A reduced complexity/side information preprocessing method for high quality softcast-based video delivery

Anthony Trioux, François-Xavier Coudoux, Patrick Corlay, M Gharbi

A REDUCED COMPLEXITY/SIDE INFORMATION PREPROCESSING METHOD FOR HIGH QUALITY SOFTCAST-BASED VIDEO DELIVERY

Anthony Trioux, François-Xavier Coudoux, Patrick Corlay, Mohamed Gharbi

UMR 8520 - IEMN, DOAE
Univ. Polytechnique Hauts-de-France, CNRS, Univ. Lille, ISEN, Centrale Lille
F-59313 Valenciennes, France

ABSTRACT

SoftCast has been recently proposed as an original wireless video transmission scheme to deal with the issues encountered by conventional wireless video broadcasting systems (e.g. cliff effect). Lately, a preprocessing method for SoftCast that takes into account the asymmetric energy distribution between coefficients has been introduced to significantly improve the received video quality at the price of an increased amount of side information to be transmitted. In this paper, we propose an alternative method based on a zigzag scan that greatly reduces the amount of additional side information (metadata) to be transmitted (75%) and divides the computation time by 2.5 while keeping similar received video quality improvements (up to 5.4dB in terms of PSNR score). Preprocessing performances are compared under different channel signal-to-noise ratios using two metrics: Peak Signal-to-Noise Ratio (PSNR) and Structural SIMilarity (SSIM), showing the effectiveness of the proposed version.

***Index Terms*—** Wireless Video Transmission, SoftCast, Uncoded Transmission, Preprocessing

1. INTRODUCTION

Broadcast video content constitutes a challenge because each user is subject to unreliable and different wireless channels that vary over time. Traditional approaches based on video codec such as H.264/AVC [1] or HEVC [2] are not suitable for broadcasting video content to multi-users since they require a permanent adaptation of the source and channel coding parameters by the transmitter. Indeed, they are adjusted to match a bitrate available that is given under predicted or assumed channel state. Due to the heterogeneity of each user's channel, receivers whose channel conditions are degraded are subject to significant visual disturbances (e.g. freeze) while receivers experiencing a better channel than the estimated one cannot take full advantage of it.

A radical approach known as *SoftCast* [3] has been proposed to tackle these problems. *SoftCast* represents the pioneer work of linear video coding systems where pixels are processed by linear operations and directly transmitted without quantization or channel coding. This allows the users to receive a video quality that varies linearly with channel quality without any feedback information, while avoiding the complex adaptation mechanisms of conventional schemes.

Following the original works [3], linear video coding has gathered a significant interest from the research community [4–7]. The authors in [7] proposed improvements for the scheme based on the characteristics of the Human Visual System (HVS) whereas [6] proposed efficient signal energy modelings to better allocate bandwidth resources and therefore improve the received video quality. Recent works [5] showed that reducing the energy of the transmitted signal help to increase the received quality. Consequently, He *et al.* [4] proposed a preprocessing method known as Optimized Power Allocation for *SoftCast* scheme (OPA-SoftCast). This preprocessing method consists of selecting high-energy components and sending them as side information to reduce the energy of the analog-transmitted signal. This results in an improved power allocation that helps to increase the received video quality. However, the selection process is based on a exhaustive search over the GoP that increase the computation time and the amount of transmitted side information to recover the signal at the decoder.

In this paper, we propose an alternative preprocessing method that reduce the required bandwidth for side information transmission and the computation time. Instead of using exhaustive search, a direct zigzag scan is used while keeping similar received video quality improvements.

The rest of this paper is organized as follows: Section 2 gives an overview of the *SoftCast* scheme. In Section 3, we analyze the OPA-SoftCast method proposed by He *et al.* [4] and introduce our alternative method. The proposed method is compared to classical *SoftCast* and OPA-SoftCast schemes in Section 4. Conclusions are presented in Section 5.

2. SOFTCAST OVERVIEW

The block diagram of *SoftCast* [3] is given in Fig. 1 where colored blocks represent the additional parts proposed in [4].

