Multiple Description Coding for Point Cloud

†Anthony Chen, †Shiwen Mao, ‡Zhu Li, §Minrui Xu, ♯Hongliang Zhang, §Dusit Niyato, and ♮Zhu Han
†Department of Electrical and Computer Engineering, Auburn University, Auburn, AL, USA
‡Department of Computer Science and Electrical Engineering, University of Missouri–Kansas City, MO, USA
§School of Computer Science and Engineering, Nanyang Technological University, Singapore
♯School of Electronics, Peking University, Beijing, China
♮Department of Electrical and Computer Engineering, University of Houston, TX, USA

***Abstract*—With the advances of Virtual Reality (VR) / Augmented Reality (AR), there arises a compelling need for transmission of point clouds over lossy channels (e.g., a 5G millimeter wave (mmWave) link that tends to be easily blocked). In this paper, we revisit the traditional Multiple Description Coding (MDC) concept and propose a simple point cloud MDC scheme that takes advantage of voxelization and is built upon a typical geometric point cloud compression codec. Our simulation study demonstrates the efficacy of the proposed scheme, as well as the trade-off between compression efficiency and point cloud quality gain offered by MDC.**

***Index Terms*—Multiple description coding (MDC), Point cloud, Virtual Reality (VR)/Augmented Reality (AR), Wireless immersive media transmission.**

I. Introduction

With the rise of Virtual Reality (VR)/Augmented Reality (AR) and three dimensional (3D) sensing, 3D presentations of data has been widely spreading and as such, point clouds, in the form of a set of data points in a 3D coordinate system, are seeing a quick rise in usage. The point clouds are typically large clouds of points that contain both geometric attributes and other features such as color. This allows for 3D objects and scenes to be represented as a large number of points, each with X, Y, and Z coordinates, R, G, and B attributes for color, and any other possible attributes required to fully describe a dataset such as reflectance [1].

With the rapid advances in sensing technology, point cloud datasets are correspondingly growing in both size and complexity. Transmission of point clouds often requires high data rates due to the extremely large numbers of points (e.g., up to millions of points each with various amounts of features per point) [2]. To address the challenge, point clouds need to be compressed through the likes of geometric point cloud compression or video point cloud compression, to significantly reduce their sizes. In order to accomplish such compression, point clouds typically undergo much processing and encoding, where points may be approximated based on their area. One such processing technique is known as *voxelization*, where a given 3D point cloud is converted into a grid of cubes known as "voxels," where each voxel stores important information about its volume of space such as their colors and other features, as well as aggregating the points that are collected within such space. This can allow for much easier processing of point cloud data for future compression. Academia research in point cloud compression over the past decade has been spearheaded by the MPEG working group [1], with the development of two main encoders for different point cloud data types: the TMC13 and the TMC2. The TMC2 is utilized for video point cloud encoding, while the TMC13 is utilized for what is known as Geometric Point Cloud Compression (GPCC), and for static point clouds. These two encoders represent the standard of point cloud compression techniques.

Although considerable research is dedicated towards the advancement of point cloud compression and its peripheral topics, contemporary literature has insufficiently addressed the issues involving point cloud transmission through lossy channels, nor the joint consideration of the coding and transmission of such point clouds. This is an especially relevant problem, since the decoders are usually sensitive to transmission errors, which can lead to loss of points, distortion in the geometry, decoloration, or even complete failure to decode the point cloud. On the other hand, the proliferation of 3D sensing and AR/VR often entails the transmission of point clouds over lossy wireless channels, e.g., a 5G millimeter wave (mmWave) link from an AR/VR headset to the controller or wireless router. Such links can be easily blocked by the player's body or other obstacles, causing completely loss of a portion of point cloud data.

