].
- J+SRM model [Fridrich and Kodovský, 2012b] – is obtained by merging of SRM and J+SRM models. Consolidated model allows revealing the stego images regardless of embedding domain and used for creation the universal stegdetectors.

- PSRM model [Holub, 2013] – is further improvement of SRM model by taking into account of first-order statistic (histogram) of the neighboring residual samples projections onto a set of random vectors. It gives opportunity to increase performance of stegdetectors in case of side-informed as well as modern adaptive embedding methods, such as UNIWARD methods.

Also it should be mentioned the cover image models, based on usage the structural analysis methods, such as fluctuation analysis and multifractal analysis [Progonov and Kushch, 2015a; Progonov and Kushch, 2015b]. Applying of these models allows improving the accuracy of stego image detection in case of modern adaptive embedding methods, such as MiPOD and Synch algorithms [Progonov, 2017].

Despite of high performance of proposed cover image models, practical applications of these models have several limitations. Firstly, it is high computational complexity of model’s parameters estimation – the number of model parameters is varied from 12,870 from PSRM model to 35,263 for J+SRM model. Secondly, accurate classification of cover and stego images requires protracted pre-calculation of model’s parameters values for cover and stego images on huge datasets, such as BOSS [Bas, 2011], MIRFlickr-25k or MIRFlickr-1M [Huiskes and Lew, 2008]. Thirdly, there should be recalculated the parameters of models in case of analysis a new embedding methods, that is increase the duration of detection methods development.

For overcome mentioned limitation of model-based steganalysis, there is proposed to use the calibration-based detection methods [Avcibas et al, 2003]. Feature of these methods is applying the calibration transformation to analyzed files for reconstruction the initial (empty) cover. Well-known example of calibration transformation is Fridrich method for suppressing artifacts of images JPEG-compression [Kodovsky, 2009] – decompression of initial JPEG-image, cropping of image first four rows and columns and further recompression the cropped image with same JPEG-encoder. On the other hand, calibration transformations are adapted for suppressing the specific types of cover distortions, such as compression, noise alteration, image enhancement etc. Therefore it is required usage of sets the calibration methods for achieve the high stego detection accuracy.

Emergence of advanced adaptive embedding methods, such as MG [Sedighi et al, 2015], MiPOD [Sedighi et al, 2016] and Synch [Denemark and Fridrich, 2015], leads to shift in attitudes of stegdetectors design. Limitation or even absence a priory information about features of used embedding methods leads to significantly reducing the performance of models-based as well as calibration-based stegdetectors. One of the proposed solutions is to use Artificial Neural Networks [Davidson et al, 2005] for construction the cover model based on huge dataset of initial (empty) covers. Despite of improving the performance of automatically-created cover models, this approach remains high computation exhausted.

Therefore it is needed new approaches for design the universal (blind) stegdetectors to be developed, that will be fast and have high detection accuracy even in case of absence the a priory information about embedding method features.

For solving mentioned task we propose to use the information-theoretic indices for disclosure and estimation a cover distortion due to message hiding. It should be mentioned that such indices are widely used as measure of steganographic algorithm security and, correspondingly, estimation of distinguishability between distributions of cover/stego images in steganalysis. As an example it can be used Kullback-Leibler divergence D_{KL} between distributions of cover (P_C) and stego (P_S) images pixels brightness:

$$D_{KL}(C\,||\,S) = \sum_{q\in\mathbf{Q}} P_C(q)\cdot\log_2\left(\frac{P_C(q)}{P_S(q)}\right), \tag{1}$$

where $\mathbf{Q}$ – is range of pixels brightness q. Values of Kullback-Leibler divergence can be also used in steganalysis for maximum likelihood estimation of image calibration’s parameters θ:

$$\hat{\theta} = \arg\min_{\theta} D_{KL}\left(\hat{P}(I), P(I,\theta)\right) = \arg\max_{\theta} \sum_i \ln\left(P(I_i,\theta)\right),$$

where $P(I_i,\theta)$ – distribution of pixel’s brightness for i[th] image; $\hat{P}(I)$ – estimation of pixel’s brightness distribution for initial cover.

