Cross-Layer-Optimized Link Selection for Hologram Video Streaming over Millimeter Wave Networks

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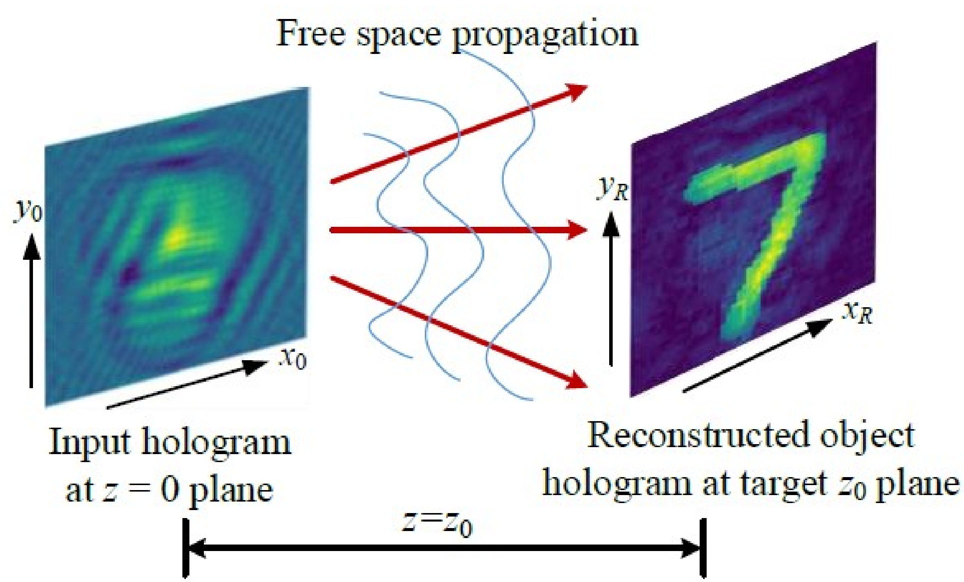
CONTENT

Background

- ***Holographic Technology: The Next Step in Communication***
  - Holographic display is considered the ultimate 3D display technology
  - Holography is emerging as a powerful tool that bridges geographical distances and enhances digital interactions.
  - Widely used in immersive 3D applications such as virtual reality, medical imaging, holo-meetings and more recently metaverse.

Background

- **Computer Generated Holography(CGH)**
  - CGH has a more *complex storage method* compared to regular images such as real and imaginary forms and amplitude and phase forms.
  - CGH needs *reconstruction*, which involves using numerical algorithms to simulate the propagation of light waves.
  - Voxel-Based holography delivery requires higher consumption of computing resources at the receiver end, while delivering CGH directly receives pre-generated holography data.



