OUTAGE AND TIMEOUT PROBABILITY USING MULTIPLE DESCRIPTION CODING FOR VIDEO TRANSMISSION OVER RELAY-ASSISTED COGNITIVE RADIO NETWORKS

By

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July 2024

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Multiple Description Coding (MDC) is a source coding technique that enhances video transmission reliability over networks by splitting data into multiple descriptions sent via different paths. The accuracy of the received data improves with more received descriptions. Delivering multimedia content, including transmitting videos over wireless networks, presents notable difficulties, including limitations in spectrum capacity and occurrences of packet losses. Cognitive radio (CR) technology addresses spectrum scarcity problem. Relay communication is recognized as a promising technique for enhancing the capacity and range of wireless communication systems and been extensively utilized in CR systems. However, existing research studies concentrated on the MDC approach to the relay-assisted CR systems for accommodating the challenges raised in multimedia transmission, leaving opportunities to be explored. The outage and timeout probability are two transmission performance indicators in video

transmission. MDC reduces the adverse effects of outages and timeouts in relay-assisted CR networks by dividing video sequences into descriptions, enabling partial reconstruction even when some packets are lost or delayed. This thesis proposed a system comprised of the MDC to a relay-assisted CR network named MDC-RC for video transmission. This work aims to recognize new opportunities to improve the received video quality and enhance the outage and timeout performance. The first part investigates the video performance of the proposed MDC-RC system to exploit the path diversity to improve error resilience. The video encoding and decoding algorithms at the transmitter and receiver are constructed with the MDC approach. The results indicate that the proposed MDC-RC system achieves better video quality improvement up to 15% compared to the system with the conventional scheme, Single Description Coding (SDC). For path diversity exploitation, the results show that the video quality improved up to 13% when both video descriptions were received compared to one description received.

The second part of the thesis focuses on the derivation of outage and timeout probability expression based on the new proposed MDC-RC system models, named MDC-RC-I and MDC-RC-U, for video transmission over the interweave and underlay mode of CR, respectively. The expression for the outage and timeout probability are derived for two scenarios, relay network and non-relay network. In relay-assisted CR networks, assessing outage and timeout probability is essential for optimizing video transmission because it reduces packet losses and delays brought on by channel variations and spectrum variability. In the last part, the proposed system models are tested for outage,

timeout, and video performance. First, the outage and timeout performance are evaluated, followed by the video performance. The results show the MDC approach's benefits towards outage performance by 7% improvement over non-relay network, and the results for video quality received indicate that the proposed MDC-RC-I improves up to 9% compared to the non-relay network and up to 4% compared to the SDC. For the MDC-RC-U model, the results demonstrate that the system model improves the timeout performance up to 6% compared to the non-relay network. As for video performance, the MDC-RC-U improves up to 15% and 3% compared to the non-relay network and SDC, respectively.

Keywords: Cognitive Radio Networks, Outage Probability, Relay, Timeout Probability, Video Coding

SDG: GOAL 4: Industry, Innovation and Infrastructure

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KEBARANGKALIAN GANGGUAN DAN TAMAT MASA MENGGUNAKAN PENGEKODAN DESKRIPSI BERBILANG UNTUK PENGHANTARAN VIDEO MELALUI RANGKAIAN RADIO KOGNITIF DIBANTU GEGANTI

Oleh

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Pengekodan Deskripsi Berbilang (MDC) ialah teknik pengekodan sumber yang meningkatkan kebolehpercayaan penghantaran video melalui rangkaian dengan membahagikan data kepada berbilang deskripsi yang dihantar melalui laluan berbeza. Ketepatan data yang diterima bertambah baik dengan lebih banyak deskripsi yang diterima. Menyampaikan kandungan multimedia, termasuk menghantar video melalui rangkaian wayarles, memberikan kesukaran yang ketara, termasuk had dalam kapasiti spektrum dan kejadian kehilangan paket. Teknologi radio kognitif (CR) dapat menangani masalah kekurangan spektrum. Komunikasi geganti diiktiraf sebagai teknik yang menjanjikan untuk meningkatkan kapasiti dan julat sistem komunikasi tanpa wayar dan telah digunakan secara meluas dalam sistem CR. Walau bagaimanapun, kajian penyelidikan sedia ada tertumpu pada pendekatan MDC kepada sistem CR berbantukan geganti untuk menampung cabaran yang dibangkitkan dalam penghantaran multimedia, meninggalkan peluang

untuk diterokai. Kebarangkalian gangguan dan tamat masa ialah dua penunjuk prestasi penghantaran dalam penghantaran video. MDC mengurangkan kesan buruk gangguan dan tamat masa dalam rangkaian CR berbantu geganti dengan membahagikan jujukan video kepada deskripsi, membolehkan pembinaan semula separa walaupun apabila sesetengah paket hilang atau tertangguh. Tesis ini mencadangkan satu sistem yang terdiri daripada MDC kepada rangkaian CR bantuan geganti bernama MDC-RC untuk penghantaran video. Kerja ini bertujuan untuk mengenali peluang baharu untuk meningkatkan kualiti video yang diterima dan meningkatkan prestasi gangguan dan tamat masa. Bahagian pertama menyiasat prestasi video sistem MDC-RC yang dicadangkan untuk mengeksploitasi kepelbagaian laluan untuk meningkatkan daya tahan ralat. Algoritma pengekodan dan penyahkodan video pada pemancar dan penerima dibina dengan pendekatan MDC. Keputusan menunjukkan bahawa sistem MDC-RC yang dicadangkan mencapai peningkatan kualiti video yang lebih baik sehingga 15% berbanding sistem dengan skema konvensional, Single Description Coding (SDC). Untuk eksploitasi kepelbagaian laluan, keputusan menunjukkan bahawa kualiti video meningkat sehingga 13% apabila kedua-dua deskripsi video diterima berbanding dengan satu deskripsi yang diterima.

Bahagian kedua tesis memfokuskan pada terbitan ungkapan kebarangkalian gangguan dan tamat masa berdasarkan model sistem MDC-RC baharu yang dicadangkan, masing-masing dinamakan MDC-RC-I dan MDC-RC-U, untuk penghantaran video melalui mod ‘interweave’ dan ‘underlay’ CR. Ungkapan untuk kebarangkalian gangguan dan tamat masa diperolehi untuk dua

senario, rangkaian geganti dan rangkaian bukan geganti. Dalam rangkaian CR bantuan geganti, menilai kebarangkalian gangguan dan tamat masa adalah penting untuk mengoptimumkan penghantaran video kerana ia mengurangkan kehilangan paket dan kelewatan yang disebabkan oleh variasi saluran dan kebolehubahan spektrum. Pada bahagian terakhir, model sistem yang dicadangkan diuji untuk gangguan, tamat masa dan prestasi video. Pertama, prestasi gangguan dan tamat masa dinilai, diikuti dengan prestasi video. Keputusan menunjukkan faedah pendekatan MDC terhadap prestasi gangguan sebanyak 7% peningkatan berbanding rangkaian bukan geganti, dan keputusan untuk kualiti video yang diterima menunjukkan bahawa cadangan MDC-RC-I bertambah baik sehingga 9% berbanding rangkaian bukan geganti dan sehingga 4% berbanding SDC. Untuk model MDC-RC-U, keputusan menunjukkan bahawa model sistem meningkatkan prestasi tamat masa sehingga 6% berbanding rangkaian bukan geganti. Bagi prestasi video, MDC-RC-U masing-masing meningkat sehingga 15% dan 3% berbanding rangkaian bukan geganti dan SDC.

Kata Kunci: Rangkaian Radio Kognitif, Kebarangkalian Gangguan, Geganti, Kebarangkalian Tamat Masa, Pengekodan Video

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Date: 17 April 2025

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1D	1 Description
2D	2 Descriptions
AF	Amplify and Forward
AVC	Advanced Video Coding
CAE	Convolutional auto-encoder
CCRN	Cognitive Cooperative Radio Networks
CF	Compressed and Forward
CIF	Common Intermediate Format
CR	Cognitive Radio
DCT	Discrete Cosine Transform
DF	Decode and Forward
DPCM	Differential Pulse Code Modulation
EF	Estimate and Forward
FCC	Federal Communications Commission
FD	Full Duplex
FEC	Forward Error Correction
FPC	Functional Principal Component
GF	Gather and Forward
HEVC	High-Efficiency Video Coding
HVS	Human Visual System
JSCC	Joint Source-Channel Coding
KSVD	K Singular Value Decomposition
LC	Layered Coding
LF	Linear-Process and Forward
MAC	Medium Access Control

MB	Macro Block
MD	Multiple Description
MDC	Multiple Description Coding
MDC-RC	Multiple Description Coding-Relay Cognitive
MDC-RC-I	Multiple Description Coding-Relay Cognitive-Interweave
MDC-RC-U	Multiple Description Coding-Relay Cognitive-Underlay
MLMDC	Mixed Layer MDC
MPEG	Moving Picture Experts Group
MRS	Multi Relay Selection
nLF	nonlinear-Process and Forward
NOMA	Non-Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OSA	Opportunistic Spectrum Access
PA	Power Allocation
PD	Primary Destination
PEO	Packet Error Outage
PER	Packet Error Rate
PF	Purge and Forward
PLR	Packet Loss rate
PS	Primary Source
PSNR	Peak Signal to Noise Ratio
PU	Primary User
QCIF	Quarter Common Intermediate Format
QoS	Quality of Service
QP	Quantization Parameter
RF	Radio Frequency

RSME	Root Mean Square Error
RV	Random Variable
SDC	Single Description Coding
SI	Smoothing Index
SNR	Signal to Noise Ratio
Sub-QCIF	Sub-Quarter Common Intermediate Format
SD	Secondary Destination
SR	Secondary Relay
SRM	Supportive Relaying Model
SS	Secondary Source
SU	Secondary User
SWIPT	Simultaneous Wireless Information and Power Transmission
TS	Temporal Splitting
TSWORS	Two-Stage with Oppurtunistic Relay Selection
TSWPRS	Two-Stage with Partial Relay Selection
VANET	Vehicular Ad-hoc NETwork
VCEG	Video Coding Experts Group
VLC	Variable Length Coding
WLAN	Wireless Local Area Network
WPAN	Wireless Personal Area Network

CHAPTER 1

INTRODUCTION

Multimedia services are rapidly expanding as heterogeneous communication networks. The number of users using higher bandwidth services like video streaming is continually growing. Due to its steady deployment in diverse applications such as military and disaster recovery, video transmission through wireless networks is fast developing. Providing error resilience video transmissions is crucial as they become essential and actively used. On the other hand, the challenges arise from spectrum capacity and packet losses caused by transmission interference. Cognitive radio (CR) technology was developed to address the spectrum constraint in high bandwidth multimedia applications, while multiple description coding (MDC) is one of the promising source coding techniques to alleviate packet loss problems and, at the same time, exploit the benefit of path diversity. This chapter highlights the background of the CR network with relay-assisted video transmission, MDC as the video coding technique, and the research objectives, followed by the scope and significance of the study. The organization of the thesis is outlined at the end of the chapter.