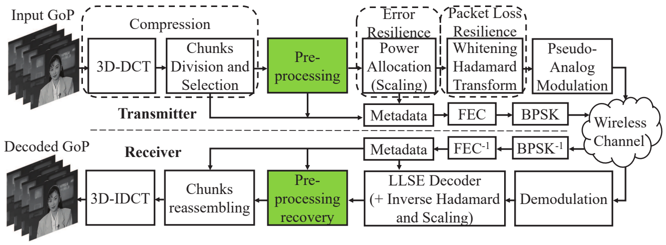


Fig. 1: Block diagram of the *SoftCast* scheme.

The *SoftCast* transmitter consists of several linear transforms and can be divided into 3 major parts: the data compression part made after 3D-DCT (Three-Dimensional Discrete Cosine Transform) by discarding micro-blocks of frequency coefficients called chunks; the error resilience block that consists of a power allocation between remaining chunks; and the packet loss resilience block performed by a Hadamard Transform. The 3D-DCT aims at compacting the information and exploits the separability of the DCT transform, i.e., the transmitter first transforms each frame with a spatial full-frame 2D-DCT and then performs a temporal 1D-DCT over each Group of Pictures (GoP). After 3D-DCT, the transformed frames are divided into small rectangular blocks called chunks and rearranged to form a new matrix $\mathbf{X}$ where each row contains a chunk. These chunks are sorted in decreasing energy order.

After the power allocation and Hadamard transform, the obtained coefficients from each chunk are directly mapped in pairs (I and Q planes in the Orthogonal Frequency Division Multiplexing technology) and transmitted without any coding step in a pseudo-analog manner referred as Raw-OFDM [5].

In the Raw-OFDM, the Forward Error Correction (FEC) is bypassed and Pseudo-Analog Modulation replaces the classical modulation part of OFDM. Therefore, instead of bitrate, only symbol rate is considered hereafter. Since coefficients are sent in pairs (I and Q planes), the maximal resulting matching channel bandwidth (BW_{max}) in *SoftCast* video transmission can be described as follows

$$BW_{max} = \frac{N_r \cdot N_c \cdot F_r}{2}, \quad (1)$$

where N_r, N_c corresponds to the resolution of the video and F_r is the frame rate expressed in frame per second (fps). For instance, a HD720p video format with 30fps represents a data volume of $1280 \cdot 720 \cdot 30 = 27.64 \cdot 10^6$ real values per second to be transmitted [7]. The resulting matching channel symbol rate considering *SoftCast* transmission is $27.64 \cdot 10^6/2$ = 13.82Msymbols/s.

If the available bandwidth at the transmitter is less than BW_{max} (i.e., bandwidth-constrained environments), *SoftCast* discards chunks, starting with lowest energy, until the source bandwidth matches the available bandwidth. The discarded chunks are replaced by null values at the receiver.

The *SoftCast* receiver consists of a Linear Least Square Error (LLSE) decoder that is used to get the best estimation of the received values. These values are then reassembled to form frames and passed through inverse processes. To retrieve video data signal at the receiver side, *SoftCast* needs also to send side information known as metadata (map of discarded chunks, mean and variance of each chunk to compute power allocation). They need to be strongly protected (Forward Error Correction code) and sent in a robust way (BPSK for example [6]) to ensure an error-free decoding process even in unreliable environments. Due to strong protection code and low channel coding used, it is of paramount importance to keep the amount of metadata small, since it causes large overhead, resulting in video quality degradation due to power and rate loss [6]. Jakubczak *et al.* [3] proposed to use a reasonable size of chunk (64 chunks per frame) as a trade-off between quality received, amount of metadata and computation cost.

