Two-Layer Lossless HDR Coding using Histogram Packing Technique with Backward Compatibility to JPEG

Osamu Watanabe†a), Hiroyuki Kobayashi†b), Members, and Hitoshi Kiya†††c), Fellow

SUMMARY An efficient two-layer coding method using the histogram packing technique with the backward compatibility to the legacy JPEG is proposed in this paper. The JPEG XT, which is the international standard to compress HDR images, adopts two-layer coding scheme for backward compatibility to the legacy JPEG. However, this two-layer coding structure does not give better lossless performance than the other existing methods for HDR image compression with single-layer structure. Moreover, the lossless compression of the JPEG XT has a problem on determination of the coding parameters; The lossless performance is affected by the input images and/or the parameter values. That is, finding appropriate combination of the values is necessary to achieve good lossless performance. It is firstly pointed out that the histogram packing technique considering the histogram sparseness of HDR images is able to improve the performance of lossless compression. Then, a novel two-layer coding with the histogram packing technique and an additional lossless encoder is proposed. The experimental results demonstrate that not only the proposed method has a better lossless compression performance than that of the JPEG XT, but also there is no need to determine image-dependent parameter values for good compression performance without losing the backward compatibility to the well known legacy JPEG standard.

key words: JPEG XT, HDR, Lossless coding, Backward compatibility to JPEG

1. Introduction

The image compression method designed to provide coded data containing high dynamic range content is highly expected to meet the rapid growth of high dynamic range (HDR) image applications. Generally, HDR images have much greater bit depth of pixel values and much wider color gamut [1-4]. These characteristic of HDR images are suitable for many applications, such as cinema, medical and masterpieces of art etc. For such applications, HDR images should be often losslessly encoded. In other words, they should be compressed without any coding loss.

Most of conventional image compression methods, however, could not efficiently compress HDR image due to its greater bit depth and uncommon pixel format including a floating-point based pixel encoding. For example, in very limited numbers of HDR rendering applications, RGBE pixel format is used. This format stores pixels for RGB in the same manner of the existing representation of uncompressed RGB data with a one byte shared exponent for floating-point representation. Several methods have been proposed for compression of HDR images [5-13] and ISO/IEC JTC 1/SC 29/WG 1 (JPEG) has developed a series of international standards referred to as JPEG XT [14-18] for compression of HDR images. The JPEG XT has been designed to be backward compatible with the legacy JPEG [19] with two-layer coding; a base layer for tone-mapped LDR image is compressed by the legacy JPEG encoder and an extension layer for residual data consists of the subtracted data between a partially decoded base layer image and an original HDR image is compressed by the JPEG-based encoding procedure which consists of color conversion, scalar quantization with tables and huffman coding. This backward compatibility to the legacy JPEG allows legacy applications and existing toolchains to continue to operate on codestreams conforming to JPEG XT. Besides this two-layer coding procedure makes it possible to compress HDR images with the backward compatibility and the extension layer contributes the improvement of the decoded image quality in lossy compression [20]. Lossless compression is possible by using the residual data in the extension layer. The ISO/IEC IS 18477-8:2016 [21], which is known as the JPEG XT Part 8, describes how to decode losslessly or near-losslessly encoded HDR images. In this Part 8, its lossless compression performance is not better than that of the other existing methods for HDR image compression with single coding layer procedure and it is required to find a combination of the parameter values which gives a good lossless compression performance. The combination could be dependent on input HDR images. That is, finding the combination is required to compress HDR images losslessly and efficiently. In Refs. [11,12,22-30], the sparseness of a histogram of an image is used for efficient compression. ‘Sparse’ histogram means that not all the bins in a histogram are utilized. It is well known that a histogram of an HDR image shows a tendency to be sparse [11,12]. In Refs. [12,31], methods for two-layer lossless coding of HDR images have been proposed, however, they are not backward compatible with the legacy JPEG.

This paper proposes a new lossless two-layer method for both integer and floating-point HDR images with the histogram packing technique. Codestreams produced by the proposed method consist of two layers, i.e. base layer and extension layer, where the base layer provides low dynamic range (LDR) images mapped from HDR images by a tone
mapping operator (TMO), while the extension layer has the residual information for reconstructing the original HDR images. For those residual data, any lossless image encoders that can handle over 16 bits, such as JPEG 2000 and JPEG XR, could be used. In addition, the codestreams for the base layer are compatible with legacy JPEG decoders. Not only the proposed method has a higher compression performance than that of the JPEG XT Part 8, but also there is no need to determine image-dependent parameter values to achieve good compression performance, because no coding parameter exists to compress the residual data for the extension layer.