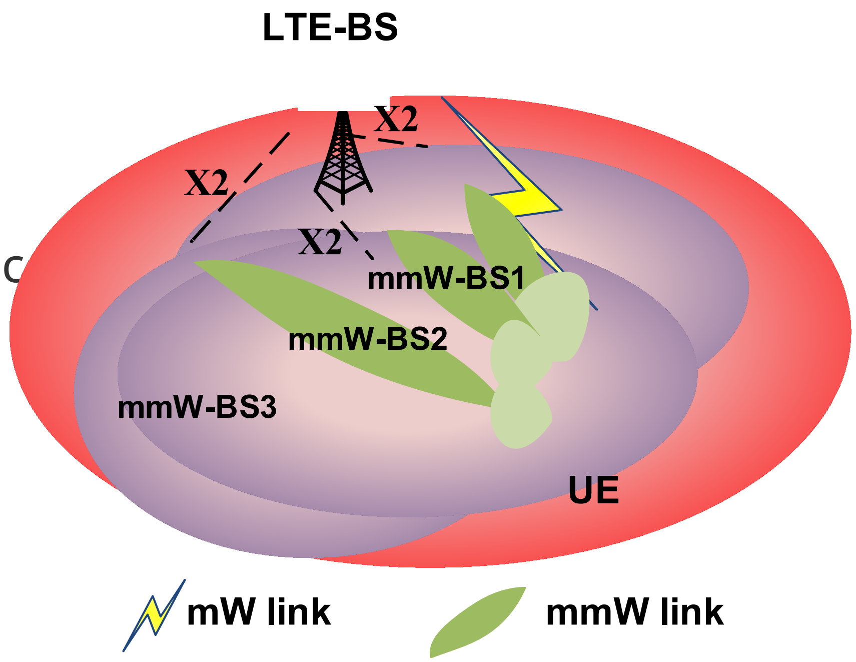
Background

Millimeter-Wave (mmWave) Networking

- Millimeter-wave networking benefits from higher frequency spectrum resources.
- It supports larger bandwidth, meeting the needs of holographic streaming.

Multi-Connectivity(MC) Architecture

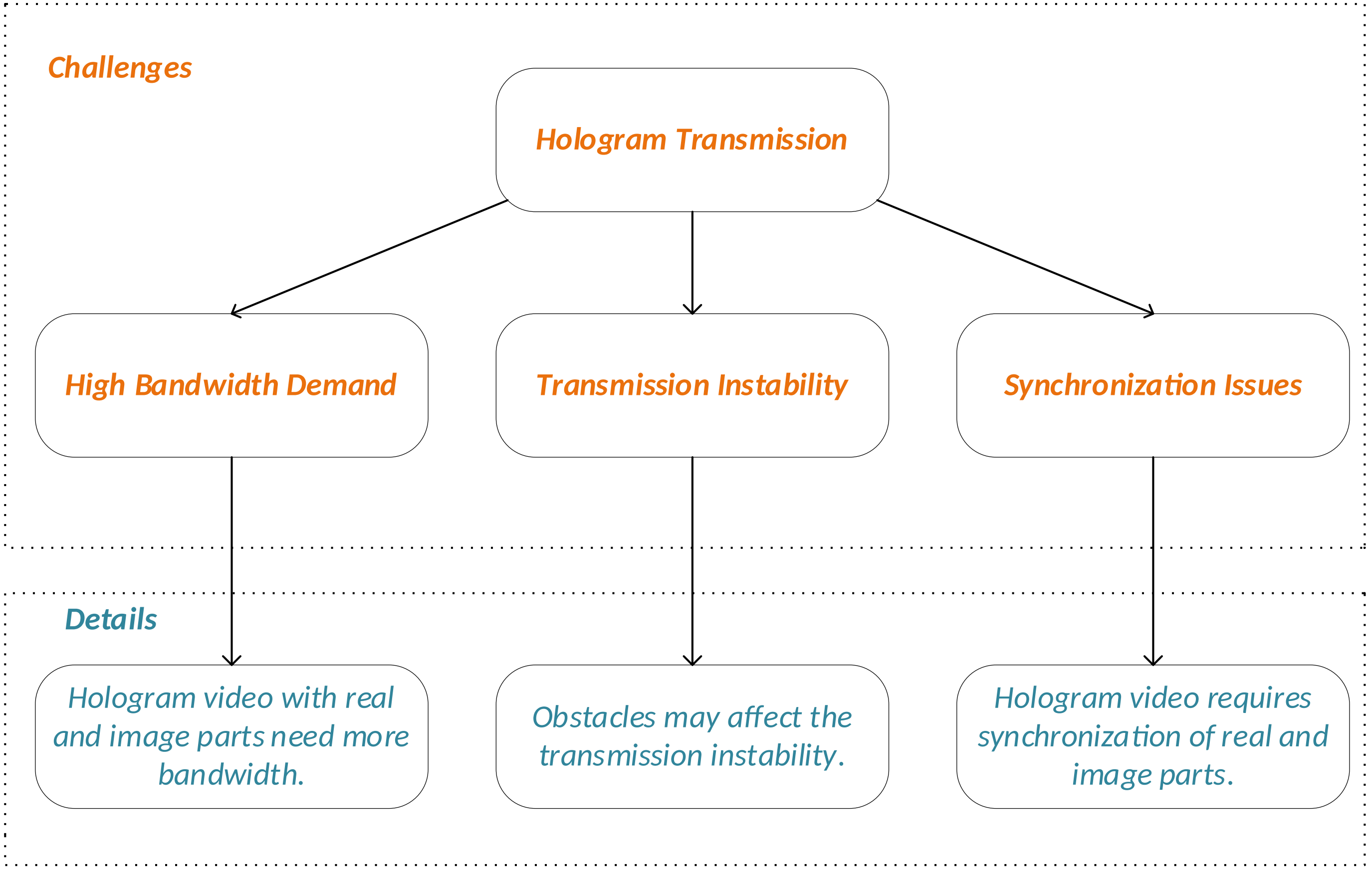
- MC architecture enables data transmission through multiple paths, which improves efficiency.
- MC architecture can be used to mitigate the obstacle occlusions in mmWave communication.