The end-to-end performances of *SoftCast* have been modeled by Xiong *et al.* [5]. They showed that the theoretical received quality is directly related to the concept of *activity* denoted by $H = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\lambda_i}$ where $\lambda_i = E[\mathbf{X_i}^2]$ is the energy of the i^{th} chunk [3] and N the total number of chunks per GoP. They demonstrated that this term directly affects the reconstructed PSNR at the receiver side as follows:

$$PSNR_{dB} = c + CSNR_{dB} - 20\log_{10}\left(H\right) \quad (2)$$

with $c = 20\log_{10}(255)$ and $CSNR_{dB}$ corresponds to the Channel Signal-to-Noise Ratio i.e., the channel quality. Please note that this model considers a Zero-Forcing (ZF) decoder instead of the LLSE one. This induces a small bias of around 1-2dB between the actual received PSNR and the theoretical one at very low CSNR.

Under the same channel characteristics, the higher the *activity*, the lower the received quality. Therefore, this formula underlines the importance of having a reduced activity and hence emphasizes the benefits of reducing the energy before applying the power allocation in the *SoftCast* scheme. For this purposes, He *et al.* [4] proposed to add a deviation optimization block at the transmitter side (colored block in Fig. 1) that selects and removes high energy DCT coefficients. These coefficients are transmitted as additional metadata to ensure a full recovery at the receiver side. In the next section, we analyze their method denoted as OPA-SoftCast and propose an alternative solution that helps to reduce the amount of additional metadata as well as the computation time while keeping the quality improvements given by OPA-SoftCast.

3. ANALYSIS OF OPA-SOFTCAST

OPA-SoftCast operates after 3D-DCT, chunks division and selection process. The input data of the algorithm is the matrix $\mathbf{X}$ where each row represents a zero-mean chunk [3]. OPA-SoftCast is an iterative algorithm that aims at reducing

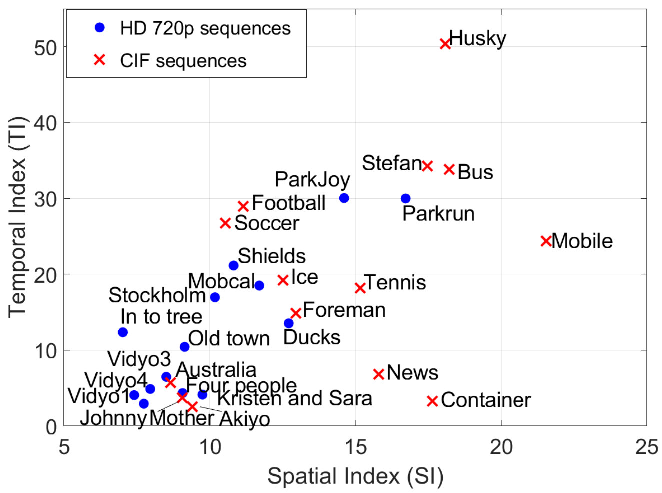


Fig. 2: Illustration of the average spatio-temporal indexes for the selected HD and CIF video sequences.

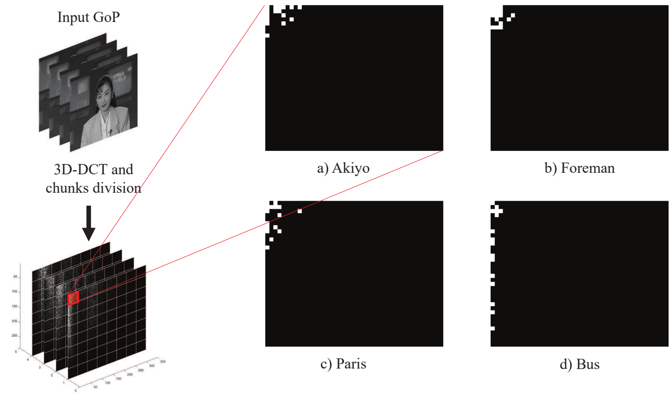


Fig. 3: Visual representation of the position of the 16 selected SFC (small white squares) by OPA-SoftCast in the upper left chunk (44×36 coefficients) of the first frame of the GoP for the selected CIF video sequences.

the energy of the chunks. This is done by removing and transmitting trough metadata channel N_d high energy DCT coefficients, called Special Frequency Coefficients (SFC). To find one SFC, the energy of each chunk is first computed and the highest value among all chunks selected. The SFC is then obtained by taking the highest energy coefficient within the selected chunk. This SFC is then removed and transmitted through metadata channel. The mean of the selected chunk is adjusted to keep a zero-mean value. After the end of the loop, the new energy of the selected chunk is recomputed. The loop is performed N_d times corresponding to N_d selected SFC. Due to the unknown positions of the highest energy chunk and coefficients, the values of the SFC and adjusted means, OPA-SoftCast needs to transmit these four values for each SFC to be able to reconstruct the DCT frames at the receiver side.