2. Problem with JPEG XT Part 8

In this section, the coding procedure of the JPEG XT Part 8 is summarized and then the problem with it is described.

The blockdiagram of the Part 8 encoder is shown in Fig.1. Although the pixel values of HDR images are often represented with floating-point numbers, these floating-point numbers are re-interpreted as integer number with IEEE floating-point representation [32,33]. This representation is exactly invertible [34] and makes it possible to compress HDR images losslessly. For lossless compression of HDR images, it is required to determine the values of several parameters. The first parameter is $q$, which controls decoded image quality of base layer. The higher $q$ gives the better quality. The second parameter $R$ is the number of bits used for refinement scan. The refinement scan is used to improve precision of DCT coefficients up to 12 bit. Thus the valid range of $R$ is from 0 to 4. The third parameter is $rR$. The $rR$ is the number of bits used for the residual refinement scan. In this lossless coding procedure, the $rR$ is considered as the control factor for the amount of coded data included in the residual data of the extension layer.

To achieve good lossless compression performance, the values of the parameters, $q$, $R$ and $rR$ should be carefully determined. Figure 2 shows the result of lossless compression of an HDR image with from $q = 0$ to $q = 100$, $R = 4$ and $rR = 0$. The other examples with the different combination of the parameter values are depicted in Fig. 9.

Clearly, we can see there is a certain variation in the coding performance. Note that it has been confirmed that the optimal values of the parameters which give the best performance is image-dependent.

3. Proposed method

A method using the histogram packing technique with the two-layer coding having the backward compatibility to the legacy JPEG for base layer is described in this section.
3.1 Histogram sparseness of residual data

HDR images often have sparse histograms due to its high dynamic range of pixel values \([12]\). Moreover, the histograms of the residual data in the two-layer coding in the Part 8 are also sparse after subtraction of LDR data in the base layer. In this paper, this histogram sparseness is denoted as \(\alpha\). The histogram sparseness was originally proposed in Ref. \([22]\). Let \(H(x)\) denotes the frequency of a pixel value \(x\) of an image. A set of pixels that have non-zero frequency is defined by

\[
X = \{ x \mid H(x) \neq 0 \}. \tag{1}
\]

Then, the range of \(x\) can be defined as

\[
D(x) = \max_{x \in X} (x) - \min_{x \in X} (x) + 1. \tag{2}
\]

Let \(|X|\) denotes the total number of all the elements of a set.
3.2 Histogram packing

In section 3.1, it has been noted that the histograms of the residual data tend to be sparse and the increase of the sparseness is effective to improve lossless coding performance \([24\text{-}29]\). In Refs. \([24\text{-}29]\), the sparseness \(\alpha\) was increased and the range \(D(x)\) became narrower by using histogram packing. It was also reported that the lossless image compression performance improved for histogram packed images. The main idea of the proposed method is to combine the two-layer coding structure with the histogram packing technique.

The range of \(\alpha\) is \(0 \leq \alpha \leq 1\) and the smaller \(\alpha\) means the sparser histogram. For example, \(\alpha = 0.5\) means half of pixels within the range \(D(x)\) has zero bin in the histogram \(H(x)\) and \(\alpha = 1.0\) means there is no zero bins in the histogram \(H(x)\) within the range \(D(x)\). Figure 5 and 6 show the ‘sparseness’ of the residual data of two types of HDR images having floating-point and integer pixel values. The remarks from these figures are summarized as follows.

- The sparseness depends on images and the quality factor \(q\) for base layer.
- The histogram of residual data tends to be sparse, especially, the luminance components (Y) has sparser histograms than that of the chroma components (C_b, C_r).

For image signals having such sparseness, it is well known that the histogram packing technique improves lossless compression performance \([24\text{-}29]\). In Refs. \([24\text{-}29]\), the sparseness \(\alpha\) was increased and the range \(D(x)\) became narrower by using histogram packing. It was also reported that the lossless image compression performance improved for histogram packed images. The main idea of the proposed method is to combine the two-layer coding structure with the histogram packing technique.