Background

Challenges about Hologram Transmission

- Although holographic videos bring a great user experience, efficient transmission, even with the MC-based mmWave networks, is still a major challenge need to be solved.



Main contributions

- ***To combine Hologram with Multi-connectivity Transmission***
  - Consider the unique transmission requirement compared to normal video
  - Introduce the dynamic human blockage during hologram transmission

- ***The Cross-layer-Optimized Link Selection scheme***
  - We propose a cross-layer-optimized link selection framework for hologram video streaming over mmWave networks.
  - The scheme considers various adjustable parameters for minimizing the end-to end hologram distortion.
  - The synchronization and quality balance among real and imaginary parts in the complex-plane are considered in the optimization.

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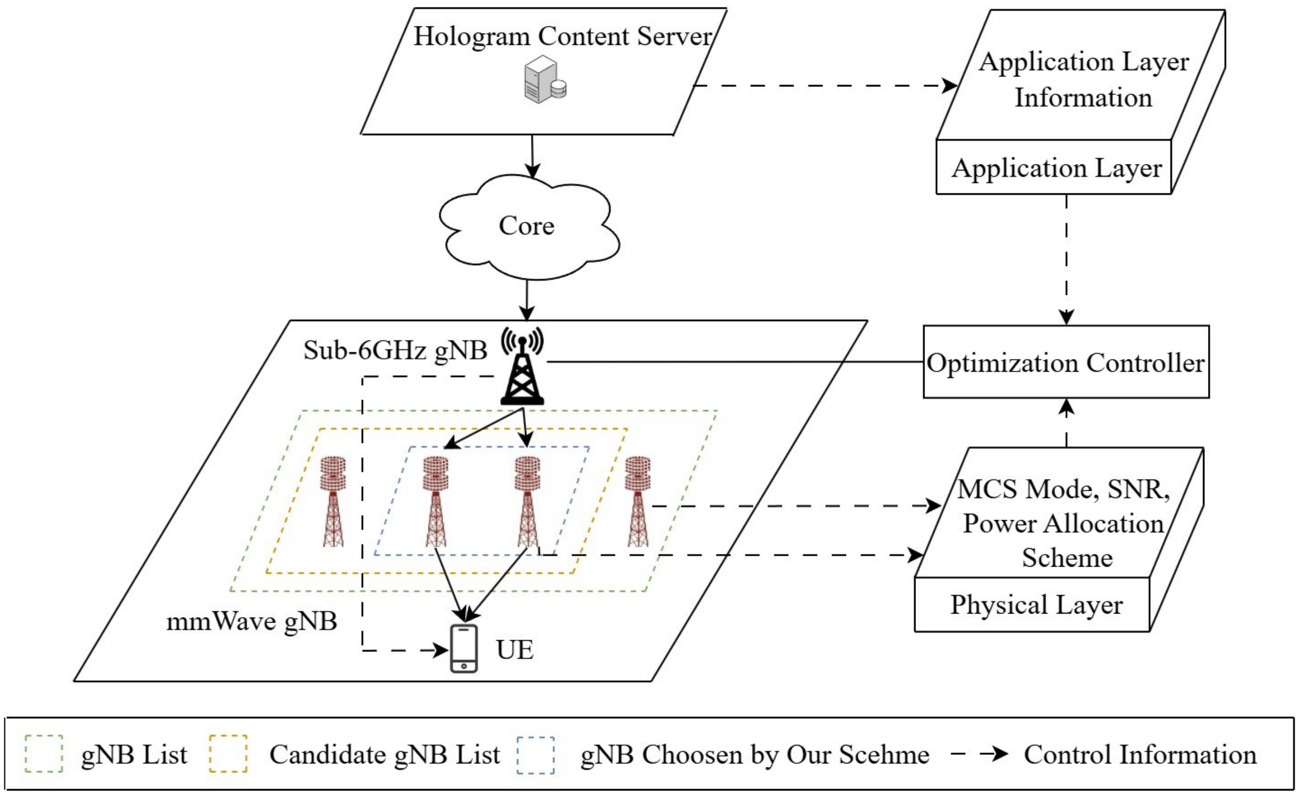
Cross-layer-Optimized Link Selection Framework