The authors assumed that each of these four values is quantized with 20 bits on average. With a BPSK modulation and a redundancy FEC code of 1/2, the total amount of bits that needs to be transmitted as additional metadata is $4 \cdot 20 \cdot 2 \cdot N_d = 160 \cdot N_d$ for each GoP [4]. Thus, the necessary bandwidth for the transmission of this additional metadata is $\frac{4 \cdot 20 \cdot 2 \cdot N_d \cdot F_r}{GoP}$ where F_r and GoP denote the number of frames per second and the GoP-size, respectively. This results in a non-negligible increase of the required bandwidth for metadata transmission. It is not desirable to have such amount of information to be transmitted since allowing more bandwidth to the metadata leads to a huge amount of chunks that cannot be transmitted in analog way [6]. To alleviate this drawback, the authors proposed a trade-off between quality improvements and additional amount of metadata. They selected an equivalent threshold of 2 SFC per frame (16 SFC for a GoP-size of 8 frames). We show by analyzing the algorithm that the amount of metadata can be further reduced while achieving similar performances.

We first analyze the position of the selected chunks as well as the position of the SFC within these chunks based on He *et al.* [4] simulation setup: the luminance part of video sequences (with a frame rate of 30 fps) from the Xiph collection [8] are used as the inputs. The process is performed GoP by GoP with a GoP-size of 8 frames and each frame is split into 64 chunks. The number of SFC N_d is set to 16. For a fair comparison, we first select the video sequences used by He *et al.*, which consist of the first 32 frames of *Foreman, Akiyo, Coastguard, Flower, Paris* and *Bus* denoted by $Mixed_{CIF}$ sequence hereafter. In addition, we also use a HD720p Mixed sequence which consist of the first 128 frames of *Ducks, Four People, Into Tree, Johnny, Kristen and Sara, Old Town, Parkjoy, Shields, Parkrun* and *Stockholm* denoted by $Mixed_{HD}$ sequence hereafter. To evaluate the characteristics of the videos, we use the Spatial Information (SI) and Temporal Information (TI) indexes proposed by the ITU-T [9] which are defined as follows:

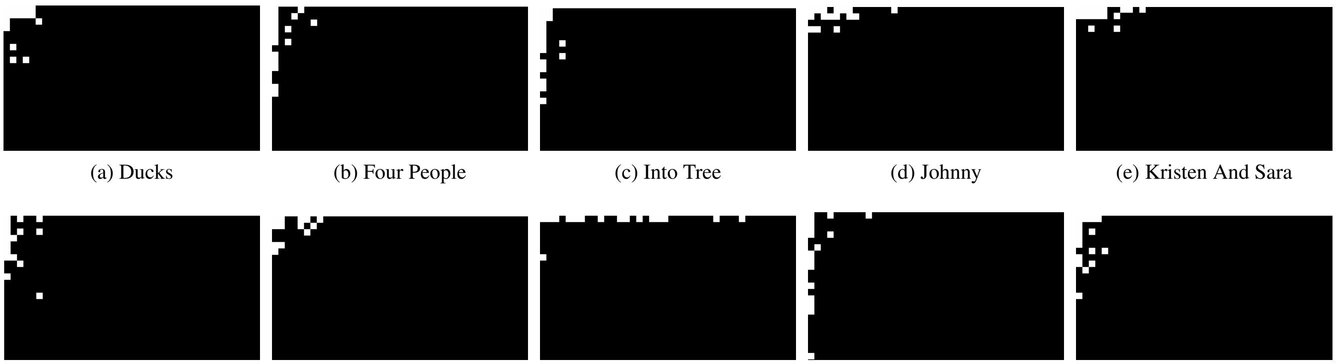
$$\text{SI} = max_{time}\{std_{space}[Sobel(F_k(i,j))]\}, \quad (3)$$

$$\text{TI} = max_{time}\{std_{space}[F_k(i,j) - F_{k-1}(i,j)]\}, \quad (4)$$

where $F_k(i,j)$ represents the k^{th} frame, (i,j) the corresponding spatial coordinates and $Sobel()$ the Sobel filtering operation, respectively.