To combat the transmission errors from high loss channels, this paper proposes to revisit the traditional coding scheme termed Multiple Description Coding (MDC) for point cloud transmission. With MDC, a single media stream is split into multiple "equal" streams for transmission over lossy networks. Although each description provides a lower quality reconstruction, the decoding of the descriptions are independent to each other and the quality of the reconstruction can be progressively improved as more descriptions are available. In the scenario of high loss networks, if we were to transmit a single stream and not utilize MDC, the single stream could be completely lost due to link failures. With MDC, however, the descriptions can be dispatched to multiple channels that are available (e.g., multiple mmWave beams, or heterogeneous wireless interfaces). As long as some descriptions are received (i.e., not all the links are broken simultaneously), the point cloud can still be recovered [3]. Compared to other coding techniques, MDC can greatly simplify the transmission schedule of coded point cloud data. Due to these properties, MDC introduces reliability and robustness for transmission over lossy channels. These can be easily utilized for point clouds since point clouds

ICC 2024 - IEEE International Conference on Communications | 978-1-7281-9054-9/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICC51166.2024.10623006

typically undergo voxelization, allowing users to create relatively equal descriptions where each description contains an equal amount of points from each of these voxel cubes. MDC implementation can be further refined through the introduction of redundancy between the various descriptions [4], [5].

We propose a simple point cloud MDC scheme that takes advantage of voxelization to easily partition a point cloud into multiple equivalent sub-clouds, and is built upon a typical geometric point cloud compression codec. Through a simulation study, we observe the effects of point cloud transmission through a high loss channel, and explore the trade-offs between compression rate and peak signal-to-noise ratio (PSNR) gain offered by MDC. The main contributions of this paper are summarized as follows:

- To the best of our knowledge, this is the first work to utilize MDC for point cloud transmission over lossy channels. A simple yet effective MDC scheme is proposed, which takes advantage of voxelization and is built upon a typical geometric point cloud compression codec.
- Our work demonstrates that in high loss conditions, the use of MDC can effectively mitigate the impact of transmission errors and improve the quality of reconstructed point cloud.
- We further demonstrate the trade-off between coding efficiency and number of descriptions implemented through MDC, which can be exploited or dynamically adjusted in response to difference wireless network conditions.

The remainder of this paper is structured as follows. In Section II, we review related works. The proposed MDC for point cloud scheme is presented in Section III and evaluated in Section IV. Section V concludes this paper.

II. Related Works

This work is mostly related to the prior works on MDC and point cloud compression, which are discussed in this section.

This paper is focused on MDC, which is depicted in [5]. MDC has been applied to video coding as in [3]–[8], with techniques built on the H.264/AVC video codec to achieve significant improvements for video transmission through high loss and unreliable wireless channels. As shown in [6], [8], with MDC, multiple equivalent descriptions of the original video or image are generated based on pixel or frame order, where every other pixels or frames are selected to be part of a description. When transmitted over a lossy network, as long as some descriptions are received, the receiver will be able to reconstruct a video or image with a quality in proportion to the number of received descriptions. Through utilization of properly introduced redundancy among descriptions, stream splitting techniques, and combinations with various transmission techniques, MDC has flourished as a useful coding technique in high loss scenarios. Considerable research has been conducted on exploiting the trade-off between the reduced coding efficiency and the enhanced robustness to transmission errors, inciting various MDC implementations as in [5].

Our paper is also focused on point cloud compression and transmission. As such, the authors in [2] and [9] both identified metrics and provided valuable insights into evaluating point clouds in transmission and recovery. When regarding the typical geometric point cloud compressor (GPCC), the publicly available GPCC codec developed by the MPEG working group [1] allows for point clouds to be compressed using a variety of methods and for many types of point cloud data types. With the TMC13 implementation, the GPCC encoder is able to encode point clouds that are represented as "Category 1" with the Trisoup geometry codec, or "Category 3" with the Octree geometric codec [1]. With the Octree representation, which is typically used for sparser point clouds, point clouds are broken into cubic sections called octants. On the other hand, with the Trisoup representation, which is typically used for denser point clouds, the 3D models are partitioned into triangle meshes (hence the term trisoup) to approximate the surface of 3D models. These codecs further employ different attribute coding methods including RAHT and Predicting/Lifting (Predlift), which are a hierarchical vs. predictive coding technique [10]. While RAHT is typically used on Category 1 data and Predlift is typically used in Category 3 data, these methods may be used on any point cloud data. While typical encoders are structured like those developed by MPEG, other point cloud research has been looking into developing encoders assisted by machine learning such as [11], [12].