1.1 Background

Wireless communication and networking have seen tremendous expansion in recent years. Various standards and technologies such as wireless personal area networks (WPAN), wireless local area networks (WLAN), wireless metropolitan area networks (WMAN), and fifth generation (5G) mobile telecommunication networks have all been developed to facilitate high-speed communication between multimedia devices. Video communication has become the dominant traffic over wireless and IP networks with various applications, including video conferencing, telemedicine, surveillance, security monitoring, disaster relief, environmental monitoring, gaming and entertainment, and wildlife activity monitoring. Though the wireless networks have deployment and user mobility advantages, video communication over wireless networks with the video transmission itself faces severe challenges such as bandwidth variation and interference. The CR technology is well-known as a viable method for dealing with the spectrum issue, as the spectrum has been regarded as the primary resource in video transmission.

According to an investigation by the FCC (Federal Communications Commission) [3], considerable portions of the licensed spectrum are constantly unused. The unused radio spectrum has piqued the interest of experts trying to figure out how to use it better. When a licensed user, known as the primary user (PU), is not present or is co-located with the presence of PU, an unlicensed user known as the secondary user (SU) is allowed to use the spectrum. These scenarios are referred to as CR interweave and underlay modes. In interweave mode, the SU will use the spectrum that is currently unexploited by the PU [11]. If PU is present, the SU will only utilize the spectrum and will not cause any unwanted interference, known as the CR underlay mode. The researchers concluded in [12] that CR technology might exploit an underutilized spectrum for a video-aware wireless network and significantly improve media transmissions.

Relay communication has been hailed as a potential method for increasing the throughput and coverage of wireless communication systems, and it has been widely applied recently in CR systems [13]. Using a relay to assist transmission from the source to the destination in the CR system as illustrates in Figure 1.1 can boost the network capacity and coverage while also increasing the spectrum efficiency.

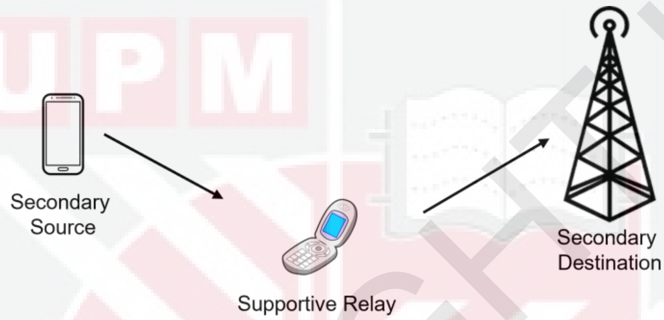


Figure 1.1 : Illustration of Relay Communication

A video transmission system usually involves five basic processes, as shown in Figure 1.2 [2]. The process starts with a decoder compressing the video to lower the data rate at the transmitter. The compressed bit stream is then divided into fixed or variable length packets and multiplexed with other data types, such as audio. If the network ensures bit error-free transmission, the packets may be sent directly across it. To protect them against transmission mistakes, if not, they often go through a channel encoding stage utilizing forward error correction (FEC). The packets are FEC decoded and unpacked at the receiver end, and the resulting bit stream is then fed into the video decoder to recreate the original video.

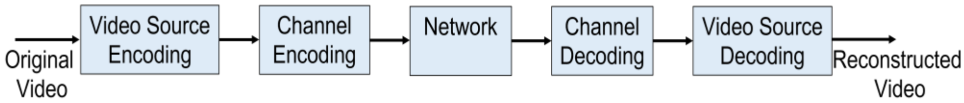


Figure 1.2 : Basic Video Transmission System [2]

Various error-resilient coding techniques have been offered for the reliability of video communication over noisy channels. These include FEC, joint source-channel coding (JSCC), adaptive source-channel coding, robust source coding and MDC. MDC is a well-known source coding technique that appears to be a promising coding mechanism for transmitting multimedia data such as images and videos. The MDC coding divides the given data into multiple descriptions, allowing the quality of the data received to be affected by the number of descriptions received. [12] – [15] are some recent studies that use MDC approaches for image and video coding. MDC was combined with the K-singular value decomposition (K-SVD) technique in [14] to achieve the sparse transform for image coding reconstruction accuracy. The study [15] developed an MDC framework with an auto-encoder to create high-quality image reconstruction. As in video coding, [16] presented MDC with a scalable coding technique (MDSC) for adaptive video streaming applications via cellular networks. The MDC was used as a low-latency coding technique for video streaming over Vehicular Ad-hoc NETworks (VANETs) in [17].

The reliability and quality of the sent video are determined by outage and timeout probabilities, which are crucial parameters in video transmission. The chance that a video broadcast may fall short of a predetermined quality threshold because of channel impairments like interference or fading is known as the outage probability. Conversely, timeout probability is the likelihood that a video packet may be broadcast with a delay greater than permitted, which can cause buffering or playback pauses that are harmful to real-time applications. MDC is a technique that enhances the robustness of video transmission by encoding the video into multiple independent streams or descriptions. Each description can be decoded separately to provide a lower quality video, but when combined, they offer a higher quality [8]. MDC effectively reduces both outage and timeout probabilities by providing redundancy and allowing for error resilience, ensuring that even if some descriptions are lost or delayed, the video can still be reconstructed with acceptable quality [18].

1.2 Problem Statement

With the ultimate growth of multimedia application users, challenges are raised for spectrum capacity and packet losses caused by transmission interference. Video transmission is one of the multimedia services that is becoming increasingly important in the present and future. It necessitates a wide bandwidth while accommodating delay constraints and maintaining the video quality. Conversely, wireless networks have few restrictions, such as bandwidth, distance, and external signal interference. As a result, there is a significant interest in adopting diversity approaches to guarantee video transmission reliability [19]. The usage of relay channels can easily accomplish the application of a diversity approach. Hence, the MDC has become a promising source coding technique to exploit the benefits of the diversity approach while reducing packet losses. In summary, the following issues have been identified and will be discussed in this thesis:

i. Video transmission demands a constant flow of data and the timely delivery of packets. On the other hand, wireless networks have difficulty achieving a reliable network [20]. As bandwidth, delay, and packet loss are not foreseen, video transmission over a dynamic channel, such as mobile wireless networks, is substantially more complex than video transmission over a static channel [21]. As a result, providing error resilience for reliable video communications across an error-prone network is essential. MDC is one possible solution, with the main concept being to encode the video sequence into several descriptions for transmission via multiple paths. The descriptions are individually decodable and can be combined to provide an acceptable video quality. The quality of the received video depends on the number of descriptions received. MDC's key advantage is delivering adequate video quality without retransmitting missing packets [22]. The advent of a massive number of new wireless systems in recent decades and the corresponding increase in bandwidth demand has led to frequency spectrum exhaustion. However, multiple measurement campaigns have revealed that nearly all allocated spectrum is inefficiently utilized most of the time [23]. As a result, spectrum scarcity is created not just by inflexible spectrum management but also by wasteful spectrum consumption. The CR technology has been proposed as a crucial enabling solution for the next generations of wireless networks to increase bandwidth utilization Cognitive Radio (CR) is a wireless communication system that is aware of its surroundings and changes and can adjust its parameters as needed. As a bandwidth-intensive application, video transmission may fully benefit from CR technology.

The unreliability of wireless channels has sparked interest in developing new algorithms and approaches that allow data to be transmitted successfully. When delivering data over a wireless channel, one of the most serious challenges is fading, which is characterized by a wide range of signal attenuation. The best strategy to combat fading effects is to use diversity techniques, which send independently fading duplicates of the original signal [19]. They could be an excellent fit for the expanding demands of next-generation wireless networks. In the networks, the diversity technique is used by inserting a relay between the transmitter and the receiver. Hence, this research proposed a relay-assisted CR network for video transmission. Unlike the traditional method, which sends a stream of packets along a single path, the proposed path diversity transmission system sends different subsets of packets through different paths.

ii. An interruption or disruption in the transport of video data from the source to the destination is referred to as an outage in video transmission. The loss or degradation of video data can result in apparent distortions, frozen frames, or lost video. Outages can happen due to various issues in the communication network such as bandwidth limitation, channel interference and noise and packet losses. Timeout probability can affect a system's overall performance and reliability, such as a network communication system. A more significant timeout probability means there is a greater chance of packet loss or communication problems, which could result in retransmissions and longer latency. Previous studies derived the timeout probability in the CR network to evaluate the proposed system's performance [24], [25] and [26].