However, as mentioned in [10] due to the current definition of these indexes that selects the highest value along the time axis, performing the TI computation for a video with slow motions that contains cut results in a high TI value. In order to have more representative (SI, TI) values, we choose to average the results over the entire sequence. Fig. 2 shows the resulting average (SI, TI) values for each sequence.

As shown in Fig. 3 and Fig. 4, the selected SFC (small white squares) are logically located in the first chunk (big black square) containing the low frequencies. For most of the video sequences, these SFC are located on the top left



(a) Ducks (b) Four People (c) Into Tree (d) Johnny (e) Kristen And Sara

(f) Old Town (g) ParkJoy (h) Shields (i) Parkrun (j) Stockholm

Fig. 4: Visual representation of the position of the 16 selected SFC (small white squares) by OPA-SoftCast in the upper left chunk (160×90 coefficients) of the first frame of the GoP for the selected HD720p video sequences. Note that only the left upper part (40×22) of each chunk is showed for display purposes. Please enlarge the figure to observe details.

corner of the first frame of the GoP. Based on extensive simulations on each video sequence in Fig. 2, we see that, for almost all sequences, the position of the selected chunk does not change if less than 80 SFC per GoP are removed. Indeed, after 3D-DCT, the energy is mostly located on low frequency coefficients (i.e., the top left corner of the first frame). Furthermore, He *et al.* [4] showed that the PSNR gain slows down after one SFC per frame. Besides, transmitting more than 80 SFC is not a realistic case due to large increase of metadata, as a consequence, there is no need to transmit the position of the selected chunk as it is usually the first. We note some exceptions for very high TI values sequences, e.g., *ParkJoy*, where a few SFC have been selected in the upper left chunk of the second frame of the GoP. However, we show in Section 4 that performances remain similar with the proposed method.

Moreover, the placement of most of the selected SFC by OPA-SoftCast in Fig. 3 and Fig. 4 can be approximated by a simple zigzag scan (starting from the DC value in the top left corner). Therefore, we propose to use an alternative solution with low computation cost that does not require an iterative process to remove frequency coefficients. Indeed, we select the first chunk representing the 3D low-frequency values and use a zigzag scan to select N_d frequency coefficients as OPA-SoftCast. However, since the proposed method is not an iterative process the adjusted zero-mean does not need to be transmitted since it is computed once and sent as classical metadata in the *SoftCast* scheme. Furthermore, since the positions of the selected chunk and frequency coefficients are always the same in our approach, the proposed method decreases the additional metadata from 4 values per frequency coefficients to only 1 saving 75% of the additional needed bandwidth compared to OPA-SoftCast (reduction from 9600Hz to 2400Hz when N_d=16). Even if the placement of the SFC does not always follow a zigzag rule (e.g. *Shields*) and/or are not located in the first chunk, we show in the next section that the performance of the proposed method remains competitive.

4. PERFORMANCE ANALYSIS OF THE PREPROCESSING METHODS

The proposed method (OPA2) is evaluated with the OPA-SoftCast algorithm (OPA) and the original *SoftCast* scheme (SC) through extensive simulations described below.

Transmissions through AWGN channels are here considered in the range of $[0 \sim 30dB]$ as in [4–6, 11].