III. Description of the Proposed System

In this paper, we propose using MDC for point cloud data transmission over lossy wireless channels. The general system model is presented in Fig. 1. To make an MDC encoder, we first split the point cloud into a prescribed amount of "sub-clouds," where the original point cloud is partitioned into a prescribed amount of $n \times n \times n$ voxel-sized cubes, and each sub-cloud contains a relatively equal amount of points from each cube. For example, we can create eight descriptions to ensure enough descriptions could be received through a high loss channel by not having too few descriptions, while on the other hand, the more descriptions, the lower the coding efficiency, which lead to a higher bits per point (BPP).

Furthermore, in our system we utilize the `longdress_vox10_1300` dataset that has been voxelized at a depth of 10, creating cubes with $1024 \times 1024 \times 1024$ voxels and 1.75 mm per voxel per side [13]. This point cloud has a resulting resolution of 1023. We choose to partition the point cloud into cubes of size $64 \times 64 \times 64$ to ensure a sufficient amount of points in each cube and a sufficient amount of cubes to create relatively equal sub-clouds. After breaking the point cloud into cubes and assigning each point in each cube to one of the eight sub-clouds, we then encode each sub-cloud to obtain eight descriptions. Each of the descriptions will then be transmitted through high loss channels. The successfully received descriptions will each be decoded in to a sub-cloud, which will be merged together in an attempt to reproduce the original point cloud.

To encode the sub-clouds, we utilize a standard point cloud encoder/decoder package provided by the MPEG working

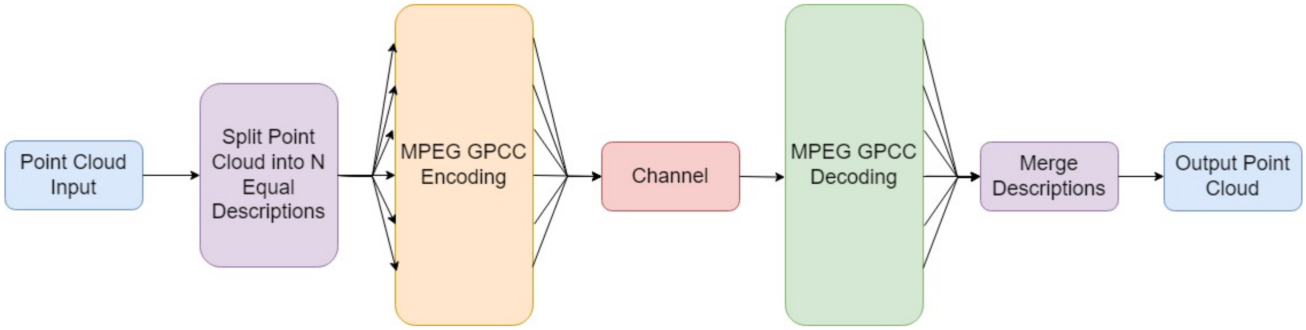


Fig. 1: System Model: The general layout of the proposed system.

group termed the `TMC13 v14` [10], [14]. The encoder takes an input of a point cloud file, compresses it based on the selected compression technique (i.e., Octree vs. Trisoup, Predlift vs. RAHT), and outputs a compressed file. Conversely, the decoder takes a compressed file and decompresses it for a reconstruction of the point cloud. To simulate various lossy compression ratios, we set the "positionQuantizationScale" (PQS) to 15/16, 7/8, 3/4, 1/2, 1/4, and 1/8 for lossy geometry, and "qp" to 51, 46, 40, 34, 28, and 22 for lossy attributes, which are similar to the configuration of the MPEG encoder, where higher attribute and geometric loss lead to a higher compression ratio.