   These studies generally investigated the data transmission performance without focusing on the type of source to be transmitted. The outage and timeout probability of this study will be derived based on the method of transmission for the proposed relay-assisted CR network model.

iii. The dynamic spectrum availability and fluctuating channel conditions provide significant obstacles to video transmission over relay-assisted cognitive radio networks. The secondary users in CR networks are required to function in either interweave or underlay mode, each of which places unique limitations on the delay and dependability of transmission. Secondary users can only transmit in the interweave mode when the spectrum is perceived as idle, which increases the likelihood of outages and causes frequent disruptions from spectrum handovers. In the underlay mode, secondary and primary users share the spectrum while strictly constrained by interference, which can deteriorate signal quality and raise the risk of transmission failure [27]. These variables influence both the timeout probability and the outage probability. The former occurs when the received signal quality drops below a reasonable level, rendering packets useless for real-time applications due to excessive delays. Although relay-assisted transmission may help address these problems, there is currently little thorough analysis of the outage and timeout likelihood in interweave and underlay scenarios. Additionally, more research is needed to determine how these probabilities affect the overall performance of video transmission, especially when MDC is used to improve dependability.

In dynamic CRN situations, filling these gaps is essential to creating adaptive methods that maximize video quality, reduce interruptions, and boost video delivery efficiency. To the author's best knowledge, no study has yet investigated how MDC as a video source coding technique can improve the outage performance. Most existing works on outage probability investigate the effect of the relay on the outage performance. The works in [28], [29], [30] focus on a technique of relay selection scheme to im- prove the outage probability. In [31] and [32], the study investigates the energy harvesting outage probability, and in [33], they proposed scheduling method in cognitive relay network to achieve the acceptable outage performance. The earlier studies focus on data transmission over relay-assisted CR networks rather than specifically video transmission. In our proposed video transmission system, the proposed video coding technique, MDC itself, can improve the outage performance instead of the relay added to the CR network.

Due to the constant stream of frames that must be delivered, video packets are often larger than voice and image packets. Depending on variables like video resolution, frame rate, and video compression, the size of video packets might vary dramatically. Larger data packets may have a more significant chance of experiencing transmission delays or errors. The proposed MDC technique to split the video frames allows the packet to be sent separately over the network channel, reducing the probability of packet timeout.

1.3 Aim and Objectives

The aim of this research is to investigate the transmission and video performance by maximizing the benefits of i) path diversity exploitation through relay added network over CR; ii) using MDC as an error resilient video coding technique, and iii) the combination of MDC with the relay-assisted network to combat the noise. The objectives of the research considered to achieve the goals are as follows:

1. To design a video transmission system employing MDC as a video source coding technique in relay-assisted CR networks, exploiting path diversity to enhance error resilience while maintaining an acceptable PSNR range of 30 - 50 dB.
2. To derive the expression for outage and timeout probabilities in video transmission over relay-assisted CR networks operating in interweave and underlay modes.
3. To evaluate the outage probability, timeout probability, and overall video transmission performance for relay-assisted CR networks under interweave and underlay modes.

1.4 Research Scope and Study Module

This thesis presents an analysis of the MDC technique for enhancing the transmission and video performance for video transmission over a relay-assisted CR network. The research aims to propose and design relay-assisted CR network systems for video transmission by applying the MDC as a video coding technique and analyzing the transmission and video performance.

To accomplish this, different stages in the design of the proposed video transmission systems, varying from the joint design of the CR network with relay-assisted adaptation to the MDC approach at the transmitter and receiver, are investigated to analyze the performance. The analysis starts with the MDC performance for CR networks with relay-assisted. The supportive relaying model is used to design the relay-assisted network. The MDC technique is applied to the video transmission system's video encoder and decoder parts. Then, the analysis continued with the outage and timeout performance when the CR networks operated in interweave and underlay modes, respectively. The probability formulation is derived and finally used to analyze the video performance.

Figure 1.3 illustrates the flow of the study in which the solid lines show the direction followed to achieve the set goal while the dotted lines refer to other research areas that are out of the scope of this thesis.

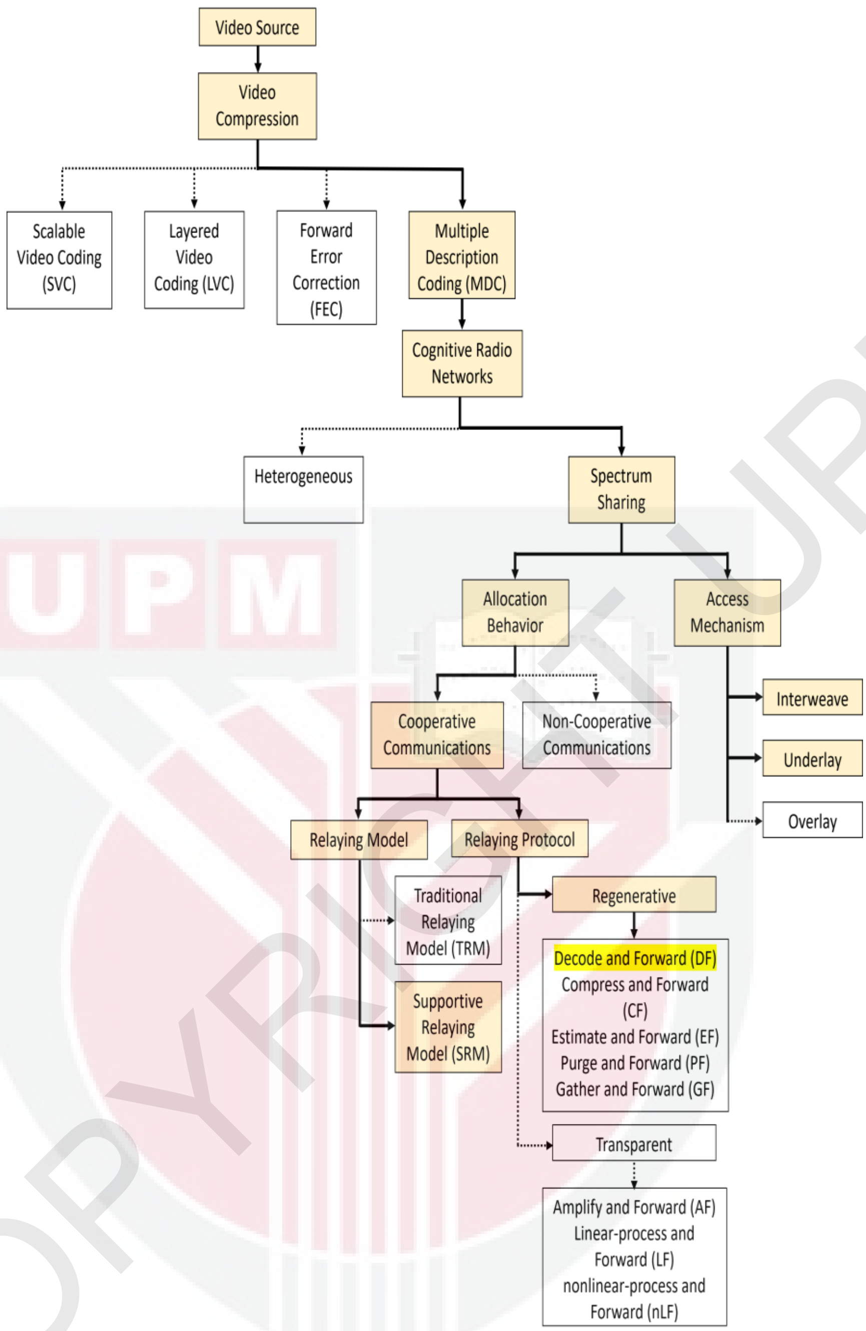


Figure 1.3 : Study Module

1.5 Significance of the Study

The CR network concept has been widely regarded as an effective technique to increase radio spectrum usage to fulfill future spectrum efficiency and system performance needs. With the adoption of the diversity technique and cooperative communication in the network, the network performance can be improved. Meanwhile, the MDC approach to the system as a coding technique enhances the robustness of the received video signal and mitigates the packet loss problem by enhancing the outage and timeout probability.

1.6 Brief Methodology

As mentioned in the problem statement earlier and followed with the three objectives, the proposed methodology is divided into three stages as shown in Figure 1.4 to achieve the goals of this study. The first stage aims to design the video transmission system with a combination scheme of MDC with relay-assisted CR network (MDC-RC) model to exploit the benefit of path diversity, and a video encoding and decoding algorithm is constructed with the MDC approach (Objective 1). The proposed system model is then tested to investigate the video performance.

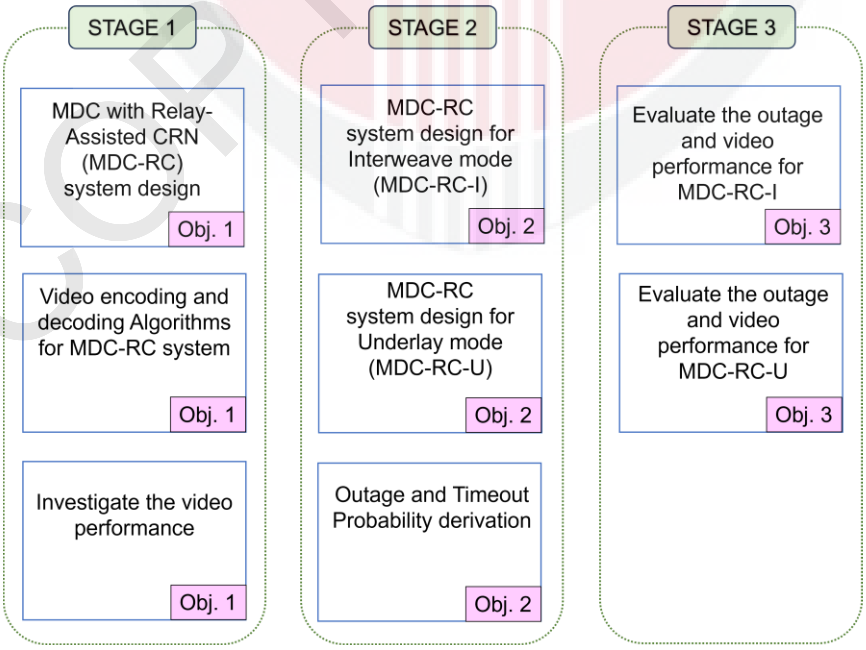


Figure 1.4 : Methodology Stages

Next, the study seeks to identify the benefit of the MDC approach when the video is transmitted over different modes of CR networks with outage and timeout probability considered. Hence, a proposed system model for video transmission over relay-assisted CR networks based on interweave and underlay mode of CR with MDC approach is designed in the second stage.