Limitation of Kullback-Leibler divergence D_{KL} is relatively “insensitivity” to small alterations of distributions, namely stego (P_S) images pixels brightness (1). Therefore it does not allow us to accurate distinguish between cover and stego images, formed by minimization of cover image parameters alteration. Thus it is needed investigation of information-theoretic indices application for increasing discernibility of cover and stego images, created according to modern embedding method.

Task and challenges

Our purpose is performance analysis of information-theoretic indices application for revealing small alteration of cover image pixels brightness distribution by message embedding according to modern adaptive steganographic methods.

Information-theoretic indices for estimation a distributions alteration

Estimation a differences between probability distributions plays important roles in various scientific domains, such as information coding, machine learning, steganalysis etc. One of the well-known information-theoretic indexes for estimation such differences is Kullback-Leibler divergences (1). An alternative to D_{KL} is Hellinger distance D_H, Bhattacharaya distance D_B, chi-square-good-of-fitness a distributions D_{χ^2} [Bishop, 2006]:

$$D_H(C\,||\,S) = \frac{1}{\sqrt{2}}\sqrt{\sum_{q\in\mathbf{Q}}\left(\sqrt{P_C(q)} - \sqrt{P_S(q)}\right)^2}, \qquad (2)$$

$$D_B(C\,||\,S) = -\ln\left(1 - D_H^2(C\,||\,S)\right), \qquad (3)$$

$$D_{\chi^2}(C\,||\,S) = \sum\nolimits_{q\in\mathbf{Q}}\frac{\left(P_C(q) - P_S(q)\right)^2}{P_S(q)}, \qquad (4)$$

Hellinger distance D_H (2) is bounded metric on the space of probability distributions [Liese and Miescke, 2008] and is used to quantity the similarity of two distributions. Also this distance is close related to the Bhattacharaya coefficient $BC(C,S) = 1 - D_H^2(C\,||\,S)$. With usage of $BC(C,S)$ we can estimate the closeness of the amount of overlap between two image pixels brightness distributions as Bhattacharaya distance D_B [Bhattacharyya, 1943]. An alternative to D_B is chi-square distance D_{χ^2} (4), which is widely used in approximation theory.

In most cases, stegodata embedding into cover image leads to alteration the small subset of pixels brightness levels. Applying of mentioned distances (2)-(4) allows us estimation of difference between cover and stego images pixel's brightness distributions without taking into account mentioned alterations. Therefore it is represented the interest of usage the spectrum of Renyi divergences D_R [Renyi, 1960]:

$$D_R^\alpha(C \,||\, S) = \frac{1}{\alpha-1}\log_2\left(\sum\nolimits_{q\in Q} P_C^\alpha(q)\cdot P_S^{1-\alpha}(q)\right), \alpha \in (0;+\infty)\setminus\{1\}. \tag{5}$$

Varying of scaling parameter α gives us opportunity to “emphasize” range of pixels brightness with small ($0<\alpha<1$) or big ($\alpha>1$) probabilities to be obtained.

It should be emphasized, that mentioned distances (2)-(5) is defined for case of distance estimation from cover to stego image pixels brightness distribution. For increasing the differences between cover and stego elements distributions ($C \,||\, S$) it is also interested taking into account the reverse distance – from stego to cover elements distributions ($S \,||\, C$). Such replacement does not change values of Hellinger distance (2), because D_H is metric. On the other side, it will lead to alteration of Kullback-Leibler distance, Bhattacharaya distance D_B , chi-square-good-of-fitness a distributions D_{χ^2} as well as spectrum of Renyi divergences D_R . Therefore it is proposed to use in steganalysis the “direct” ($C \,||\, S$) as well as “reverse” ($S \,||\, C$) values of distances between cover and stego elements distributions.

Advanced methods for data embedding in digital images

Feature of modern embedding methods is minimization of cover image parameters alteration during stegodata hiding. As target functions there can be used heuristically defined distortion estimation, for example in UNIWARD-based methods, or statistical detectability of obtained stego images, for instance, MG and MiPOD methods. Let us describe each variant in detail.