After encoding the point cloud into multiple descriptions, we next simulate the transmission of the encoded point cloud descriptions over high loss wireless channels. First, the encoded descriptions are packetized into packets of equal payloads. Then, for each packet transmitted through the channel, we determine whether or not the packet is dropped based on a predetermined packet loss rate varying from 1% to 25% to emulate different channel conditions. To ensure the random chance is relatively accurate, each of our simulations is repeated 100 times and averaged for proper results. On the other hand, to facilitate the simulation of blockage-limited 5G mmWave links, we assume a system where the descriptions are either completely lost or completely recovered and test the quality of the point cloud recovered from varying number of received descriptions [15]. To represent the high loss conditions, we simulate with varying percentages of packet loss (from 1% to 25%) to demonstrate the effectiveness of MDC for point cloud transmission over wireless channels.

IV. Performance Evaluation and Discussion

A. Performance Metrics

In our experimental study, we choose to utilize the common point-to-point distance based MSE (D1), point-to-plane distance based MSE (D2), and color distortion per RGB MSE from MPEG as metrics of choice [16]. By utilizing these metrics, we are able to compare the corresponding geometric distortions after analyzing D1 and D2 in the form of PSNR, as well as the color distortion utilizing the MPEG color distortion metrics. We generate their corresponding rate-distortion (RD) curves with the bits measured by bits-per-input-point to compare the various compression rates. Finally, these metrics are computed and compared for the various MDC settings, as well as against a typical encoder/decoder baseline scenario without MDC that we implement.

Assume A is the original point cloud and B is the reconstructed point cloud. The common point-to-point distance based error D1 is given by:

$$e^{D1}_{\mathbf{B},\mathbf{A}}(i) = ||E(i,j)||^2_2, \tag{1}$$

where $E(i,j)$ is the error vector and $e^{D1}_{\mathbf{B},\mathbf{A}}(i)$ depicts the error between two points each belonging to point clouds A and B, respectively. Therefore, the MSE between the two entire point clouds can be represented by:

$$e^{D1}_{\mathbf{B},\mathbf{A}} = \frac{1}{N_B}\sum_{\forall b_i \in \mathbf{B}} e^{D1}_{\mathbf{B},\mathbf{A}}(i), \tag{2}$$

where N_B is the total number of points in point cloud B.

On the other hand, with the point-to-plane distance based error D2, the error vector $E(i,j)$ is projected along the normal direction N_j to produce the error vector $\hat{E}(i,j)$, as:

$$e^{D2}_{\mathbf{B},\mathbf{A}}(i) = ||\hat{E}(i,j)||^2_2. \tag{3}$$

The point-to-plane MSE for the overall point cloud B is:

$$e^{D2}_{\mathbf{B},\mathbf{A}} = \frac{1}{N_B}\sum_{\forall b_i \in \mathbf{B}} e^{D2}_{\mathbf{B},\mathbf{A}}(i). \tag{4}$$

Finally, the PSNR value for the reconstructed point cloud can be calculated as:

$$PSNR = 10\log_{10}\left(\frac{3p^2}{MSE}\right), \tag{5}$$

where p is the peak constant value for the point cloud (which is 1023 in the case of longdress). Eq. (5) is also the PSNR equation utilized for computing the color distortions, which are calculated using the MPEG software PC_error [16].

B. Results and Discussions

When we look at the effects of packet loss rate on point cloud transmissions, applying MDC yields significantly better PSNR values in both geometry and attributes, which is further solidified in the case of higher loss rates, even with only few descriptions are received. A basic demonstration can be seen in Fig. 2(a). When transmitting a single stream without multiple description coding, packet loss can result in a variety of inaccuracies within the reconstructed point cloud. Points can vastly change positions or be dropped completely, while the coloration of the point cloud itself could become completely discolored. At higher loss rates, the compressed point cloud could even fail to decode, leading to a completely lost point cloud. However, as can be seen from Fig. 2(b), when more descriptions are lost, rather than losing points and complete decoloration, the resulting point cloud still greatly resembles the original point cloud even with a very low number of received descriptions (e.g., two). The reconstructed point cloud only becomes more sparse with slight decoloration as demonstrated by the zoomed in look in Fig. 2(c), where most changes are almost invisible to the human eye without close inspection. Compared to completely losing the point cloud or having major errors in decoding, the MDC alternative allows to reconstruct a point cloud so long as a single description is received, while remaining relatively faithful to the original point cloud. Furthermore, utilization of MDC mainly results in a sparser point cloud, the original point cloud could be recovered through some point cloud completion techniques such as AIGC [17].