In the second stage, the MDC-RC-I system model is designed for video transmission over relay-assisted CR based interweave mode, where the PU is idle. On the other hand, the system model MDC-RC-U is designed to transmit the video over underlay mode of CR network, where the PU exists, and SU must not give any harmful interference to the PU. The probability of the outage and timeout is derived for the proposed system models. The derivation will be based on the method of the transmission from source to the destination (Objective 2).

In the third stage, the outage and timeout probability will be evaluated based on the expression derived in objective 2 and used to measure the transmission and video performance (Objective 3).

1.7 Thesis Contributions

The main contributions of this thesis are summarized as follows:

i. MDC is a different strategy to improve the durability of the transmitted video signal and counteract the impact of packet loss. We propose the MDC as a video coding technique where the video signal is split into two correlated descriptions, much like a standard MDC scheme, and sent to the decoder via separate channels. The decoder offers a high-quality reconstruction of the original video if both descriptions are obtained. On the other hand, if one of the descriptions is lost during transmission, the decoder estimates it from the description received and then offers a reconstruction of lesser but still acceptable quality. The MDC is applied as a source coding for video transmission over relay-assisted CRN. Thus, we refer to this technique as MDC-RC. The relationship between the MDC and the relay-assisted CRN is explored while investigating the combination's benefits.

To enhance the performance of the video transmission over CRN, the diversity strategies such as multipath transmission and cooperative communication is adopted to design the network. Diversity techniques are well-known as a successful defense against fading in wireless channels.

Two paths are designed over the network in multipath transmission system, with one path with a relay added between the source and the destination. The receiver, in this case, receives multiple descriptions of the transmitted signal. Notably, the receiver may still receive the information using the other description even if one description is lost. Meanwhile, in cooperative communications, the technique has demonstrated advantages for increasing radio coverage and enabling reliable communications. The source signal is processed and forwarded to the destination by one or more relays. When the transmission distance increases, a relay in the transmission can improve the quality of the signal received.

ii. First, the proposed system model named MDC-RC-I for video transmission over interweave mode of relay-assisted CR network is designed and the corresponding outage probability expression is derived for the proposed system to evaluate the outage performance. Secondly, a video transmission system with MDC technique over underlay mode of CR network named MDC-RC-U is proposed. The system model is designed with the co-existence of SU and PU and the timeout probability is derived.

iii. The impact of MDC to enhance the outage performance followed by video performance are investigated and analyzed. This analysis provides new insights into the approach of MDC to mitigate the outage issues in video transmission. The measured probability is used to analyze the video performance.

The impact of MDC to enhance the outage performance followed by video performance are investigated and analyzed. This analysis provides new insights into the approach of MDC to mitigate the outage issues in video transmission. The measured probability is used to analyze the video performance. is analyzed. Moreover, the video performance is analyzed based on the timeout probability measured previously. Finally, the performance of the proposed system model and probability derivation is compared with CR network without relay added and SDC video coding technique presented in [136].

1.8 Thesis Organization

The remainder of this thesis is organized as follows:

Chapter 1 entails the introduction and overview of the research study, the general background of wireless communication, specifically video communication and its challenges, and the general information on CR technology, cooperative communication, and MDC. Followed by defining the research's problem statement, listing the research objectives and questions, and stating the scope of the study, the research contributions, and the significance of the study.

Chapter 2 presents a brief overview of the proposed relay-assisted CR system for video transmission alongside the conventional non-relay CR system. Firstly, The CR background and architecture are presented. Then, the video format and compression are discussed, followed by an overview of the MDC technique.

A summary of the transmission performance, outage, and timeout probability is also provided in this chapter. Lastly, the recent related works in the reviewed literature about the application of relays in CR networks and the MDC approach for video transmission are enumerated. Several MDC approach for video transmission over relay and CR networks were proposed in earlier studies to improve the transmission performance. The research gaps were discovered as the novelty for video transmission over CR systems' further improvement.

Chapter 3 presents the research design, the description of the relay-assisted CR networks architecture and system models with the MDC technique approach for video transmission. Moreover, the step-by-step algorithms in the MDC technique detailed procedures are presented. Lastly, the mathematical derivation for outage and timeout probability are provided.

Chapter 4 provides the simulation settings and the simulation results of the proposed CR system model with the MDC technique for both relay and non-relay networks. The outage and timeout probability performance are presented together with the video performance for each respected model. The results from the performance evaluation indicate that the proposed CR system with the MDC technique approach offers great improvement compared to the conventional method.

Chapter 5 concludes this thesis by highlighting the research study's novelty and considering the implication of the achieved results on the proposed objectives and the recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a brief fundamental of cognitive radio (CR) networks, their architecture components, their challenges, and the advantages of video transmission over the networks. Then, relay-assisted cooperative communication in CR is discussed with some existing related works on video transmission over CR networks. After that, a brief review of multiple description coding (MDC) techniques as the video encoding technique is presented. Finally, the summary of the related literature review and the research gap is outlined.

2.1 Cognitive Radio Networks with Relay and MDC

2.1.1 Cognitive Radio Networks: Background and Architecture

A paradigm for developing wireless communications systems called "cognitive radio" seeks to use the radio frequency (RF) spectrum better. The lack of accessible frequency spectrum and rising demand brought on by new wireless applications for mobile users are the driving forces behind cognitive radio. Only a limited portion of the available radio spectrum can be licensed to new wireless applications because most of it has already been assigned to wireless systems in use [11]. However, according to a Federal Communications Commission (FCC) investigation [3], a considerable portion of the radio spectrum is not in use for a prolonged period, even though practically all the frequency appropriate for wireless communications has been allotted.

The vacant radio spectrum has attracted the attention of researchers in finding better ways to utilize it. J. Mitola introduced the cognitive radio (CR) technology in 1999 [36]. It was a novel approach to use the term “intelligent radios” to characterize devices that can learn and formulate plans based on their prior experiences and make decisions automatically utilizing information about the RF environment was unique. Since its inception, academics and regulatory organizations have offered many definitions of CR.

In 2005, Simon Haykin described the cognitive radio as an intelligent wireless communication system that is conscious of its surroundings and uses the understanding-by-building methodology to learn from the surroundings and adjust to statistical fluctuations in the input stimuli with two main goals. These two main goals were highly reliable communication and effectively utilizing the spectrum [37]. As a result, CR Networks were suggested as a potentially effective method for utilizing the spectrum by enabling interactive wireless users to detect and learn about their environment and subsequently modify their transmission tactics [38].

2.1.1.1 CR Architecture

Cognitive radio can adjust its transmission settings in response to what it learns about its operating environment. It is a technology that enables the intelligent operation of unlicensed users, also known as secondary users (SUs), within underutilized licensed frequency channels without interfering with the rights of licensed users, known as primary users (PUs) [3]. Figure 2.1 shows the components of a CR network’s architecture consist of the primary and secondary networks. The primary network, also known as the legacy network, comprises PU.

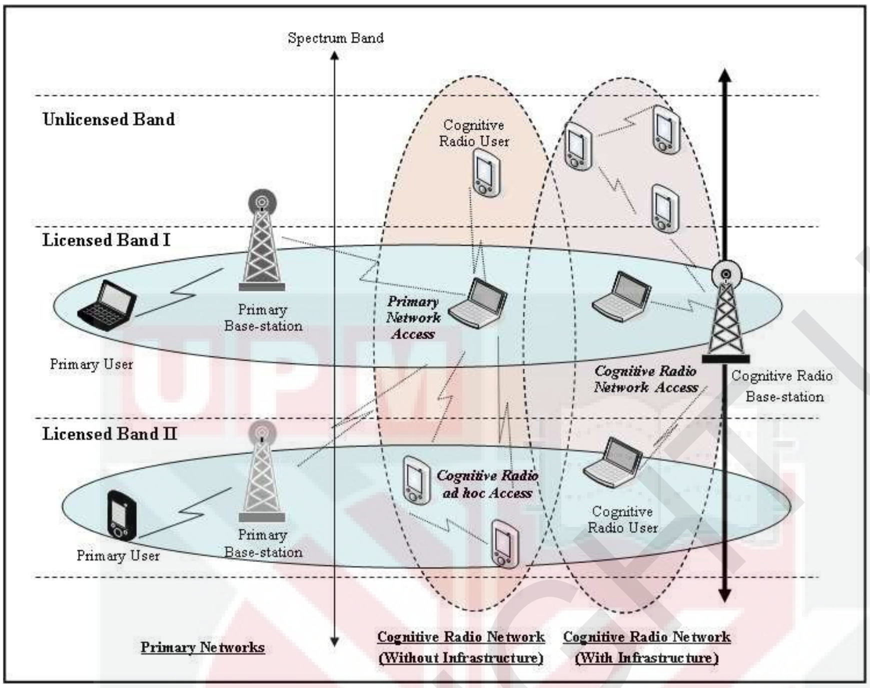


Figure 2.1 : CR Network Architecture [3]

It is granted with the exclusive use of their licensed spectrum band and the primary base stations, such as the base station in a cellular system. Conversely, in the secondary network, also known as the cognitive network, composed of SU, the user does not have a license to use the intended band for operations and the CR base station. The CR network's basic components, as in Figure 2.1, are summarized as follows:

SU/CR User: User with no spectrum license. The SUs are only permitted to use the authorized band opportunistically. They can sense a particular spectrum through observations and report the results to their base station.