Group of UNIWARD embedding methods is based on minimization the heuristically defined distortion function [Holub et al, 2014]:

$$\rho(\mathbf{x},\mathbf{y}) = \sum_{k=1}^{3}\sum_{u=1}^{n_1}\sum_{v=1}^{n_2}\frac{\left|W_{uv}^{(k)}(\mathbf{x}) - W_{uv}^{(k)}(\mathbf{y})\right|}{\sigma + \left|W_{uv}^{(k)}(\mathbf{x})\right|}, \tag{6}$$

where $\mathbf{x}, \mathbf{y}$ – correspondingly cover and stego images; $W_{uv}^{(k)}(\mathbf{x})$ – uv[th] wavelet coefficient in the k[th] subband of the first level the two-dimensional discrete wavelet transformation the cover image; $\sigma(\sigma > 0)$ – constant stabilizing the numerical calculations. It allows create the state-of-art uniform approach to cover image parameters disturbances regardless of the message embedding domains, for instance S-UNIWARD for embedding in spatial domain, J-UNIWARD – in JPEG domain, SI-UNIWARD – side-informed embedding in spatial domain [Holub et al, 2014].

Limitation of distortion-minimization based embedding methods is impossibility of estimation the statistical detectability of obtained stego images. Design of distortion functions that measure cover image distortions as well as statistical detectability of formed stego images is one of open problems in modern digital steganography [Ker et al, 2013].

One of possible solution for mentioned problem is to model the cover pixels as a sequence of independent Gaussian random variables with unequal variances (multivariate Gaussian or MVG). It gives opportunity to achieve the empirical security of the embedding methods, that is comparable with state-of-the-art steganographic methods [Holub and Fridrich, 2012; Holub et al, 2014]. Example of steganographic techniques, based on such approach, is MiPOD embedding method, which uses the locally-estimated multivariate Gaussian cover image model.

Message hiding in grayscale cover image $\mathbf{x}$ with size $M \times N$ (pixels) according to MiPOD method is carried out in several steps [Sedighi et al, 2016]:

1. Suppress the image content $\mathbf{x} = (x_1, x_2, \ldots, x_L)$, $L = M \cdot N$, using a denoising filter F:

$$\mathbf{r} = \mathbf{x} - F(\mathbf{x}),$$

   where $\mathbf{x}$ is represented in column-wise order;

2. Measure pixels residual variance σ_l^2 using Maximum Likelihood Estimation and local parametric linear model:

$$\mathbf{r}_l = \mathbf{G}\mathbf{a}_l + \xi_l, \tag{7}$$

where $\mathbf{r}_l$ – represents the value of the residual $\mathbf{r}$ inside the $p \times p$ block surrounding the l[th] residual put into a column vector of size $p^2 \times 1$; $\mathbf{G}$ – a matrix if size $p^2 \times p$ that defines the parametric model of remaining expectation; $\mathbf{a}_l$ – a vector of $q \times 1$ of parameters; ξ_l – the signal whose variance is need to be estimated.

The pixels residual variance σ_l^2 is estimated according to further formula:

$$\sigma_l^2 = \frac{\left\| \mathbf{P}_{\mathbf{G}}^{\perp} \mathbf{r}_l \right\|^2}{p^2 - q}, \tag{8}$$

where $\mathbf{P}_{\mathbf{G}}^{\perp} = \mathbf{I}_l - \mathbf{G}\left(\mathbf{G}^T \mathbf{G}\right)^{-1} \mathbf{G}^T$ – the orthogonal projection of the residual $\mathbf{r}_l$, estimated according to (7), onto the $p^2 - q$ dimensional subspace spanned by the left null space of $\mathbf{G}$; $\mathbf{I}_l$ – the $l \times l$ unity matrix.

3. Determine the probability of l[th] embedding change $\beta_l, l \in \{1, 2, \ldots, L\}$ that minimize the deflection coefficient ς^2 between cover and stego image distributions:

$$\varsigma^2 = 2\sum_{l-1}^{L} \beta_l^2 \sigma_l^{-4}, \tag{9}$$

under payload constrain

$$R = \sum_{l=1}^{L} H(\beta_l),$$

where $H(z) = -2z\log z - (1-2z)\log(1-2z)$ – is ternary entropy function; R – cover image payload in nats.