Histogram packing

In section 3.1, it has been noted that the histograms of the residual data tend to be sparse and the increase of the sparseness is effective to improve lossless coding performance \([24\text{-}29]\). The histogram packing \([22]\) maps a pixel value \(x\) to \(f\) according to

\[
f = F(x),
\]

where

\[
F(x) = \begin{cases} 
0 & \text{for } x = \text{min}, \\
F(x-1) & \text{for } x > \text{min} \land H(x) = 0, \\
F(x-1) + 1 & \text{for } x > \text{min} \land H(x) \neq 0.
\end{cases}
\]
color space conversion from RGB to YCbCr is different from the Part 8 encoder as depicted in Fig. 8. The histogram of each color component of the color converted residual data is analyzed and packed by using the histogram packing technique. Then, the packed residual data is compressed by an arbitrary lossless image encoder. After the subtraction described above, the residual data for each color component may have 17 (= 16 + 1) bit integers. This over 16 bit in the bit-depth is the reason for using such lossless encoders as the JPEG 2000 and the JPEG XR in this paper because they are able to accept up to 32 bit integer pixel value per component [6].

For the inverse operation of the histogram packing, unpacking table is sent to the decoder. The unpacking table is one-to-one correspondence function between the packed index value and the original pixel value. Since this is monotonically increasing, DPCM is performed and then the unpacking table encoded by using DPCM is compressed by bzip2 [35] algorithm to reduce the amount of data.

Finally, the base layer which is compatible with the legacy JPEG, the extension layer consists of the lossless JPEG 2000 or JPEG XR codestream, and unpacking table compressed by using bzip2 algorithm are multiplexed into a codestream and it shall be sent to the decoder. Note that the proposed method does not need to adjust the value of the coding parameters to meet the input image and to get sufficient lossless coding efficiency. The LDR quality $q$ is the only parameter to be determined according to the user’s demand. Thus, the proposed method can be considered to be image-independent and almost-parameter-free.

4. Experimental results

To verify the effectiveness of the proposed method, the lossless compression performance in terms of bitrate of the generated codestreams was evaluated and compared with that of the JPEG XT Part 8.

Table 1   Test images (bpp means bit-depth per component): All images have three color components in RGB color space.

| Pixel value type | Index | Name          | bpp | Size    |
|------------------|-------|---------------|-----|---------|
| Floating-point   | f1    | memorial      | 16  | 512x768 |
|                  | f2    | Blooming Gorse | 16  | 4288x2848 |
|                  | f3    | MtTamWest     | 16  | 1214x732 |
|                  | f4    | Desk          | 16  | 644x874  |
| Integer          | i1    | Books         | 12  | 3840x2160 |
|                  | i2    | Kimono        | 12  | 3840x2160 |
|                  | i3    | Moss          | 12  | 3840x2160 |
|                  | i4    | MusicBox      | 12  | 3840x2160 |

4.1 Conditions

4.1.1 Test images

Images having both floating-point and integer pixel values were selected for the experiments. For floating-point images, four of images common to HDR related experiments were collected. For integer images, four of the ITE test images [36] were selected. The specifications of these test images are summarized in Table 1. Although some of floating-point images have full precision float value for each pixel, we have converted the values into half precision float because the JPEG XT encoder only accepts half precision floating-point pixels as its inputs. Note that image names are all represented by the index shown in Table 1. The first character of the index means the type of pixel values; “f” and “i” stand for floating-point and integer respectively, the following number of the first character corresponds to each image name.

4.1.2 Encoder software

For the JPEG XT Part 8 encoder, the reference software [37][38] available from the JPEG committee was used. For the proposed method, the modified encoder of the reference software, whose coding path for the residual data was
changed to have the histogram packing and JPEG 2000/JPEG XR encoder, was used. The Kakadu software [39] and the reference software of the JPEG XR [40] were used as those encoders that were used to compress the histogram-packed residual data. The lossless performances of the proposed method and the JPEG XT Part 8 were evaluated with several values of $q$ (quality factor of LDR image) and $R$ (number of refinement bits for base layer). For the JPEG XT, another parameter, the effect of $rR$ (number of refinement bits for extension layer), was also evaluated.