SU/CR base station: The SU base station is a fixed infrastructure component with the capabilities of the CR. A single hop connection is provided to the SU without the license to access the spectrum within their transmission range.

PU: Users with the license to operate based on their spectrum allocation. The PU base station controls the access and will not be affected by any unlicensed user.

PU base station: The PU base station is a fixed infrastructure component with a spectrum license with no CR capability to share the spectrum with CR users.

2.1.1.2 CR Network Challenges

The essence of CR networks is to ensure that the SU function intelligently without interfering with the PU's rights to utilize the unused licensed frequency bands successfully. Although PU activity may be completely arbitrary and unrelated to CR networks, it is essential for CR networks to detect spectrum availability and effectively control the spectrum used promptly. Four key elements for efficient spectrum management make up the operation of CR networks to accomplish this goal are [39]:

Spectrum Sensing: CR users should timely check the available spectrum bands, utilize the unused spectrum, and identify the presence of PU when they operate in a licensed band to make the most use of the available spectrum bands and to prevent any potential incursion on PU.

Spectrum Sensing: CR users should timely check the available spectrum bands, utilize the unused spectrum, and identify the presence of PU when they operate in a licensed band to make the most use of the available spectrum bands and to prevent any potential incursion on PU.

Spectrum Sharing: CR network access should be coordinated to prevent multiple SUs from colliding in overlapping spectrum sections because several CR users may be attempting to access the spectrum. In other words, a medium access control (MAC) is necessary to settle any potential conflict amongst CR users.

Spectrum Mobility: The CR base station controls mobility in the centrally located CR network. Users of CR are viewed as guests on the spectrum. Therefore, the communication must continue in another unused portion of the spectrum if a PU needs the specific portion of the spectrum that is in use.

Users of the CR networks can actively monitor and use the temporarily unoccupied spectrum, often known as a spectrum hole or white space, using spectrum management [37]. Whenever a PU uses this band, as indicated in Figure 2.2, the secondary user shifts to a different spectrum hole to prevent interfering with the first user. However, the CR customer's quality of service (QoS) may scarcely be guaranteed due to the unpredictability of channel availability and status, which constitutes a severe difficulty in CR networks.

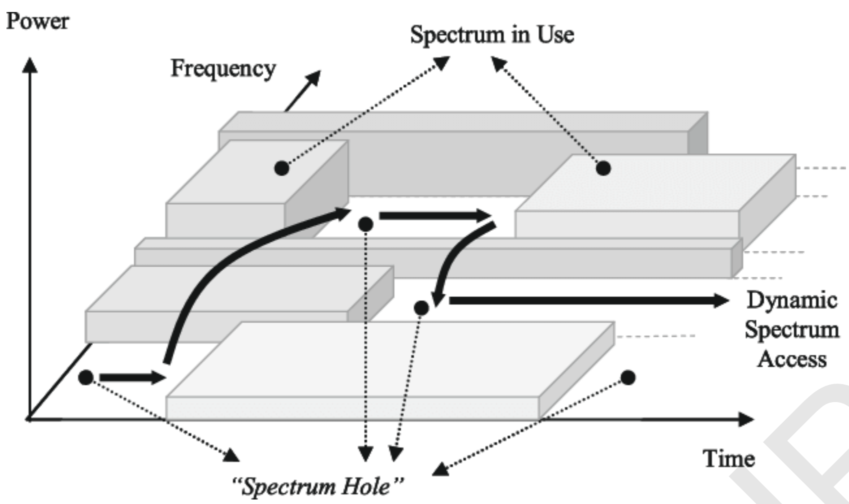


Figure 2.2 : Concept of Spectrum Hole [4]

2.1.2 Spectrum Sharing

2.1.2.1 Spectrum Sharing Scheme

The hierarchical access model's goal is to allow SUs access to the licensed spectrum while limiting harmful interference to the PU. The primary and secondary networks have access priority in this paradigm of spectrum sharing. The hierarchical architecture might offer the best chance of increasing spectrum utilization when compared to the exclusive usage model and the open sharing model. Three spectrum sharing strategies, interweave, overlay, and underlay techniques as illustrated in Figure 2.3, have been taken into consideration in this situation [40].

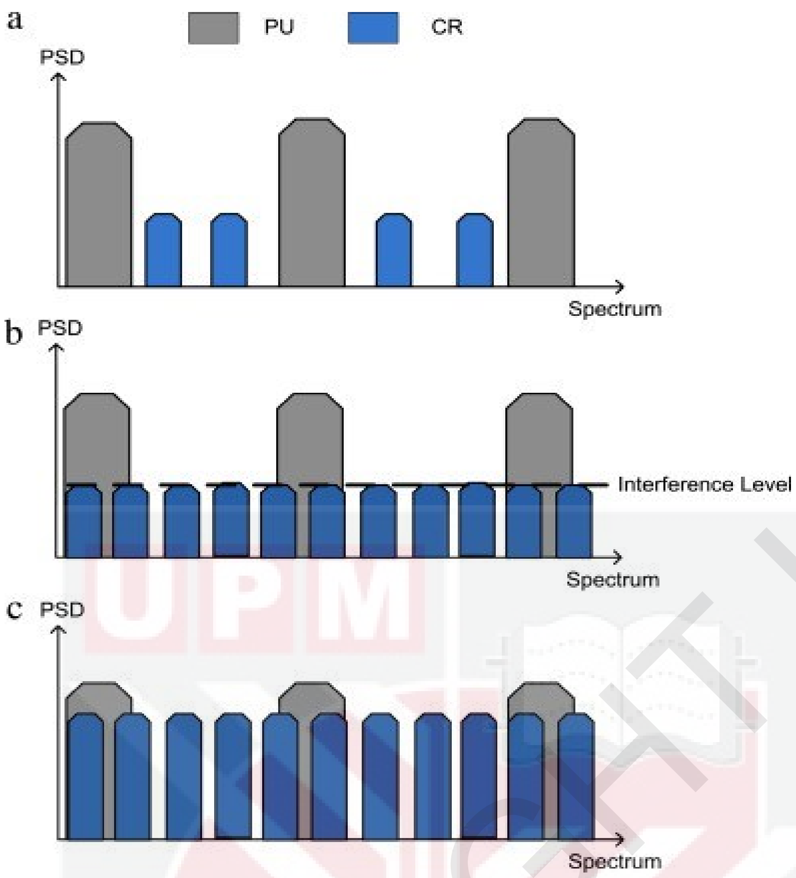


Figure 2.3 : CR Networks Modes; a) Interweave b) Underlay c) Overlay [5]

Interweave: The SUs access the spectrum while the PUs are idle in the interweave or opportunistic spectrum access (OSA) paradigm. The SU must halt transmission when the PU is engaged to prevent interference with the PU. The OSA relies on techniques for spectrum sensing, where SUs must sense the authorized frequency band and find the spectrum gaps. The SU can broadcast with its highest power once a spectrum hole has been found. However, due to channel uncertainty, noise uncertainty, sensing interference, and a finite amount of observation time, sensing flaws may appear in the highly time-variant radio environment. In this scenario, a false alarm could lead to missed opportunities and poorer spectrum usage. Additionally, in the event of missed detection, the SU transmitter may interfere with the PU receiver, thereby degrading the performance of the primary network. Additionally, the interweave technique prevents cognitive users from coexisting in the underutilized spectrum with licensed users. Due to a lack of spectrum holes, this paradigm is ineffective in congested places [3].

Underlay: The underlay paradigm is based on interference management, where the transmit power of the SU is subject to an interference constraint. In other words, if the interference caused by SUs to the PU receiver is kept below a predetermined level, simultaneous primary and secondary transmissions are permitted in the same frequency band, and geographical area [27] [40]. The underlay strategy is the one that this thesis concentrates on since, if the interference limitation is met, it is the most adaptable. The underlay spectrum sharing strategy may be put into use through band management coordination [37] or under the supervision of the regulatory body [41]. However, the secondary communication range is constrained by the limitations on transmission power.

Overlay: For the overlay paradigm, the PUs and SU communicate about their signal codebooks and messages. Additionally, the SUs may use these messages to either reduce the interference caused by the primary transmission at the SU receiver or enhance the performance by relaying the message to the PU receiver. By utilizing advanced signal processing and coding methods such as dirty paper coding, the SU may retrieve the essential data [40]. The performance of primary and secondary networks can both be enhanced by the overlay system. The fundamental signals at the SU-Tx must be understood and decoded, and the complexity of encoding and decoding SUs broadcasts in the system presents technological challenges for the overlay paradigm in practice. Furthermore, sharing sensitive PU data with the SUs makes the principal system's security vulnerable.

Table 2.1 summarize the comparison of the three modes of CR networks.

2.1.2.2 Cooperative Communication

Cooperative communication is an effective and growing option that can get beyond the limitations of wireless networks. The fundamental concept of cooperative transmission is based on the observation that, in a wireless environment, a source's signal broadcast to a destination node, each using a single antenna, is also received by other terminals, frequently referred to as relays or partners. The signals that the relays receive are processed and retransmitted. By utilizing multiple receptions of the same data at the various terminals and transmission pathways, the destination combines the signals originating from the source and the relays to create spatial diversity.