Minimization of (9) can be achieved by using the method of Lagrange multipliers. The change rate β_l and the Lagrange multiplier λ can be determined by numerically solving of further $(l+1)$ equations:

$$\beta_l \sigma_l^{-4} = \frac{1}{2\lambda} \ln\left(\frac{1-2\beta_l}{\beta_l}\right), l \in \{1, 2, \ldots, L\},$$

$$R = \sum_{l=1}^{L} H(\beta_l).$$

4. Convert the change rate β_l to cost ρ_l:

$$\rho_l = \ln\left(1/\beta_l - 2\right); \tag{10}$$

5. Embed the desired payload R using syndrome-trellis codes (STCs) with pixel costs determined according to (10).

Applying the locally-estimated multivariate Gaussian cover model in MiPOD algorithm gives opportunity to derive a closed-form expression for the performance of the detector and capture the non-stationary character of natural images [Sedighi et al, 2016].

Also we considered the MG embedding method [Sedighi et al, 2015] that is similar to MiPOD algorithm but uses the simplified variance estimator instead of more precise one (10):

$$\sigma_l^2 = \frac{\left\|\mathbf{r}_n - \hat{\mathbf{r}}_n\right\|^2}{p^2 - q}, \tag{11}$$

$$\hat{\mathbf{r}}_n = \mathbf{G}\left(\mathbf{G}^T\mathbf{G}\right)^{-1}\mathbf{G}^T\mathbf{r}_n.$$

Experiments

Analysis of cover image pixels brightness distribution alteration by message embedding were conducted on set of 10,000 images, which were pseudo randomly chosen form standard test packet MIRFLickr-25k [Huiskes and Lew, 2008]. Images were scaled to the same size 512×512 pixels with usage of Lanczos kernel and saved in lossless JPEG format (Image Quality Factor is equal to 100%).

Stego images were formed with usage of adaptive embedding methods S-UNIWARD, J-UNIWARD, SI-UNIWARD, MG and MiPOD. Cover image payload was changed from 5% to 25% with step 5%, and from 25% to 95% with step 10%.

At the first step there were investigated of changes of Kullback-Leibler $D_{KL}(C\,||\,S)$, Hellinger $D_H(C\,||\,S)$ and Bhattacharaya $D_B(C\,||\,S)$ distances for cover and stego images formed according to adaptive embedding methods (fig. 1). Dependencies of mentioned distances on cover image payload are represented at figure 1.