- The proposed scheme considers *the cross-layer process*.
  - The physical layer adjust various parameters by optimization controller to enhance the transmission quality.
  - The application layer feedbacks information to the optimization controller to control the parameters adjustment of the physical layer.

Human Blockage Model

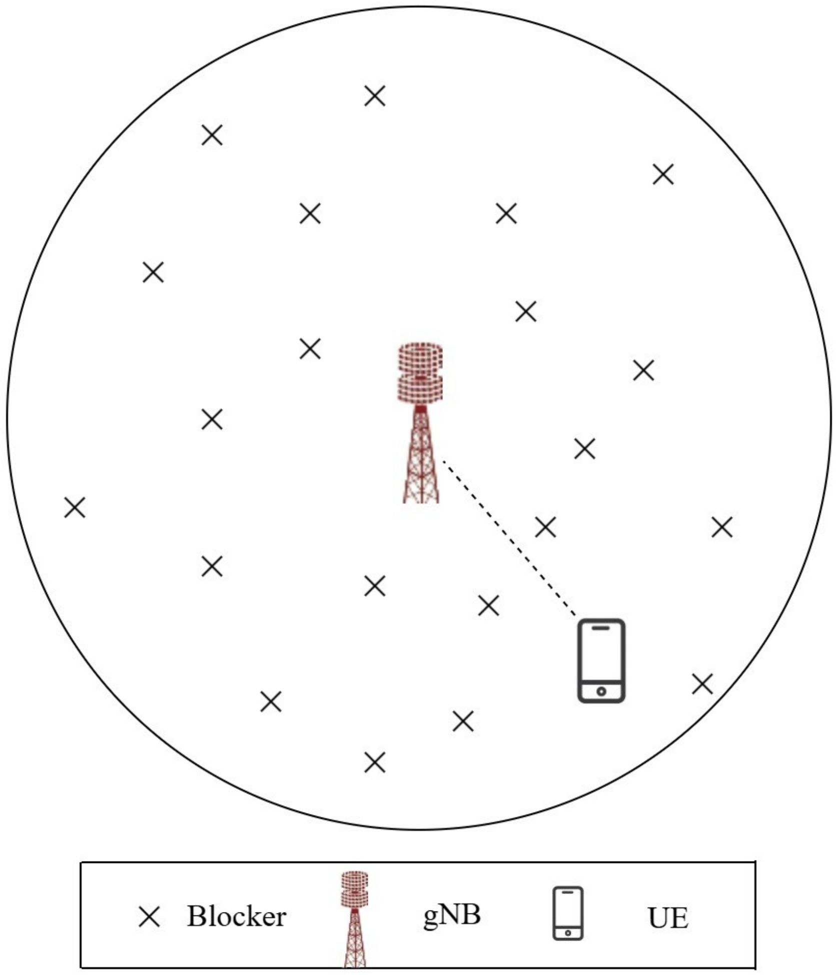


Figure: Dynamic Human Blockage Model

Dynamic Human Blockage Model

- *Poisson Point Process (PPP) Simulation*
  - Simulate random blockage events dynamically.
- *Dynamic Blocker Density (λB)*
  - Impact blockage frequency
- *Blockage Duration and Power Loss*
  - Blockage causes power loss and last for some time.
- *Recovery Process*
  - After a period of time, the power recover to normal.

Packet Loss Rate Estimation

- To ensure the hologram video quality of receiver, we need to decrease the *packet loss rate*.
- Different *Modulation and Coding Scheme(MCS) mode* provide varying levels of error resilience and data rate. Hence the MCS mode will affect the packet loss rate during transmission, so the mode need to be adjusted dynamically.
- Data in each transmission slot is sent in Transmission Blocks (TBs), composed of multiple Coding Blocks (CBs).
  - BLER for an individual CB are shown below.

$$C_{B,i}(\beta_i) = \frac{1}{2}\left[1 - erfc(\frac{\beta_i - b(m)}{\sqrt{2}c(m)})\right]$$

  - Then BLER for a TB can be caculated as below.

$$T_B = 1 - \prod_{i=1}^{N_T} (1 - C_{B,i}(\beta_i))$$

  - Hologram packets consist of multiple TBs, and the overall packet loss rate is calculated as below.