Four available channel bandwidth cases are evaluated: *full, three-quarter, half* and *quarter* bandwidth. As explained in Section 2, the coefficients are directly mapped in pairs on I and Q planes in OFDM, therefore, the four resulting matching channel bandwidths correspond to $13.82, 10.36, 6.91$ and 3.45MHz. We choose to show results for *Full* and *quarter* bandwidth cases, which correspond to 100% i.e., no compression applied (denoted by CR=1) and 25% of transmitted coefficients (CR=0.25), respectively. Results for others cases are similar since the first chunk is always sent regardless of the available bandwidth at transmitter side.

The simulations are performed on the selected HD720p sequences (1280×720 pixels, 30fps) and CIF sequences (352×288 pixels, 30fps) as shown in Fig. 2. The $Mixed_{CIF}$ and $Mixed_{HD}$ video sequences described in Section 3 are also used in this paper to evaluate the proposed method.

The PSNR is used as a purely objective metric to assess performances in [4]. In this paper, we also add the SSIM index, which provides a quality index more correlated with the Human Visual System (HVS) [7].

Table 1: *Data activity* H in dB for the SoftCast scheme, OPA-SoftCast method and the proposed one

Sequences	*H* (SC)	*H* (OPA)	*H* (OPA2)	PSNR loss
Soccer	23.88dB	20.11dB	20.27dB	0.16dB
Into Tree	21.52dB	17.94dB	18.10dB	0.14dB
ParkJoy	26.53dB	25.42dB	25.47dB	0.05dB
Shields	23.58dB	21.99dB	22.18dB	0.19dB

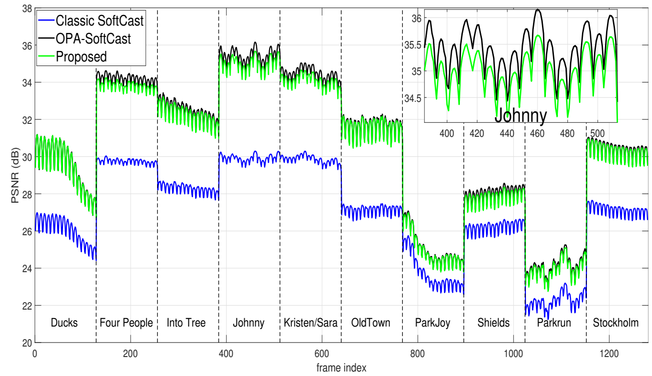


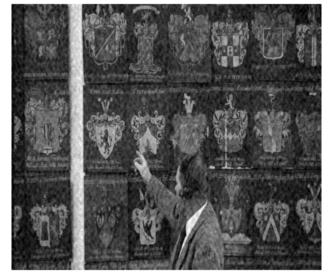
Fig. 5: PSNR_{dB} per frame for the $Mixed_{HD}$ sequence, CSNR=0dB, CR=1 (no compression applied).

As a first performance indicator, we give the resulting *Data Activity* H expressed in dB from eq. (2) for the sequences that do not comply with the key assumption of this paper (i.e., the fact that the frequency coefficients are selected in the first chunk and/or the fact that the selected coefficients do not follow a zigzag rule). Results given in Table 1 show that, even if these videos do not follow the above rules, the reduction of the activity remains close to the optimal performances given by the OPA-SoftCast algorithm (recalling that a lower activity implies a better received quality). This is due to the fact that even if the selected frequencies with the proposed method are not the highest energy coefficients, they are still high energy DCT coefficients since they are located on the low-frequency band after 3D-DCT. As a consequence, the received quality remains almost the same as shown with simulations in Fig. 5. As explained in the Section 2, we note a difference between the theoretical PSNR given by eq. (2) and the displayed one in Fig. 5 due to the fact that eq. (2) considers a ZF decoder instead of a LLSE decoder as used in the *SoftCast* scheme. Even if there exists a small bias of about 1-2dB in terms of PSNR scores at very low CSNR (0dB typically), the *Data Activity* H represents a quick way to evaluate the preprocessing methods. The average PSNR loss between the proposed method and OPA-SoftCast for these sequences is about 0.2dB, which is insignificant.