Table 2.1 : CR Modes Comparison (Interweave, Underlay, Overlay)

Interweave	Underlay	Overlay
PU existence: No	**PU existence:** Yes	**PU existence:** Yes
Simultaneous Transmission: SU transmits simultaneously with a PU only during false hole detection event.	**Simultaneous Transmission:** SU can transmit simultaneously with a PU with condition that the interference is below an acceptable limit.	**Simultaneous Transmission:** SU and PU can both transmit simultaneously, and the interference to PU can be reduced by using some of SU's power to relay the PU's message.
Transmit Power: SU transmit power is limited by the spectrum hole sensing range.	**Transmit Power:** SU transmit power is limited by the PU's interference constraint.	**Transmit Power:** SU can transmit at any power with the interference to the PU will be offset by relaying the PU's message.
Network Side Information: SU can identify the spectrum holes from the absent PU.	**Network Side Information:** SU knows the PU's channel strength.	**Network Side Information:** SU knows the channel gain, encoding techniques/codebook and the PU message.

Additionally, distributed spatial processing technology can significantly reduce terminal interference [42]. Direct point-to-point or point-to-multipoint such as cellular topologies have been the most commonly employed in traditional wireless networks. Cooperative communications and networking, in contrast to conventional point-to-point communications, allow various users or nodes in the network to share resources and collaborate through distributed transmission where the user information is sent out not only by the user but also by the collaborating users [43].

Cooperative communications and networking can significantly boost wireless networks' capacity, and multiplexing gain [44]. To counteract the negative consequences of excessive fading, it also develops a novel form of spatial diversity [45].

There is many distinct relaying techniques used today, and they can be broadly divided into two groups: transparent relaying protocols and regenerative relaying techniques. The transparent relaying approach does not alter the data conveyed by a particular waveform. Basic operations like simple amplification, phase rotation, etc., are typically carried out. The analogue signal is received in one frequency band, amplified, and then briefly re-transmitted on another frequency band because no digital operations are performed on the signal. Examples of protocols from the family of transparent relaying include [6]:

Amplify and Forward (AF): One of the simplest and most widely used relaying techniques involves amplifying, translating the frequency of the signal received by the relay, and retransmitting it.

Linear-Process and Forward (LF): After the signal has been amplified, several further straightforward linear operations are applied in the analogue domain as part of this relaying technique. Phase shifting illustrates such a linear operation that makes distributed beamforming possible.

Nonlinear-Process and Forward (nLF): This protocol conducts some nonlinear operations on the received analogue method prior to retransmission. An example of this method's application is the nonlinear amplification of the received signal, which reduces the end-to-end error rate.

More powerful hardware is needed for digital baseband operations. Regenerative relaying protocols modify the information (bits) or waveform (samples) that are being transmitted. Regenerative relays typically perform better than transparent ones. The following are the most notable instances of regenerative relaying:

Estimate and Forward (EF): The baseband representation of the analogue signal is recovered by some detection methods after the signal has been amplified and down-converted. The estimation is done and then retransmitted. For instance, the EF relay retransmits its estimate of the modulated signal using the same or a different modulation order.

Compress and Forward (CF): This protocol is comparable to the EF in that it transmits a compressed copy of the information stream that has been detected to the target. This includes applying some source coding to the samples of the sampled signal, and it has been demonstrated to have the best capacity and performance when the compression node is close to the destination.

Decode and Forward (DF): Since it is a well-known alternative to the transparent AF protocol, DF detects the signal, decodes it, and then re-encodes it before retransmitting. Many distinct DF protocols are in use today, and this study also used this relaying protocol. DF is well known for having the best performance across many application contexts compared to common metrics like error rate.

Purge and Forward (PF): Most modern communication systems are built to be interference-limited rather than noise-limited. This design idea also holds for cooperative systems because PF allows for interference between the various relaying streams and handles it by reducing it to the minimum at each relay node.

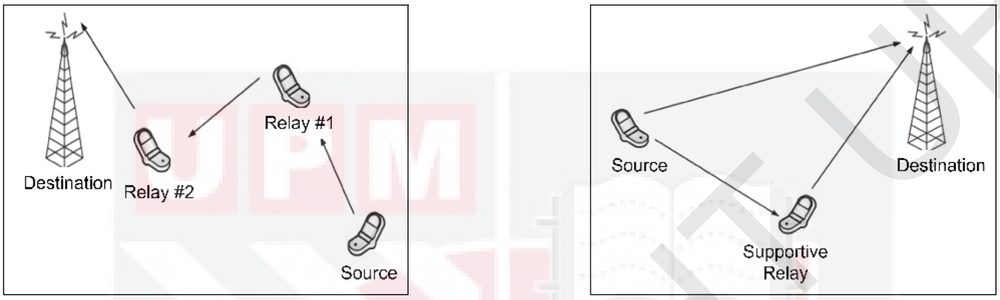
Gather and Forward (GF): This protocol, also known as an aggregate and forward protocol, extends CF in that a relay node conducts source coding over both the sampled data and the data itself, which is aggregated across a few communication slots.

One protocol may perform better than the other depending on the network topology and the channel quality of the link between the source and relay. For example, AF is more advantageous for systems with relatively lousy channel conditions, but DF-based relaying schemes are more favorable for systems with good channel conditions. Additionally, the AF protocol operates more simply than the DF protocol, but it could make the system noisier [45].

There are two relaying models with different parameters impacting the realization of a particular relaying architecture as follows:

Traditional Relaying: Traditional relaying has been around for decades and is realized by an arbitrary number of serial and/or parallel relays delivering the information from the source to the destination.

Supportive Relaying: Based on the degree of cooperation parameter, supportive relaying can be extended to cooperative communications when two or more cooperative nodes act as each other's respective relays simultaneously to strengthen each other's communication links. The architectures have been visualized in Figure 2.4.



(a) Traditional Relaying **(b) Supportive Relaying**

Figure 2.4 : Relaying Models [6]

2.1.3 Related Works on Relay-Assisted Cognitive Radio Network

The CR technology addressed the issue of a lack of spectrum resources by supplying adequate spectrum resources to accommodate the explosive development in mobile communication. On the other hand, channel fading and shadowing may impede and impair the transmission's performance. To address the noise and fading effects, several diverse strategies are used to prevent multimedia transmission disruptions to the mobile user [46].

The study in [47] considers a relay-assisted hybrid overlay/underlay CR with peak interference power constraints to safeguard the PU. The performance then increased once the SU outage probability with the power restriction was computed. For underlay relay-assisted CR, a precise closed-form outage probability was determined in [48]. The correlation between received SNR, power limitations, and independently identically distributed (i.i.d) channels was considered in their derivation. The study investigates how power is allocated for CR's underlay and overlay using a common relay, the same as in [49]. In this research, they analyzed outage performance and presented the auction mechanism.

A cognitive relay was utilized as an underlay CR system in [50]. The underlay paradigm is used in their study by the cognitive relay, also known as the SU, to support the secondary utilization of the spectrum by indoor devices. The study recommended a multi-relay selection for CR to test outage performance in [51]. Under the imperfect spectrum sensing in Rayleigh fading channel, the outage probability closed-form expression is generated. The author in [52] analyses the SU performance in the relay-assisted overlay mode of the CR network. Their simulation results demonstrated how distance affected outage performance, showing that the likelihood of an outage rose as distance increased. The study [53] looked at the implications of various cognitive relays. They suggested an optimization algorithm to improve the QoS needs for both SU and PU.

In [54], the simultaneous wireless information and power transmission (SWIPT) in the CR relaying network is explored. They used a fading channel and the examined system to calculate the outage probability. In the meantime, [55] investigated the likelihood of CR relaying networks with energy collecting going offline. The Nakagami-m fading channel was used to analyze the outage performance in their investigation. The study in [56] and [19] proposed two optimal power allocations for the hybrid interweave-underlay mode of CR relay networks, which increased the channel capacity and reduced outages. The Rayleigh fading channel was subjected to the suggested technique. A meta-heuristic genetic algorithm based MRS and PA scheme is introduced in relay-assisted CR networks in [57]. The algorithm is used to maximize the secondary relay of the networks. Research in [58] details the design and analysis of the researchers' proposed framework for wireless energy harvesting in CR networks' relay-assisted underlay mode. They developed a reliable relay

selection system to choose the appropriate relay to use during the transmission.

A study from [59] developed the scheme of joint sensing time and power allocation for secondary network. Their results show that the proposed scheme can maximize the energy efficient problem by analyzing the throughput, energy consumption and outage probability. In [60], they applied NOMA into cooperative CR networks with SWIPT to compare the outage performance with SWIPT OMA. Meanwhile, in [61], they designed the relay frameworks based on error vector magnitude (EVM) for the rate relay selection (RRS) for PU network to improve the energy efficiency. A fully energy harvested two-hop relay is developed in [62] to minimize the outage probability.

A full-duplex (FD) based underlay CRN's relay selection criteria were looked into in [28]. The study also suggested two sum rate maximization-based simple relay selection strategies. In [63], they investigate the transmission performances with the existence of PU emulator and relay using the greedy transmission policy to be compared with other transmission policies. The use of direct link communication for buffer-aided relaying in cognitive relay networks was presented in [29] by a link selection policy. Their suggested policy can reduce the likelihood of outages and average packet delays from end to end. The authors in [64] introduced the cooperative NOMA systems with imperfect successive interference cancellation. The outage performance investigates in their research.

A novel buffer state-based relaying selection strategy for relay-assisted CRN was put forth in [30]. Several links between the secondary source (SS) and secondary relay (SR) nodes are simultaneously activated in the scheme. The author in [31] developed a framework for the probability of an energy harvesting outage for underlay CRN.