$$p_{n,i} = 1 - \prod_{i=1}^{N_B} (1 - T_{B,i}))$$

Distortion Estimate Model

- ***Distortion Estimate Model*** : To perform the cross-layer-optimized link selection, we are supposed to estimate the end-to-end hologram distortion under different parameter for entire Group of Pictures(GOP) .
  - Packet loss leads to end-to-end distortion, measured by MSE.

$$D_\gamma(GOP) = \sum_{k=0}^{2^N-1} p^{(k)} D^{(k)} = \sum_{k=0}^{2^N-1} \left(\prod_{i=0}^{N-1} (1-p_i)^{(1-b_i^{(k)})} p_i^{b_i^{(k)}} \right) D^{(k)}$$

  - Direct computation is too complex for real-time hologram streaming. So we use the Taylor expansion to simplify the actual computational process.

$$D_\gamma(GOP) \approx D_{\bar{\gamma}}(GOP) + \sum_{i=0}^{N-1} \frac{\partial D_\gamma(GOP)}{\partial p_i}\Big|_{\gamma=\bar{\gamma}} (p_i - \bar{p}_i) = D_{\bar{\gamma}}(GOP) + \sum_{i=0}^{N-1} \lambda_i (p_i - \bar{p}_i)$$

Distortion Estimate Model

- ***Distortion Estimate Model*** : After using the Taylor expansion, we could simplify the equation by using the source encoding distortion.
  - The distortion can be transmitted to the form below.

$$D_\gamma(GOP) = (1-p_i)D_\gamma(GOP)|_{b_i=1} + p_i D_\gamma(GOP)|_{b_i=0}$$

  - Hence the λ_i can be simplified as

$$\lambda_i = D_\gamma(GOP)|_{b_i=0} - D_\gamma(GOP)|_{b_i=1}$$

  - Using the equation below to simplify.

$$D_\gamma(GOP)|_{b_i=1} = D_{\bar{\gamma}}(GOP)$$

  - However, source encoding distortion can be obtained easily during hologram video encoding. So we can make sure the distortion estimate can suit for our requirement.