4.2 Results and remarks

4.2.1 Overall lossless performance

Figure 9 shows the bitrates of lossless compressed images by the proposed method and the JPEG XT Part 8 with fixed LDR quality $q = 80$. The bitrate for the proposed method includes the amount of unpacking table which is compressed by bzip2 algorithm. For the JPEG XT, the combinations of the parameters for the number of the refinement bits for both the base and extension layer, $(R, rR) = (0, 0), (0, 4), (4, 0), (4, 4)$ were used. Figure (a) and (b) show the bitrate of lossless compressed images having floating-point and integer pixel values, respectively. Among all test images, it was confirmed that the lossless bitrates provided with the proposed method were smaller than those with the JPEG XT.

4.2.2 Effect of LDR quality $q$

Figures 10 and 11 show the results of lossless bitrate with the proposed method with the different LDR quality $q$ and those with the JPEG XT Part 8 with the different parameter values of $q$, $R$ and $rR$. From these results, it is clearly confirmed that the results of the proposed method show the better lossless performance regardless of images and those pixel value types, the values of LDR quality $q$. It is worth noting that the values of $R$ and/or $rR$ should be carefully determined for the JPEG XT. For example, in Fig. 10(b) the bitrates of JPEG XT with the combination of the refinement parameters $(R = 4, rR = 0)$ illustrated in a green line are higher than 32 bpp from $q = 0$ to $q = 60$, while those with the other combinations are lower than 32 bpp. However, the green line is the lowest position over $q = 80$. Thus, the combination $(R = 4, rR = 0)$ results in the worst lossless performance between $q = 0$ and $q = 60$, although it results in the best performance over $q = 80$. From these figures, it is observed that the best combination of $R$ and $rR$ depends on the LDR quality $q$ and the input image. On the other hand, the proposed method with the JPEG 2000 encoder gives the best performance. The second best is the result of proposed method with the JPEG XR encoder. Although there is some difference between the results, those two types of the proposed method give the lower bitrate than those obtained by the JPEG XT encoder, even though there is no dependency on the LDR $q$ and the input image. The ratios of the data amount for the unpacking table to the total bitrate are illustrated in Fig. 12. The ratio can be considered to be almost negligible because it is less than 0.4% at maximum.

5. Conclusions

A novel method using the histogram packing technique with the two-layer coding having the backward compatibility with the legacy JPEG for base layer has been proposed in this paper. The histogram packing technique has been used to improve the performance of lossless compression for HDR images that have the histogram sparseness. The experimental results in terms of lossless bitrate have demonstrated that the proposed method has a higher compression performance than that of the JPEG XT Part 8. Unlike the JPEG XT Part 8, there is no need to determine image-dependent values of the coding parameters to achieve good compression performance. Moreover, as well as the JPEG XT Part 8, the base layer produced by the proposed method preserves the backward compatibility to the legacy JPEG standard.

References

[1] E. Reinhard, W. Heidrich, P. Debevec, S. Pattanaik, G. Ward, and K. Myszkowski, High dynamic range imaging - acquisition, display and image based lighting, 2nd edn., Morgan Kaufmann, Burlington, 2010.
[2] A. Artusi, T. Richter, T. Ebrahimi, and R.K. Mantiuk, “High Dynamic Range Imaging Technology [Lecture Notes],” IEEE Signal Process.
Fig. 10 Bitrates of lossless compressed image (float): image names are represented by index (see Table 1.)

Mag., vol.34, no.5, pp.165–172, Sept 2017.

[3] A. Artusi, F. Banterle, T. O. Aydin, D. Pan zoo no, and O. Sor kine-Hournung, Image Content Retargeting: Maintaining Color, Tone, and Spatial Consistency, AK Peters, Ltd (CRC Press), 2016.

[4] F. Banterle, A. Artusi, K. Debattista, and A. Chalmers, Advanced High Dynamic Range Imaging: Theory and Practice, 1 ed., AK Peters, Ltd (CRC Press), Feb. 2011.

[5] G. Ward and M. Simmons, “JPEG-HDR: A Backwards-compatible, High Dynamic Range Extension to JPEG,” ACM SIGGRAPH 2006 Courses, SIGGRAPHH ’06, New York, NY, USA, ACM, 2006.

[6] R. Xu, S.N. Pattanaik, and C.E. Hughes, “High-dynamic-range still-image encoding in JPEG 2000,” IEEE Comput. Graph. Appl., vol.25, no.6, pp.57–64, Nov 2005.

[7] D. Springer and A. Kaup, “Lossy compression of floating point high-dynamic range images using JPEG2000,” Proc. SPIE, pp.7257 – 7257 – 11, 2009.