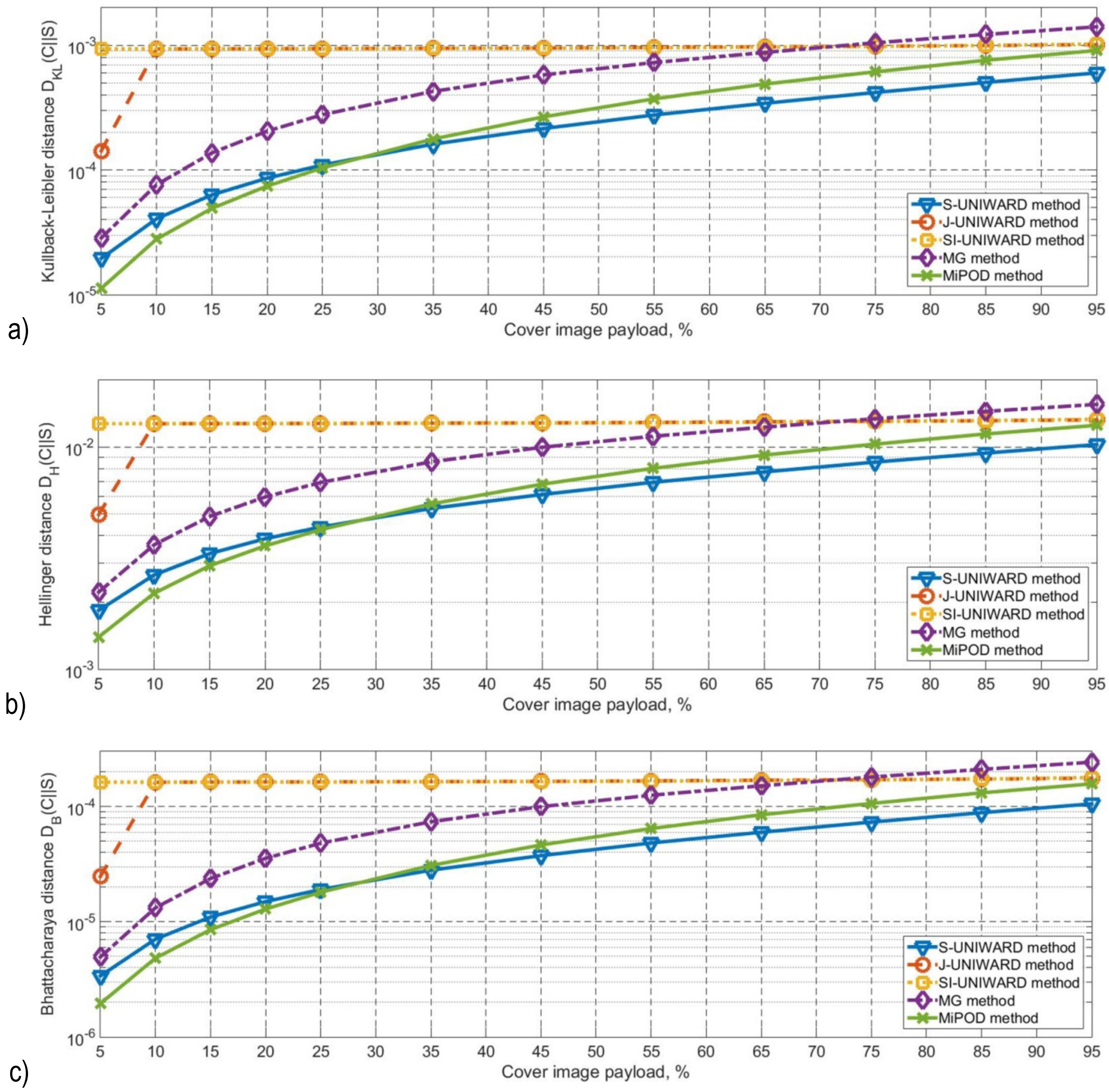
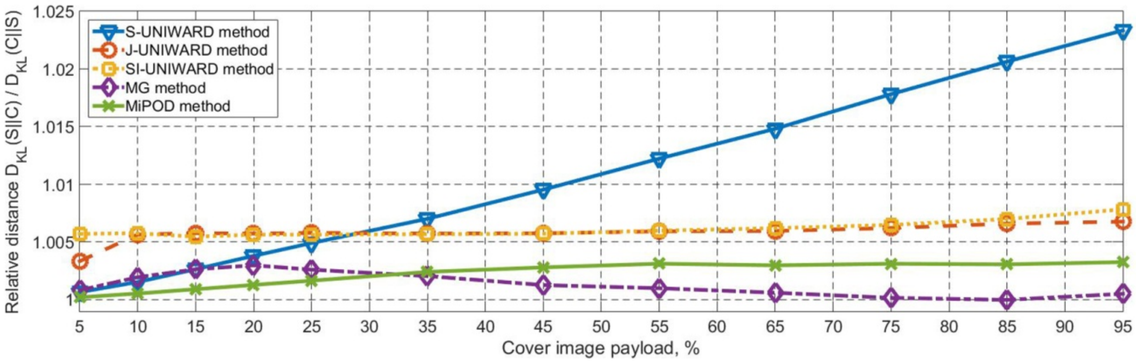