An example of a visual comparison is given in Fig. 6, the CSNR is set to 0dB to accentuate the noise during transmission. The selected frame corresponds to a case where the zigzag rule is not verified, i.e., the *Shields* sequence as shown in Fig. 4. We can clearly observe that the original *SoftCast* scheme gives the lowest video quality received. By contrast, the preprocessing methods achieve better reconstructed quality under the same channel characteristics. The loss between the two methods is imperceptible ($\leq$0.1dB) even if the coefficients selected by OPA-SoftCast do not follow a zigzag rule.

The proposed method increases the received quality between 1.3dB (*ParkJoy* sequence) and up to 5.4dB (*Johnny* sequence) as shown in Fig. 5. The difference between the ob-

(a) Original Image



(b) PSNR=30.44dB, SSIM=0.686

(c) PSNR=31.54dB, SSIM=0.728

(d) PSNR=31.44dB, SSIM=0.724

Fig. 6: Visual quality comparison at a CSNR = 0dB and *full* available bandwidth for *Shields* sequence (first frame). From left to right, top to down: (a) Original image, (b) Classic SoftCast, (c) OPA-SoftCast, (d) The proposed method.

tained gains is due to the characteristics of the videos. Indeed, the *Johnny* sequence that has low (SI, TI) values is easy to decorrelate and most of the energy is therefore concentrated on low frequency coefficients after 3D-DCT. Protecting the most important low frequency coefficients allows to greatly improve the received quality. On the contrary, due to strong motions and textures in the *ParkJoy* sequence, the signal is difficult to decorrelate and the energy is spread across the entire GoP. As a result, the received video quality is not as good as the *Johnny* sequence. We verified that similar conclusions were obtained with the CIF sequences.

In addition, the computation time and the required additional bandwidth to perform the preprocessing methods are also indicated in Table 2. The computation time is defined as the total time required to do the preprocessing at the transmitter and the receiver part over the full $Mixed_{HD}$ sequence composed of 1280 frames. The different times were obtained with Matlab R2018b on a computer equipped with an Intel processor (R) Core (TM) i7-4510U CPU, 2GHz, 12G RAM. As we can see, the proposed method divides the computation time by 2.5 compared to the OPA-SoftCast method. This is due to the fact that the proposed method is not an iterative process. Furthermore, since only the value of each frequency coefficient is sent as additional metadata, the required bandwidth for the proposed method is reduced by 75% compared to the one for OPA-SoftCast. We note that similar results were obtained for the $Mixed_{CIF}$ sequence.

Finally, we show in Fig. 7, the average quality scores for the $Mixed_{HD}$ and $Mixed_{CIF}$ sequences. Regardless of the total

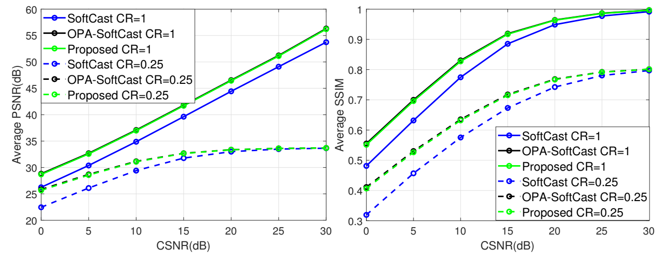
Table 2: Comparison between the OPA-SoftCast method and the proposed one

Method	Average Gain	Comput. Time	Required BW
OPA-SoftCast [4]	**PSNR = 2.36dB** **SSIM = 0.032**	12.43s	9600Hz
Proposed method	PSNR = 2.24dB SSIM = 0.031	**5.05s**	**2400Hz**