[8] Y. Zhang, D. Agrafiotis, and D.R. Bull, “High Dynamic Range image amp; video compression a review,” 2013 18th International Conference on Digital Signal Processing (DSP), pp.1–7, July 2013.

[9] I.R. Khan, “Two layer scheme for encoding of high dynamic range images,” Proc. IEEE Int. Conf. on Acoustics, Speech and Signal Processing, pp.1169–1172, March 2008.

[10] T. Jinno, M. Okuda, and N. Adami, “New local tone mapping and two-layer coding for HDR images,” Proc. IEEE Int. Conf. on Acoustics, Speech and Signal Processing, pp.765–768, March 2012.

[11] M. Iwahashi and H. Kiya, “Efficient lossless bit depth scalable coding for HDR images,” APSIPA ASC, 2012 Asia-Pacific, pp.1–4, Dec 2012.

[12] M. Iwahashi and H. Kiya, “Two layer lossless coding of HDR images,” Proc. IEEE Int. Conf. on Acoustics, Speech and Signal Processing, pp.1340–1344, May 2013.

[13] H. Kobayashi and H. Kiya, “An Extension of JPEG XT with JPEG2000,” 2017 IEEE International Conference on Consumer Electronics - Taiwan (ICCE-TW), pp.373–374, June 2017.

[14] T. Richter, “On the standardization of the JPEG XT image compression,” Picture Coding Symposium (PCS), pp.37–40, Dec 2013.

[15] A. Artusi, R.K. Mantiuk, T. Richter, P. Hanhart, P. Korshunov, M. Agostinelli, A. Ten, and T. Ebrahimi, “Overview and evaluation of the JPEG XT HDR image compression standard,” Journal of Real-Time Image Processing, Dec 2015.

[16] A. Artusi, R.K. Mantiuk, T. Richter, P. Korshunov, P. Hanhart, T. Ebrahimi, and M. Agostinelli, “JPEG XT: A Compression Standard for HDR and WCG Images [Standards in a Nutshell],” IEEE Signal Process. Mag., vol.33, no.2, pp.118–124, March 2016.

[17] “Information technology — Scalable compression and coding of continuous-tone still images — Part 1: Scalable compression and coding of continuous-tone still images,” ISO/IEC 18477-1, 2015.

[18] T. Richter, A. Artusi, and T. Ebrahimi, “JPEG XT: A New Family of JPEG Backward-Compatible Standards,” IEEE Multimedia, vol.23, no.3, pp.80–88, July 2016.

[19] “Information technology — Digital compression and coding of continuous-tone still images: Requirements and guidelines.” International Standard ISO/IEC IS-10918-1, Feb. 1994.

[20] R.K. Mantiuk, T. Richter, and A. Artusi, “Fine-tuning JPEG-XT compression performance using large-scale objective quality testing,” Proc. IEEE Int. Conf. on Image Processing, pp.2152–2156, Sept 2016.

[21] “Information technology — Scalable compression and coding of continuous-tone still images — Part 8: Lossless and nearly-lossless coding,” ISO/IEC 18477-8, 2016.

[22] M. Iwahashi, H. Kobayashi, and H. Kiya, “Lossy compression of sparse histogram image,” Proc. IEEE Int. Conf. on Acoustics, Speech and Signal Processing, pp.1361–1364, March 2012.

[23] S. Minewaki, M. Iwahashi, H. Kobayashi, T. Yoshida, and H. Kiya, “Near lossless coding of sparse histogram images based on zero-skip quantization,” Multimedia Tools and Applications, Sep 2017.

[24] A.J. Pinho, “On the impact of histogram sparseness on some lossless image compression techniques,” Proc. IEEE Int. Conf. on Image
Fig. 11  Bitrates of lossless compressed image (integer): image names are represented by index (see Table. 1.)

Fig. 12  Ratio of unpacking table to total bitrate (%)

[25] P.J.S.G. Ferreira and A.J. Pinho, “Why does histogram packing improve lossless compression rates?” IEEE Signal Process. Lett., vol.9, no.8, pp.259–261, Aug 2002.

[26] A.J. Pinho, “An online preprocessing technique for improving the lossless compression of images with sparse histograms,” IEEE Signal Process. Lett., vol.9, no.1, pp.5–7, Jan 2002.

[27] A.J. Pinho, “A comparison of methods for improving the lossless compression of images with sparse histograms,” Proc. IEEE Int. Conf. on Image Processing, pp.II–673–II–676 vol.2, 2002.