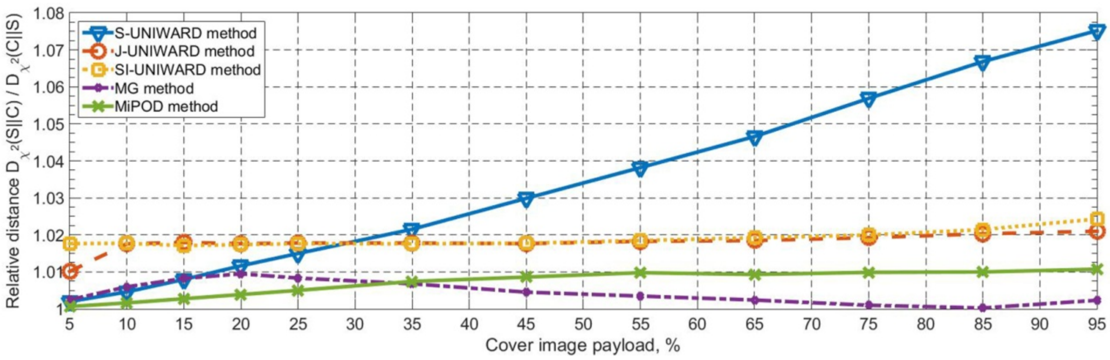
Figure 1. Kullback-Leibler $D_{KL}(C\,||\,S)$ (a), Hellinger $D_H(C\,||\,S)$ (b) and Bhattacharaya $D_B(C\,||\,S)$ (c) distances for cover and stego images formed according to adaptive embedding methods

It should be mentioned the low changes of Kullback-Leibler $D_{KL}(C\,||\,S)$, Hellinger $D_H(C\,||\,S)$ and Bhattacharaya $D_B(C\,||\,S)$ distances between cover and stego images pixel brightness distributions irrespectively of used embedding methods (Fig. 1). These negligible distortions are stable in wide payload range, which limited theirs applications in real stegdetectors.

The widespread approach of cover file distortion revelation is based on estimation of differences between cover and stego image parameters. Feature of proposed approach is opportunity to estimate not only “direct” distance from cover to stego image elements distributions $D(C\,||\,S)$, but also vice versa – from stego to cover file $D(S \| C)$. It is possible because of non-symmetric character of used information-theoretic indices (1), (4) and (5). Dependencies of relative distance $D(S \| C)/D(C \| S)$ on cover image payload are represented at figure 2.



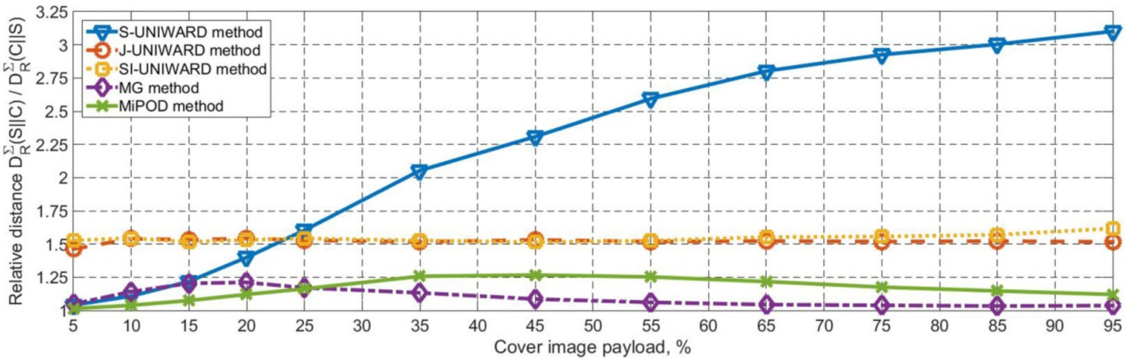
a)