The framework makes data communication between SUs for N-hop primary transmission easier. The author in [33] develops a brand-new decentralized scheduling method for cognitive multi-user multi-relay networks. When the relaying links are more robust than the direct links, their suggested technique offers an acceptable outage performance. A framework has recently been devised to include interference cancellation in the outage analysis of the energy harvesting cognitive relay network [32]. In their study, the ideal relay selection range is developed and applied to reduce the likelihood of outages. Table 2.2 summarized the application of the relay in the CR network to combat the shortage of the spectrum resources for transmission.

Table 2.2 : Related Works on the Application of the Relay in the CR Network

Reference and Year	CR Modes	Proposed Approach	Findings/Advantages
[56] (2018)	Hybrid Interweave Underlay	Propose two optimal power allocation strategies for hybrid interweave-underlay cognitive cooperative radio networks (CCRNs) to maximize channel capacity and minimize outage probability.	Outage probability and channel capacity for hybrid CR outperformed the underlay CR.
[57] (2018)	Underlay	Propose a metaheuristic genetic algorithm based MRS and PA scheme to maximize the SR of the networks while meeting their transmission power and interference criteria.	Achieved near-optimal SR performance when compared to another scheme and improved the SR.
[58] (2018)	Underlay	Propose combi- nation of CR and wireless energy harvesting to study the impact on outage probability.	Outage performance decreases with the density of the secondary and distance between source and destination
[59] (2018)	Overlay	Propose the scheme of joint sensing time and power allocation for secondary net- work.	Maximize the energy efficient problem by analyzing the throughput, energy consumption and outage probability.
[60] (2019)	Underlay	Propose application of NOMA into coop- erative CR networks with SWIPT.	Outage performance improved in SWIPT NOMA compared to SWIPT OMA.
[61] (2019)	Interweave	Propose cooper- ative frameworks based on error vector magnitude (EVM) for the rate maximized relay selection (RRS) for PU network.	PU achieved higher capacity and im- proved the energy efficiency compared to the conventional scheme.
[62] (2019)	Underlay	Propose energy har- vested two-hop relay to minimize the outage problem.	Achieved outage minimization by ~ 11.71% and ~ 12.7% gain compared to other schemes.

Table 2.2 : Continued

[28] (2019)	Underlay	Propose two sum rate maximization- based low-complexity relay selection strategies.	The proposed methods' sum rate performance is comparable to that of high complexity relay se- lection schemes.
[63] (2019)	Interweave Underlay	Propose study on transmission performance with the existence of PU emulator and relay.	The greedy transmission policy outperformed other transmission policies.
[29] (2019)	Hybrid Interweave Underlay	Propose a combination of direct communication and buffer-aided relaying benefits as a transmission policy.	Significance im- provement achieved on outage performance and end-to-end average packet delay compared to the conventional link selection methods.
[31] (2020)	Underlay	Develop framework of wireless energy harvesting outage probability for multihop PU in relay-assisted CR network.	Optimized the pri- mary density that minimized the existence of SU outage probability.
[33] (2020)	Underlay	Propose a novel de- centralized scheduling method for the incremental relaying-based cognitive multi-user multi-relay network.	The outage performance of the proposed method outperformed the benchmark schemes, two-stage with partial relay selection (TSW- PRS) and two-stage with opportunistic relay selection (TSWORS).
[32] (2021)	Underlay	Develop framework for minimizing the outage probability in energy-harvesting cognitive radio networks with significant interferer cancellation.	The outage probability of the secondary networks with different parameters is reduced.
[65] (2022)	Underlay	Develop relay selection scheme to analyze the outage probability considering Nakagami-m fading.	The max-min relay selection scheme achieved full diversity order of user's outage.
[66] (2022)	Underlay	Investigate a security aware MIMO two-way relay-assisted CR NOMA networks with SWIPT.	The proposed algorithm achieved same security performance and lower computational complexity.
[67] (2023)	Underlay	A study on a relay-based underlay CR	Vehicle relative rate, channel quality and

Table 2.2 : Continued

		vehicular network.	estimation and time allocation influenced the network's outage performance.
[68] (2023)	Underlay	Propose UAV relay selection schemes and interference away relay selection scheme to analyze the security reliability tradeoff.	The proposed schemes perform better than round robin scheme.
[69] (2023)	Underlay	Design a MIMO IoT cognitive multi relay network with deep learning based framework.	The proposed scheme minimized power consumption while maintaining the user's QoS.
[70] (2024)	Underlay	Investigate the over the air computation in CR data network to improve network's performance.	The proposed scheme minimized the sum MSE of the computation.
[71] (2024)	Underlay	Study the cooperative NOMA in underlay CR network aided with energy harvesting relay performance.	MRC scheme out-performs SC scheme and Nakagami-m fading improves the system's outage.

2.1.4 Multiple Description Coding (MDC)

The initial motivating factor for creating MDC was the requirement for high network reliability to enhance the mechanisms for handling outages. A practical method to give transmission networks resiliency is to use path diversity. In telephone networks, redundant standby transmission lines were used to achieve path variety. By dividing the spoken signal between two different connections or routes, the network's resiliency could be increased without using standby links. As a result, communication would typically be done with high quality. When a link or path fails, the other channel link will provide uninterrupted communication with a reduced but adequate quality.

In the past, to prevent communication breakdowns, a backup transmission link was kept ready to go and would be used if the primary link went down. This strategy, however, was not financially advantageous, leading to the idea of spreading the information over two channels, or MDC, being developed in the 1970s, the MDC was firstly used for speech communication over circuit-switched networks. The channel splitting concept gained traction in Bell

Laboratories' speech coder and information theorist groups in 1978 and 1979. Gersho [72], who could move between these two groups, was crucial to this spread.

He was made aware of the issue by Goodman, came up with an encoding strategy, and most likely was the first to mention it to Jayant, Ozarow, Witsenhausen, Wolf, and Wyner [73]. Working independently with Miller, Jayant also suggested channel splitting using a voice coding algorithm that distinguished between odd and even samples. Jayant's straightforward yet highly efficient approach was applied for a long time. In the early 1990s, random losses in packet-switched telephony inspired the development of a comparable system.

A speech signal is typically band restricted to 3.2 kHz and sampled at 8 kHz in telephony [74]. With initial sampling set at 12 kHz in Jayant's system, there is barely any aliasing when subsampling by a factor of two. Differential pulse code modulation (DPCM) is used to individually compress and send the odd and even numbered samples on two distinct channels. Each block with several milliseconds' duration has its quantization step sizes adjusted once. The interleaving of the samples plus the need for a DPCM decoder for each channel when decoding from both channels yields a signal with 12 kHz sampling and some DPCM quantization noise. A single channel is decoded using adaptive linear interpolation. Considering this to be speech sampled at 6 kHz with aliasing and quantization noise is essentially the same thing [75].

MDC emerged in the second part of the 1990s as a helpful tool for reducing transmission mistakes in best-effort wireless and Internet networks. Since then, many MDC coders have been suggested for coding multimedia (Speech, Image, and Video). Later, a few MDC were put forth, including [76].

Many MDC algorithms were designed for photos but eventually found use in videos. Because many video applications have such strict delay requirements, MDC is particularly promising for video. The temporal correlation between video frames can be successfully tapped into through motion compensated prediction, as is widely known.

The MDC's fundamental block diagram is depicted in Figure 2.5. A higher number of descriptions may be used than what is shown in the figure. From the block diagram, the source is coded to produce several complementing, independently decodable descriptions. The descriptions can then be constructed and transmitted independently across various network pathways. If only one description is available at the receiver side, it is decoded by the side decoder, and the quality or distortion that results is known as side quality.

When both descriptions are available, the central decoder decodes them, and the quality of the results is known as central quality.

The descriptions are combined in the central decoder, producing a movie of superior quality. In other words, two different forms of decoding are available at the receiver: side decoding is used for the received description when one or more descriptions are not received, and central decoding is used when all descriptions are received. Indeed, the quantity of descriptions received improves quality.

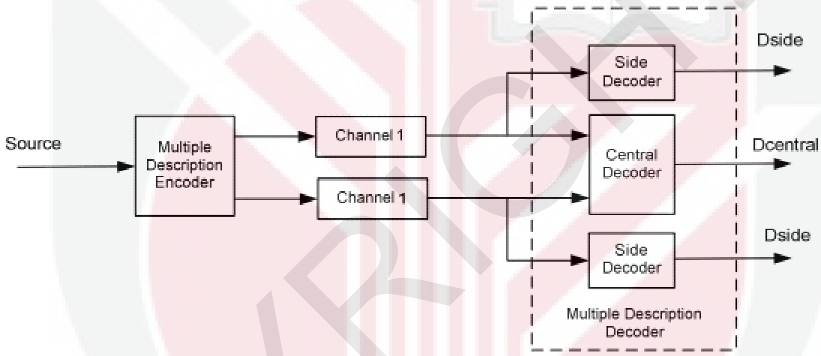


Figure 2.5 : MDC General Block Diagram [7]

Each description in MDC must have some fundamental data from the source to be independently decodable. Only one copy of that primary data is used at the central decoder; the others are redundant. As a result, MDC and the conventional Single Description Coding (SDC), as shown in Figure 2.6 offer the same quality over a lossless channel at a higher bit rate. The excess rate is called redundancies. To put it another way, the descriptions are correlated since they all come from the same source (although one has been distorted). Coding two correlated descriptions individually result in redundancy.

Redundancy rises for better side quality because the descriptions are more connected and closer to the source.

Figure 2.6 : SDC General Block Diagram [8]

2.1.4.1 Video MDC Scheme

The MDC process involving generating and splitting the information into descriptions can be done in several domains. The descriptions are constructed by partitioning the pixels, frames, transformed data, and compressed data for spatial, temporal, frequency, and compressed domains, respectively.