[28] M. Aguzzi and M. Albanesi, “A novel approach to sparse histogram image lossless compression using JPEG2000,” ELVIA Electronic Letters on Computer Vision and Image Analysis, vol.5, no.4, pp.24–46, 2006.

[29] S. Jallouli, A. Masmoudi, S. Zouari, W. Puech, and N. Masmoudi, “A Preprocessing Technique for Improving the Compression Performance of JPEG 2000 for Images with Sparse or Locally Sparse Histograms,” 25th European Signal Processing Conference, pp.1962–1966, Aug 2017.

[30] M. Iwahashi, H. Kobayashi, and H. Kiya, “Fine rate control and high SNR coding for sparse histogram images,” Picture Coding Symposium (PCS), pp.205–208, May 2012.

[31] T. Yoshida, M. Iwahashi, and H. Kiya, “Two-Layer Lossless Coding for High Dynamic Range Images Based on Range Compression and Adaptive Inverse Tone-Mapping,” IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences, vol.E101-A, no.1, pp.259–266, Jan 2018.

[32] “IEEE Standard for Floating-Point Arithmetic,” IEEE Std 754-2008, pp.1–70, Aug 2008.

[33] J.F. Blinn, “Floating-point tricks,” IEEE Comput. Graph. Appl., vol.17, no.4, pp.80–84, Jul 1997.

[34] T. Richter, “On the integer coding profile of JPEG XT,” Proc.SPIE, pp.9217 – 9217 – 19, 2014.

[35] J. Seward, “bzip2 and libbzip2, version 1.0.5.” http://www.bzip.org.

[36] The Institute of Image Information and Television Engineers, “Ultra-high definition/wide-color-gamut standard test images,” Aug 2014.

[37] “Text of CD21ISO/IEC 18477-5 (Reference Software),” ISO/IEC JTC 1/SC 29/WG 1 N71012, Feb. 2016.

[38] https://jpeg.org/jpegxt/software.html.

[39] “kakadu software,” http://www.kakadusoftware.com.

[40] https://jpeg.org/jpegxr/software.html.
Osamu WATANABE received his B.S., M.S., and Ph.D. degrees from Tokyo Metropolitan University in 1999, 2001, and 2004, respectively. In 2004, he joined the faculty of Takushoku University as a research associate in electronics and computer systems. Since 2008, he has been an Associate Professor in the Department of Electronics and Computer Systems. He is a member of IEEE, ITE and an Associate Editor for The Journal of ITE. He is also an expert of ISO/IEC/JTC1/SC29/WG1 committee “Joint Photographic Experts Group” (JPEG). His areas of research interest are image processing, image coding, and signal processing.

Hiroyuki KOBAYASHI received his B.E., M.E., and Ph.D. degrees in Electrical Engineering from Tokyo Metropolitan University in 1992, 1994, and 1997. In 1997, he joined Tokyo Metropolitan College of Technology, where he is currently a Professor in the Electrical and Electronic Engineering Course, Tokyo Metropolitan College of Industrial Technology. His research interests are in the areas of digital signal processing, multi-rate systems, and image compression.

Hitoshi KIYA received his B.Eng. and M.Eng. degrees from Nagaoka University of Technology, Japan, in 1980 and 1982, respectively, and his D.Eng. degree from Tokyo Metropolitan University in 1987. In 1982, he joined Tokyo Metropolitan University as an Assistant Professor, where he became a Full Professor in 2000. From 1995 to 1996, he attended the University of Sydney, Australia as a Visiting Fellow. He currently serves as the President of APSIPA and Regional Director-at-Large for Region 10 of IEEE Signal Processing Society. He was the Chair of IEEE Signal Processing Society Japan Chapter, an Associate Editor for IEEE Trans. Image Processing, IEEE Trans. Signal Processing and IEEE Trans. Information Forensics and Security, respectively. He also served as the President of IEICE Engineering Sciences Society (ESS), the Editor-in-Chief for IEICE ESS Publications, and a Vice President of APSIPA. He received IEEE ISPACS Best Paper Award in 2016, IWAIT Best Paper Award in 2014 and 2015, ITE Niwa-Takayanagi Best Paper Award in 2012, the Telecommunications Advancement Foundation Award in 2011, and IEICE Best Paper Award in 2008. He is a Fellow of IEEE, IEICE and ITE.