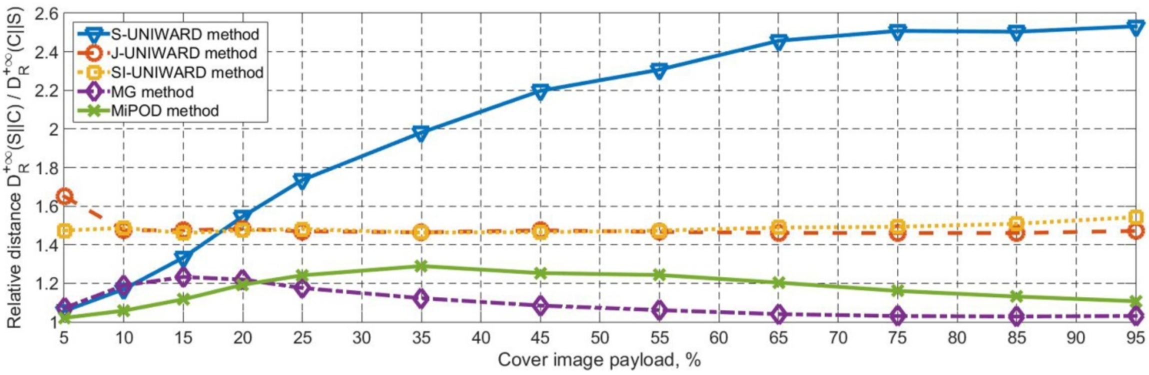
b)

Figure 2. Relative Kullback-Leibler divergence D_{KL} (a) and chi-square distance D_{χ^2} (b) for cover and stego images formed according to adaptive embedding methods

Taking into account the relative distances between cover and stego image elements distributions allows us revealing increasing the “reverse” distance by stego creation according to S-UNIWARD method (Fig. 2). For advanced embedding methods, such as MG an MiPOD algorithm, alteration of relative distances $D(S \| C)/D(C \| S)$ is very small, that can be explained by “integral” character of Kullback-Leibler divergence D_{KL} and chi-square distance D_{χ^2} – they allows estimate distortion of whole distributions the cover file, without taking into account an alteration of limited set the cover elements. Therefore it is represent interest to investigate changes of spectrum the Renyi distances by message hiding, namely integral Renyi divergence $D_R^{\Sigma} = \sum_{\alpha} D_R^{\alpha}$ as well as boundary Renyi divergence $D_R^{+\infty} = D_R^{\alpha}\big|_{\alpha \to +\infty}$ (Fig. 3).



a)



b)

Figure 3. Relative integral D_R^{Σ} (a) as well as boundary $D_R^{+\infty}$ (b) Renyi divergence for cover and stego images formed according to adaptive embedding methods

It should be mentioned that usage of spectrum of Renyi divergences allows us revealing the differences in distributions of cover and stego elements (Fig. 3) – different from one relative values of D_R^{Σ} and $D_R^{+\infty}$ testify to used assumptions about changes only limited set the cover elements values by message hiding. This alterations are intensified by non-symmetric processing of cover and stego elements distributions b Renyi divergence calculations according to formula (5) – increasing of parameter α leads to corresponding amplification cover elements that have high probability to be obtained ($P_C^{\alpha}(q)$) and suppression stego image elements with low probability to appear ($P_S^{1-\alpha}(q)$). Revealed effect allows us reveal weak alteration of cover elements distribution even in case of low cover payload (less than 10%).

Conclusion

The key element of hidden message detector is used cover file model. In most cases such model is adapted for provide high detection accuracy for known embedding method. For increase stegdetector performance in case of limitation or absence of a priory information about embedding methods there is proposed to use information-theoretic indices of differences between distribution of cover and stego file elements, such as Kullback-Leibler divergence, Hellinger distance, Bhattacharyya distance, spectrum of Renyi divergences.

Based on the results the performed analysis, it is shown that applying of well-known information-theoretic indices, namely Kullback-Leibler divergence, Hellinger distance, Bhattacharyya distance and chi-square distance, do not allow revealing the cover file distortion by message hiding. It is explained by "integral" character of mentioned indices – they allows estimate distortion of whole distributions the cover file, without taking into account an alteration of limited set the cover elements.

On the other hand, it is revealed that data embedding in cover image significantly increase the "reverse" distance (from stego to cover file elements distributions). Revealed differences between "direct" (from cover to stego) and "reverse" (from stego to cover) distances gives us additional information for detection a stego files.

Also it is shown that usage of spectrum the Renyi divergences gives opportunity to reveal weak alteration of cover elements distribution even in case of low cover payload (less than 10%) and applying advanced adaptive embedding methods, such as MG and MiPOD algorithms.

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