Next, we compare the actual PSNR values between geometries with MDC and normal GPCC encoding/decoding in Figs. 3 and 4. It can be seen that under higher packet loss rates, MDC achieves significantly higher PSNR when utilizing the same compression settings. However, as can be seen from the resulting BPP of the encoder, by encoding 8 sub-clouds each being 1/8 the size of the original point cloud, the coding efficiency greatly suffers, resulting in an increased overall bitrate. Although the resulting file sizes are still much smaller compared to the original point cloud when utilizing MDC due to the reduced size of the sub-clouds, the total compressed file size of all the descriptions combined increases significantly compared to not utilizing MDC.

As shown in Fig. 4, the curves appear more irregular than those in Fig. 3. This discrepancy is due to the effect of random dropping of packets of descriptions of different sizes along with varying packet loss rates. For example, when utilizing a high compression ratio, there are much fewer packets to be transmitted, making packet drops more detrimental to point cloud recovery and usually causing either complete failure to decode the point cloud or complete recovery of the point cloud. On the other hand, with lower compression rates, there are significantly more packets that have a chance of being dropped, increasing the chances of success but inaccurate decoding. This results in higher variance with higher amounts of packets and when packet loss rates are higher. Generally, if the alternative in high loss channels is to completely lose the point cloud or the introduction of major inaccuracies to the point cloud, the trade-off between coding efficiency and PSNR makes it worth utilizing MDC.

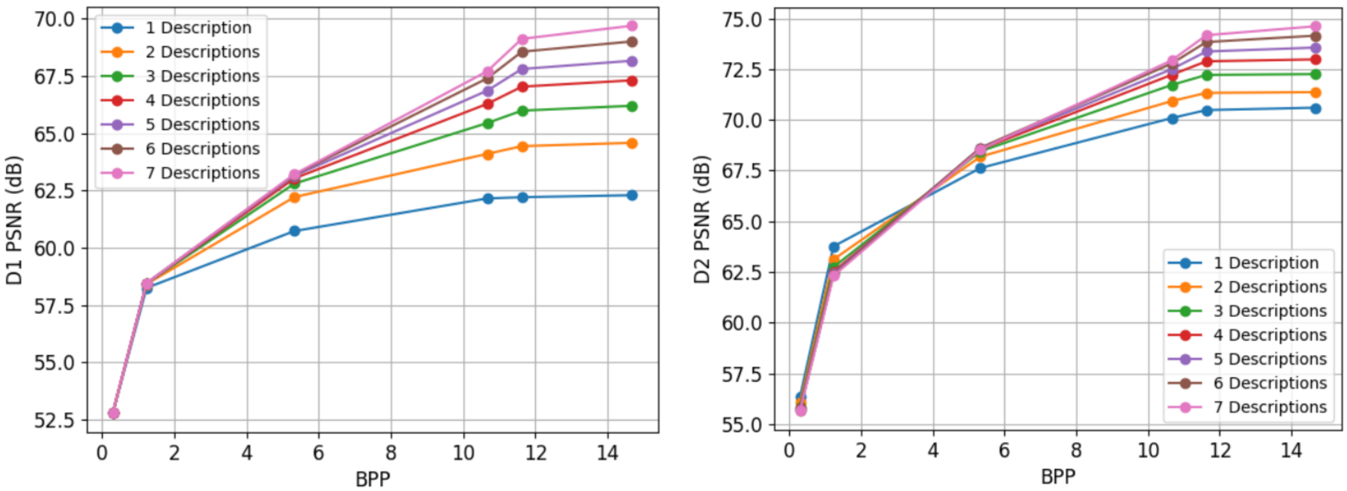
To further examine the effect of MDC descriptions on compression rates, we plot in Fig. 5 the number of descriptions versus their resulting BPP for given PQS values at the encoder when performing lossy geometric and attribute coding. As can be seen from the figure, when generating an increasingly larger number of descriptions, the bits required for each point is

(a) Impact of packet loss with the GPCC encoder.

(b) Impact of description loss with the GPCC encoder.