The Cross-layer-Optimized Link Selection Scheme

- ***The Cross-layer-Optimized Link Selection Scheme***: Dynamic link selection with the adjustments of network parameters of difficult protocol layers is very necessary to ensure the performance of hologram streaming.

$$
\begin{aligned}
& q_R^{opt}, m_R^{opt}, \Omega_R^{opt}, l_R^{opt}, q_I^{opt}, m_I^{opt}, \Omega_I^{opt}, l_I^{opt} \\
& = \underset{\substack{q_R,\, q_I \in Q \\ m_R, m_I \in M \\ l_R, l_I \in L}}{\arg\min} \; D_H(q_R, m_R, \Omega_R, l_R, q_I, m_I, \Omega_I, l_I) \\
& = \underset{\substack{q_R,\, q_I \in Q \\ m_R, m_I \in M \\ l_R, l_I \in L}}{\arg\min} \; (D_R(q_R, m_R, \Omega_R, l_R) + D_I(q_I, m_I, \Omega_I, l_I)) \\
& \text{s.t.}\ |D_R(q_R, m_R, \Omega_R, l_R) - D_I(q_I, m_I, \Omega_I, l_I)| \le D_T, \\
& \quad\ \Omega_R + \Omega_I \le \Omega
\end{aligned}
$$

- ***Target***: To minimize end-to-end hologram distortion D_H to enhance video quality and ensure synchronization and quality balance between real and imaginary parts.

- ***Optimization method***: Iterative search over different parameter combinations under restricted conditions to find the best two links.

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Simulation Setup

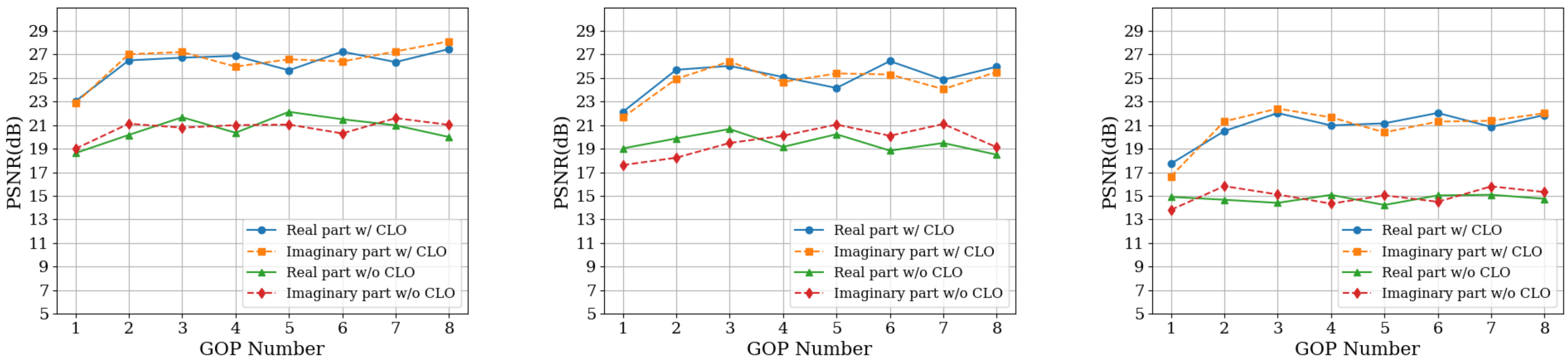
- ***Experimental Hologram Video***
  - We use BreakDancer sequence with a resolution of 1920×1080 and Ballet sequence with a resolution of 3840×2160 for experiments.
- ***Simulation Tool***
  - Network simulation platform: NS-3
  - Open source architectures: NYUSIM mmWave Channel Model
  - Encoding mode : HEVC
  - Open source reconstruction software: NRSH
- ***Simulation Parameters***