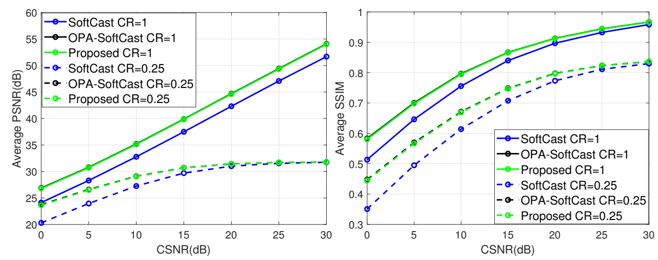
available bandwidth for transmission, preprocessing methods brings significant improvements to the received quality compared to the classical *SoftCast* scheme. The average gain is about 2.24dB for the PSNR score and 0.031 for the SSIM index, respectively. The loss of quality between the proposed method and OPA-SoftCast is only about 0.12dB for the PSNR score and 0.004 for the SSIM index in average, whereas the additional needed bandwidth for metadata is reduced by 75% and the computation time is divided by 2.5. The loss of quality is due to the fact the proposed method does not ensure to always select the highest frequency coefficients compared to OPA-SoftCast. However, as mentioned above, most of the energy is located on low frequency coefficients and as verified above, even when the selected frequencies are not well described by a zigzag scan (see Fig. 3 and Fig. 4), the PSNR loss remains under 0.5dB (see the zoom in Fig. 5) showing the effectiveness of the proposed version.

5. CONCLUSION

In this paper, we propose an alternative preprocessing method based on a zigzag scan for the *SoftCast* scheme. Compared to the original scheme, this helps to improve the received quality in terms of PSNR scores up to 5.4dB and 2.24dB in average and in terms of SSIM index up to 0.105 and 0.031 in average. In comparison to the OPA-SoftCast method, the proposed one reduces by 75% the additional needed bandwidth for metadata and divides by 2.5 the computation time while keeping similar received video quality improvements. The saved bandwidth can be used to transmit more frequency coefficients in analog way and is useful for hardware-constrained or low available bandwidth applications.



(a) $Mixed_{HD}$ sequence



(b) $Mixed_{CIF}$ sequence

Fig. 7: Average quality scores vs CSNR. First column: PSNR results. Second column: SSIM results.

6. REFERENCES

[1] I. E. G. Richardson, *The H.264 advanced video compression standard*, Wiley, Chichester, 2. edition, 2010.

[2] G. J. Sullivan, J. R. Ohm, W. J. Han, and T. Wiegand, "Overview of the High Efficiency Video Coding (HEVC) Standard," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 22, no. 12, pp. 1649–1668, Dec. 2012.

[3] S. Jakubczak and D. Katabi, "SoftCast: Clean-slate scalable wireless video," *MIT Technical report*, Feb. 2011.

[4] C. He, H. Qin, Z. He, and K. Niu, "Adaptive GoP dividing video coding for wireless broadcast based on power allocation optimization," in *Int. Conf. on Wireless Comm. & Signal Process. (WCSP)*, 2016, pp. 1–5.

[5] R. Xiong, F. Wu, J. Xu, X. Fan, and al., "Analysis of decorrelation transform gain for uncoded wireless image and video communication," *IEEE Trans. Image Process.*, vol. 25, no. 4, pp. 1820–1833, Apr. 2016.

[6] T. Fujihashi, T. Koike-Akino, T. Watanabe, and P. V. Orlik, "High-Quality Soft Video Delivery With GMRF-Based Overhead Reduction," *IEEE Trans. Multimedia*, vol. 20, no. 2, pp. 473–483, Feb. 2018.

[7] D. He, C. Luo, C. Lan, F. Wu, and W. Zeng, "Structure-preserving hybrid digital-analog video delivery in wireless networks," *IEEE Trans. Multimedia*, vol. 17, no. 9, pp. 1658–1670, Sep. 2015.

[8] "Xiph.org media," .

[9] P. ITU-T RECOMMENDATION, "Subjective video quality assessment methods for multimedia applications," Sept. 1999.

[10] T. Brandao, L. Roque, and M. P. Queluz, "Quality assessment of H.264/AVC encoded video," in *Proc. of Conference on Telecommunications - ConfTele*, Sta. Maria da Feira, Portugal, 2009, p. 5.

[11] M. Cagnazzo and M. Kieffer, "Shannon-Kotelnikov mappings for softcast-based joint source-channel video coding," in *Proc. IEEE Int. Conf. on Image Process. (ICIP)*, Sept. 2015, pp. 1085–1089.