(c) Closeup look of the point cloud with lost descriptions (right) and the original (left)

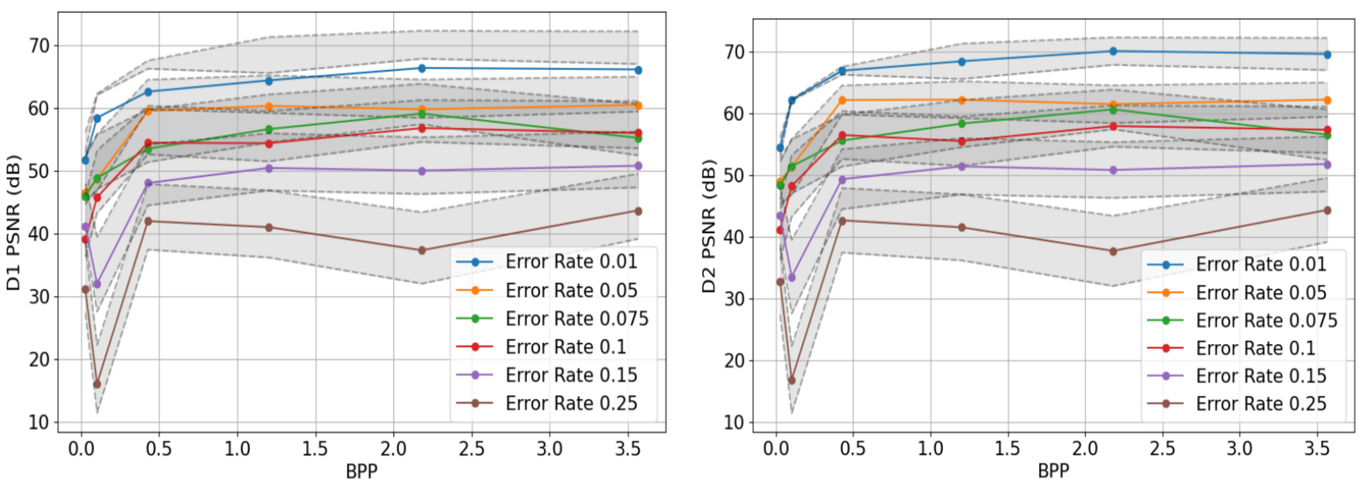
Fig. 2: Impact of channel losses: (a) Comparison between the recovered point clouds under increasing rates of packet loss (0%, 1%, 10%, and 25%, respectively) with 0.75 PQS and 34 qp lossy compression; (b) Effects of recovering 8, 6, 4, and 2 descriptions (out of 8 descriptions), respectively, with the same scale for compression; (c) Closeup look on the effects of losing 6 descriptions (right) in contrast with the error-free ground truth (left).



(a) D1 PSNR.

(b) D2 PSNR.

Fig. 3: Geometric PSNRs with MDC under varying number of recovered descriptions from 1 to 7.



(a) D1 PSNR with 95% confidence intervals.

(b) D2 PSNR with 95% confidence intervals.

Fig. 4: Geometric PSNR under varying packet loss rates from 0.01 to 0.25.

magnified by the amount of descriptions created. However, at high compression rates, the effect of increased description counts becomes much less noticeable due to the extremely small file sizes.

As shown in Figs. 3 and 4, using MDC still well outperforms normal transmission in terms of PSNR at various rates. Although we could reduce the number of descriptions to improve coding efficiency, it would also increase the likelihood of losing all descriptions and the resulting quality of the decoded point cloud would suffer. If the channel has extremely high loss rates, a high number of descriptions might be required for successful recovery.

Lastly, we examine the impact of increasing packet loss rates on point cloud transmission in terms of color distortions in Tables I and II. It is evident that using MDC yields superior PSNR values across all colors, especially at higher packet loss rates. With bit rate gains up to 10 dB and improvements across almost every scenario under similar quantization settings, MDC achieves considerable gains per recovered description at the cost of BPP in colors as well.