SIMULATION PARAMETERS

Coding structure	IPPP
Candidate QP	27,37,45
Distance between node (m)	10
Number of mmWave links	6
frequency	30GHz
Total txPower	60dBm
Noise figure (dB)	9dB
mmWave simulation Scenario	UMi
Height of UE	1.5m
Height of gNB	10m
SNR threshold S_T	15dB
Human blockage density (bl/m^2)	0.03, 0.05, 0.1
Distortion threshold D_T in terms of PSNR	1.5dB

Performance Evaluation

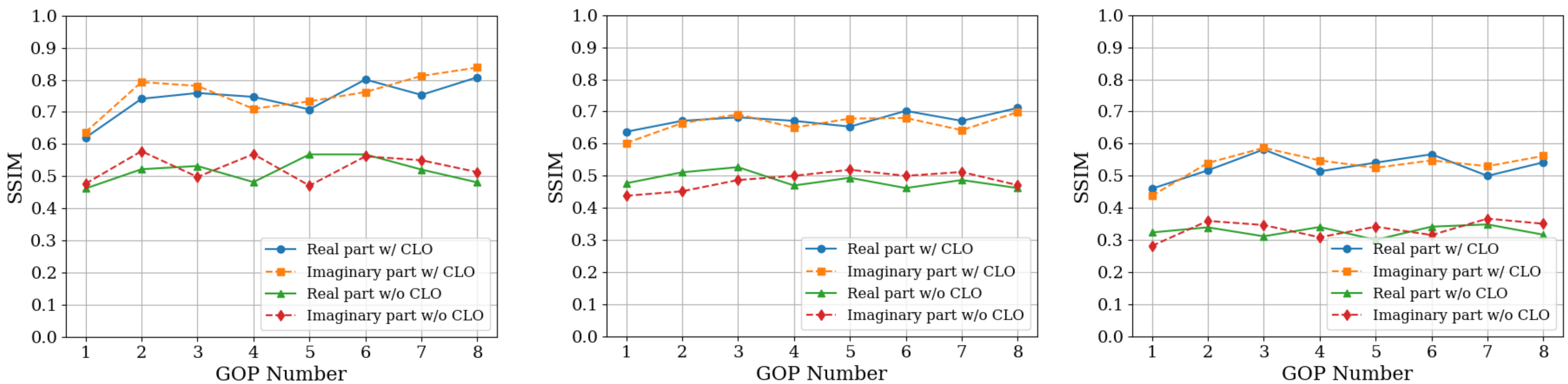
- The experiments use the ***BreakDancer sequence (1920×1080)*** as the test video to caculate ***PSNR and SSIM*** under different blockage density.
  - ***PSNR Improvement***: Across the range of λB = 0.03 to 0.1 bl/m², the CLO scheme outperforms the w/o CLO scheme with a PSNR gain of 2.3dB to 6.4dB.
  - ***SSIM Improvement***: The CLO scheme achieves an average SSIM increase of at least 9.7% compared to w/o CLO.



$(a)\ \lambda_B = 0.03 bl/m^2$ $(b)\ \lambda_B = 0.05 bl/m^2$ $(c)\ \lambda_B = 0.1 bl/m^2$