V. Conclusions

This work evaluated the effectiveness and prospective efficacy of MDC in the transmission of point clouds. We proposed a simple MDC scheme that is built upon a typical geometric point cloud compression codec. The proposed MDC scheme was then evaluated under simulated high loss wireless channel scenarios. Through our experimental study, we demonstrated the increase in BPP as a result of increasing the number of descriptions created from the point cloud, as well as the trade-off between reduced coding efficiency and the enhanced robustness to transmission errors. In our future work, we aim to further explore the trade-offs in utilizing MDC for

TABLE I: Comparison of Per Color PSNR (dB) Under Varying Packet Loss Rates

	Packet Loss Rate 0.01			Packet Loss Rate 0.1			Packet Loss Rate 0.25		
BPP	R PSNR	G PSNR	B PSNR	R PSNR	G PSNR	B PSNR	R PSNR	G PSNR	B PSNR
0.027	20.1	26.64	24.89	15.17	20.12	18.79	12.1	16.04	14.98
0.102	22.59	29.46	27.92	15.94	21.7	20.46	5.4	7.48	7.04
0.428	22.97	30.36	29.08	14.83	22.01	20.54	11.73	17.65	16.4
1.201	20.93	28.16	26.91	14.35	21.42	19.99	11.4	17.11	15.97
2.181	19.08	26.53	25.15	14.95	22.4	20.88	10.28	15.42	14.36
3.564	17.84	25.28	23.84	14.62	21.95	20.43	12.03	18.07	16.82

TABLE II: Comparison of Per Color PSNR (dB) With Varying Recovered Descriptions

	Recovered 1 Description			Recovered 4 Descriptions			Recovered 7 Descriptions		
BPP	R PSNR	G PSNR	B PSNR	R PSNR	G PSNR	B PSNR	R PSNR	G PSNR	B PSNR
0.29	18.42	17.52	18.28	18.79	17.81	18.64	18.83	17.83	18.7
1.225	21.26	23.75	23.93	22.09	24.71	23.99	22.27	24.95	24.25
5.322	24.33	27.34	27.15	24.96	27.85	25.31	25.5	28.61	25.98
10.666	27.39	30.58	30.5	27.49	30.15	25.58	27.99	30.49	25.84
11.63	31.6	36.38	36.28	30.28	34.44	26.56	30.72	34.58	26.66
14.686	35.37	39.79	40.05	31.88	36.25	26.57	32.19	36.34	26.61

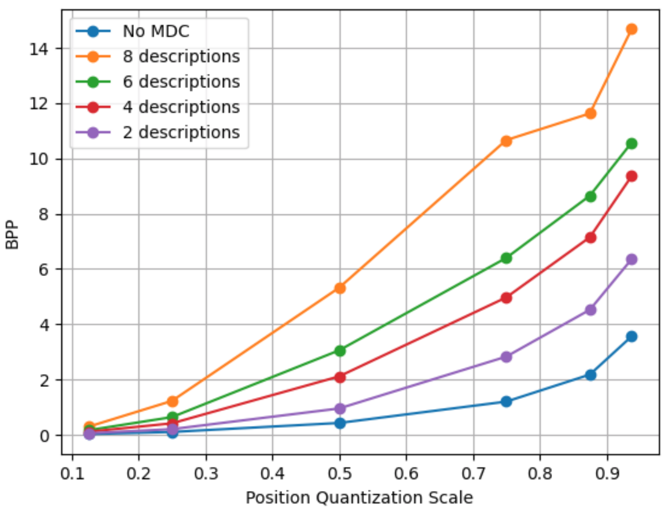


Fig. 5: Compression performance vs. number of descriptions.

point cloud transmission and develop more sophisticated MDC schemes for point clouds.

ACKNOWLEDGEMENTS

This work is supported in part by the NSF under Grant CCNS-2148382. Special thanks to Mr. Birendra Kathariya for helps with the code and dataset.

REFERENCES

[1] A. Chen, S. Mao, Z. Li, M. Xu, H. Zhang, D. Niyato, and Z. Han, "An introduction to point cloud compression standards," *ACM GetMobile*, vol. 27, no. 1, pp. 11–17, Mar. 2023.

[2] X. Ma, Q. Yin, X. Zhang, and L. Tang, "Foldingnet-based geometry compression of point cloud with multi descriptions," in *Proc. 2022 IEEE ICME Workshops*, Taipei, Taiwan, July 2022, pp. 1–6.