Figure: Hologram video streaming performance in terms of PSNR

Performance Evaluation

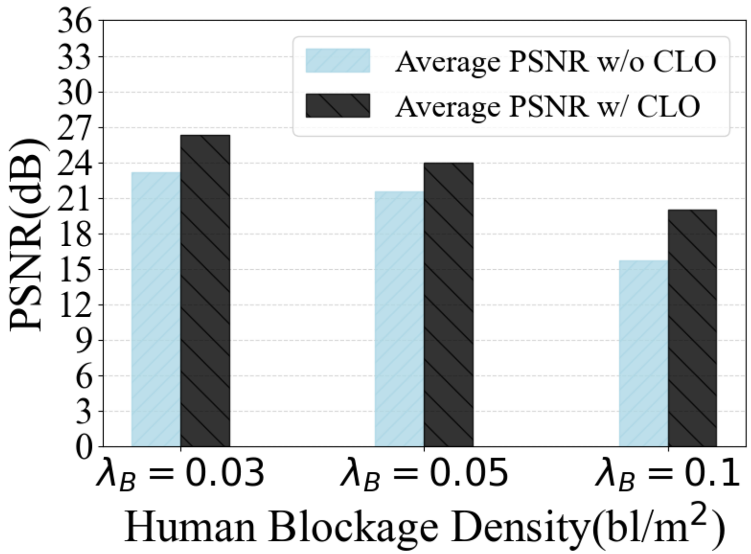


$(a)\ \lambda_B = 0.03bl/m^2$ $(b)\ \lambda_B = 0.05bl/m^2$ $(c)\ \lambda_B = 0.1bl/m^2$

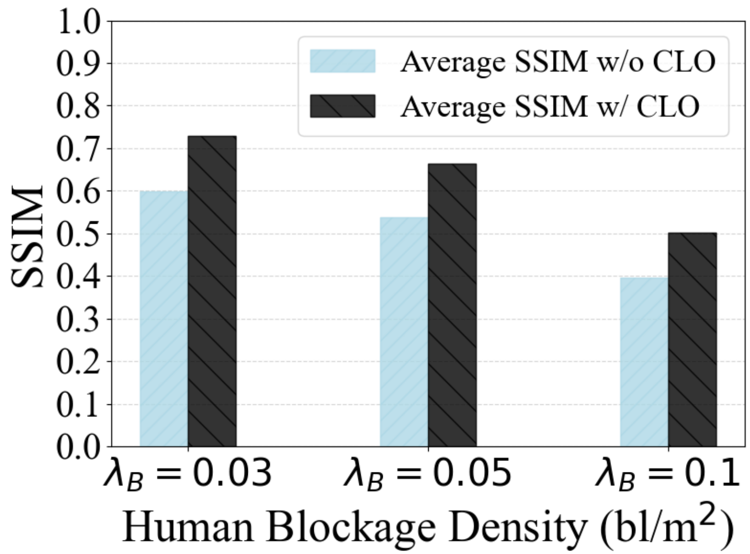
Figure: Hologram video streaming performance in terms of SSIM

Performance Evaluation

- We evaluate the effectiveness of our scheme by using the ***Ballet sequence (3840×2160).***
  - ***PSNR Improvement***: The CLO scheme achieves a PSNR gain of 1.2dB to 4.1dB compared to the w/o CLO scheme.
  - ***SSIM Improvement***: The CLO scheme improves SSIM by at least 10.5% over the w/o CLO scheme.



(a) Average PSNR



(b) Average SSIM

Figure: Hologram video streaming performance for Ballet

Performance Evaluation

- We use NRSH software to reconstruct the hologram video to ***subjectively assess the visual quality*** of finally displayed hologram video.
  - ***With CLO Scheme***: The outlines of the dancers are clearer after CLO and are more pronounced at the focus of the image.
  - ***Without CLO Scheme***: It can be seen that the image without CLO is relatively blurred compared to the one with CLO.

(a) w/ CLO

(b) w/o CLO

Figure: The comparison of reconstructed BreakDancer hologram image with and without CLO

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Conclusions

- This paper proposed a ***cross-layer optimized link selection scheme*** for hologram video streaming over mmWave networks.
  - Our model incorporates multi-connectivity architecture and the characteristics of hologram videos, and introduces a dynamic blockage model to simulate more realistic scenarios.
  - The scheme jointly optimizes hologram coding bitrate, MCS modes, and channel power allocation to minimize distortion.
  - We evaluate the transmission performance and subjective quality of hologram videos with different resolutions.

THANKS

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