[3] S. Mao, Y. T. Hou, X. Cheng, H. D. Sherali, S. F. Midkiff, and Y.-Q. Zhang, "On routing for multiple description video over wireless ad hoc networks," *IEEE Transactions on Multimedia*, vol. 8, no. 5, pp. 1063–1074, Oct. 2006.

[4] Z. Zhao, J. Ostermann, and H. Chen, "Low complexity multiple description coding for the scalable extension of H.264/AVC," in *Proc. 2009 Picture Coding Symposium*, Chicago, IL, May 2009, pp. 1–4.

[5] M. Kazemi, S. Shirmohammadi, and K. H. Sadeghi, "A review of multiple description coding techniques for error-resilient video delivery," *Springer Multimedia Systems*, vol. 20, pp. 283–309, Apr. 2014.

[6] N. Gadgil, H. Li, and E. J. Delp, "Spatial subsampling-based multiple description video coding with adaptive temporal-spatial error concealment," in *Proc. 2015 Picture Coding Symposium (PCS)*, Cairns, Australia, May/June 2015, pp. 90–94.

[7] C. Lamy-Bergot, B. Candillon, B. Pesquet-Popescu, and B. Gadat, "A simple multiple description coding scheme for improved peer-to-peer video distribution over mobile links," in *Proc. 2009 Picture Coding Symposium*, Chicago, IL, May 2009, pp. 1–4.

[8] N. K. Ibrahim, A. Sali, H. A. Karim, A. F. Ramli, N. S. Ibrahim, and D. Grace, "Multiple description coding for enhancing outage and video performance over relay-assisted cognitive radio networks," *IEEE Access J.*, vol. 10, pp. 11 750–11 762, Jan. 2022.

[9] T. Fujihashi, T. Koike-Akino, S. Chen, and T. Watanabe, "Wireless 3D point cloud delivery using deep graph neural networks," in *Proc. IEEE ICC'21*, Virtual Conference, June 2021, pp. 1–6.

[10] MPEG Group, "G-PCC codec description V2," ISO/IEC JTC1/SC29/WG11 N18189, Jan. 2019.

[11] K. You and P. Gao, "Patch-based deep autoencoder for point cloud geometry compression," in *Proc. ACM Multimedia Asia 2021*, Gold Coast, Australia, Dec. 2022, pp. 1–7.

[12] W. Wu, Z. Qi, and L. Fuxin, "PointConv: Deep convolutional networks on 3D point clouds," in *Proc. IEEE/CVF CVPR'19*, Long Beach, CA, June 2019, pp. 9613–9622.

[13] E. d'Eon, B. Harrison, T. Myers, and P. A. Chou, "8i Voxelized Full Bodies - A Voxelized Point Cloud Dataset," ISO/IEC JTC1/SC29 Joint WG11/WG1 (MPEG/JPEG) Input Document WG11M40059/WG1M74006, Jan. 2017.

[14] S. Schwarz, M. Preda, V. Baroncini, M. Budagavi, P. Cesar, P. A. Chou, R. A. Cohen, M. Krivokuća, S. Lasserre, Z. Li, J. Llach, K. Mammou, R. Mekuria, O. Nakagami, E. Siahaan, A. Tabatabai, A. M. Tourapis, and V. Zakharchenko, "Emerging MPEG standards for point cloud compression," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 9, no. 1, pp. 133–148, Mar. 2019.

[15] Y. Wang and S. Lin, "Error-resilient video coding using multiple description motion compensation," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 12, no. 6, pp. 438–452, June 2002.

[16] MPEG Group, "Call for proposals for point cloud compression V2," ISO/IEC JTC1/SC29/WG11 MPEG2017/N16763, Apr. 2017.

[17] Z. Lyu, Z. Kong, X. Xu, L. Pan, and D. Lin, "A conditional point diffusion-refinement paradigm for 3D point cloud completion," *arXiv preprint arXiv:2112.03530*, Dec. 2021. [Online]. Available: https://arxiv.org/abs/2112.03530