Spatial Domain: The MDC procedure is applied in the pixel domain. The simplest method is to separate the image/frame into several sub-images and separately encode each one. If all descriptions are received at the decoder side, the sub images are combined, and the full resolution image is rebuilt. If not, any missing description must be made up using interpolation or other similar methods [77]. However, there is no method to add redundancy to this fundamental strategy. Therefore, there is no provision for raising the side quality. Then, the following ideas were put out to deal with this issue. Note that reducing the correlation between the data through subsampling in the spatial or temporal domain diminishes the source's ability to be compressed. So, subsampling imposes some redundancy indirectly when compared to SDC, but this redundancy is not particularly beneficial in terms of side quality

[7].

Temporal domain: The descriptions in temporal domain MDC are produced by a procedure carried out at the frame level, i.e., the granularity of this class of methods is a frame. Frame splitting between descriptions is a straightforward example; odd frames are in one description and even frames are in the other, as seen in Figure 2.7. Both frames will be individually encoded to a description by the H.264 encoder before being transmitted via two distinct channels and separately decoded at the receiver.

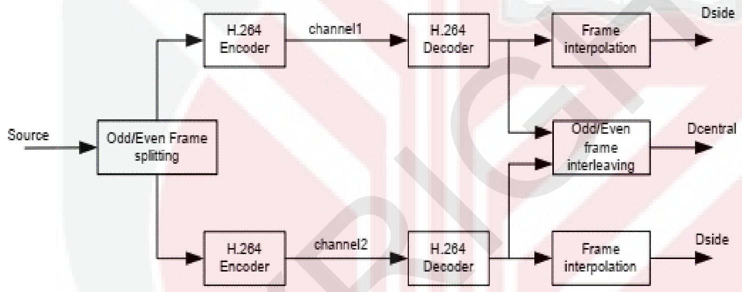


Figure 2.7 : Block Diagram of MDC Temporal Domain [7]

If even and odd frames are received, the frames are interleaved at the central decoder, while if only one frame, either odd or even, is received, the frame will be interpolated at the side decoder [7]. Frame freezing or estimation techniques are used at the side decoder to replace the lost frames. Even (or odd) frames are anticipated from the even (or odd) frames via intra description motion estimation/compensation [78]. However, the inter-frame or temporal correlation affects how effective this method is. In other words, the interpolated version of the missing frame in the side decoder is very different from the original if the interframe motion is not slow enough. The following list includes several suggested remedies to this issue. As we shall see, all other solutions except the first result in introducing new frames into the descriptions, which may be identical in all descriptions, lower rate versions, or intermediate virtual frames.

1. Motion information duplication [78] - [79]
2. Less recoverable data duplication [80]
3. Multi rate MDC [81]-[82]
4. Local frame rate changes [83]

Frequency domain: There are various methods in the frequency domain MDC. The methods are MDSQ, MDTC, Multi-Rate MDC, Coefficients Partitioning, and Mixed Layer MDC (MLMDC).

Compressed Domain: These MDC techniques are used after the video has already been encoded. Another name for this technique is packet domain MDC. Partitioning a layer into *K* segments, which are subsequently enlarged to $N > K$ segments using FEC codes, is the fundamental concept here. This plan can be a JSCC approach because it employs channel codes. These *N* segments are then divided up once more into numerous descriptions that are sent separately. It is well known that the *K* source segment can be recovered with any of these *N* segments. The concept was established and altered for multiple description coding in [84] and [85] after being inspired by [86].

2.1.5 Video Formats and Compression

2.1.5.1 Video Format

A video sequence comprises a succession of images displayed with either fixed or variable time gaps between them. A visual rate of at least 24 images per second is necessary to create the illusion of motion. The Common Intermediate Format (CIF) is the foundation of a common group of formats listed in Table 2.3. The luma component of a video frame was sampled at various resolutions, from 4CIF down to Sub-QCIF [9]. The application and available storage or transmission capacity determine the frame resolution used.

For example, 4CIF is suitable for DVD-video and standard-definition television, CIF and QCIF are well-liked for videoconferencing applications, and QCIF or SQCIF is ideal for mobile multimedia applications with constrained bitrates and display resolutions.

Table 2.3 : Video Frame Formats [1]

Format	Luminance resolution (horizontal x vertical)	Bits per frame (4:2:0, 8 bits per sample)
Sub-QCIF	128 x 96	147456
Quarter CIF (QCIF)	176 x 144	304128
CIF	352 x 288	1216512
4CIF	704 x 576	4866048

A video signal is a group of frames that together depict a moment in time in digital form as video. The human visual system (HVS), which cannot distinguish between individual frames when a video signal is sampled at a rate of 15 frames per second (fps) or higher, interprets this succession of frames as a continuous movement of the object in the image. Spatial and temporal properties are two essential qualities that capture the color, brightness, and movement of objects in a video stream. While the video's temporal elements catch objects' motion and changes in illumination or color, color and brightness are represented by the spatial features of the video signal. A natural video scene is unbroken in both space and time.

To represent the video scene in the digital domain, digital video, however, uses spatial and temporal sampling. Each still frame acquired at a particular moment in time with spatial sampling is recorded for its brightness and hue. At each sampling time, the temporal sampling gathers fresh still frames. A way to store color data is necessary for a digital, colored video. Red, green, and blue are combined to describe the brightness and hue of pixels in the RGB color space, which is the simplest color system. However, video standards often employ YUV or YCbCr systems, which use luminance (Y) and variations in two chroma colors (U and V, or Cb and Cr). The human visual system is more sensitive to brightness than to elements of color variation. This suggests that the spatial resolution needed to represent the chrominance components can be lower than the required resolution to represent the luminance components [87].

Many mathematical techniques have been created to assess video quality objectively. The term "objective" in this context means the absence of human involvement. By simply applying the image quality metric to each frame of the video sequence, the early techniques were eventually expanded to still photos and video sequences. This group's most straightforward method is the peak signal to noise ratio (PSNR). The most significant value in the frame is (2^n-1) if we represent the number of bits per sample by *n*. PSNR is defined as follows:

$$PSNR_{dB} = 20_{log10} \frac{(2^n - 1)}{RMSE} \quad (2.1.1)$$

where *RMSE* is the root mean square error, which is used to calculate the distances between two frames.

2.1.5.2 Video Coding

Video coding or video compression is an important technology for applications like digital television, DVD-Video, mobile TV, videoconferencing, and internet video streaming. Encoders, decoders, and storage media from various vendors can work together when video compression is standardized. Video is converted into a compressed format by an encoder, and it is converted back into an uncompressed format by a decoder [9]. The construction of a whole video coding system can be organized as shown in the block diagram in Figure 2.8.

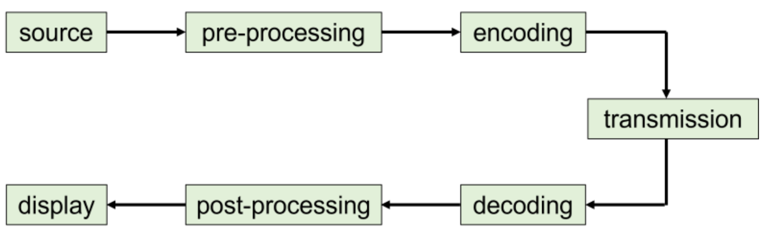


Figure 2.8 : General Block Diagram of a Video Coding System [1]

The following list summarizes the components of the general video coding system [1]:

Video Acquisition: The source of the video sequence is the digital form output. The acquisition process may be spatially and temporally uncoupled from the subsequent processing steps.

Pre-Processing: Operations on the uncompressed raw video source material, including noise reduction, color format conversion, trimming, and color correction.

Encoding: Process of converting the video sequence input into a coded bitstream. The goal of encoding is to generate a concise representation of the input video sequence appropriate for the transmission mode in the specified application scenario.

Transmission: Convert the bitstream into the proper format before sending it across the channel. The video data must be sent and delivered to the receiver side during transmission and any potential loss protection and recovery techniques. Feedback from the receiver side to the sender side may be provided in particular circumstances, such as conversational applications with real-time requirements. It can be utilized to control the encoder setup. For instance, such feedback can also be used to ask for retransmission if the information is lost.

Decoding: Converting the received bitstream into a reconstructed video sequence. The decoded video approximates the original source video since lossy compression is typically required for video encoding to meet the target transmission bitrate limits. The decoder employs concealment tactics to recover the corrupted video sequence as much as feasible in the case of irrecoverable transmission losses.

Post-Processing: Operations on the reconstructed video sequence to improve or adjust the sequence for display. For instance, these operations can involve resampling, trimming or color correction. Additionally, special effects might be used, depending on the application.

Display: The video sequence is shown for viewing. To provide the desired visual impact, the output time of the video sequence's visuals is crucial. The video sequence must be converted to the proper color format for presentation.

H.264 is a technique and format for video compression, transforming digital video into a format that uses less storage or transmission space. The Moving Picture Experts Group (MPEG) of ISO/IEC and the Video Coding Experts Group (VCEG) of ITU-T have collaboratively developed the Advance Video Coding (AVC) for H.264 [88]. Redundancy or similarities between neighboring frames in a video sequence are eliminated by the video coding standard such as H.264/AVC. Video frame sequences contain two types of redundancies which are spatial and temporal [15] [29] [48].

Temporal quality relates to the number of frames per second; the more frames are played, the smoother the motion in a scene appears. The video will become frozen if the broadcast frames are not received and played back according to their deadlines. The number of pixels in the video frame, where the texture frame offers details about the spatial segmentation or chosen region of interest in the video frame, can be used to represent spatial quality. The video frame resolution can be adjusted in size to match different display screens.

The H.264/AVC standard was first released in 2003, and since then, it has undergone a number of tweaks and improvements. H.264/AVC offers the potential for better compression efficiency, such as better-quality compressed video and greater flexibility in compressing, transmitting and storing video [9]. An H.264 video encoder performs prediction, transformation, and encoding processes as shown in Figure 2.9 to create a compressed H.264 bitstream.

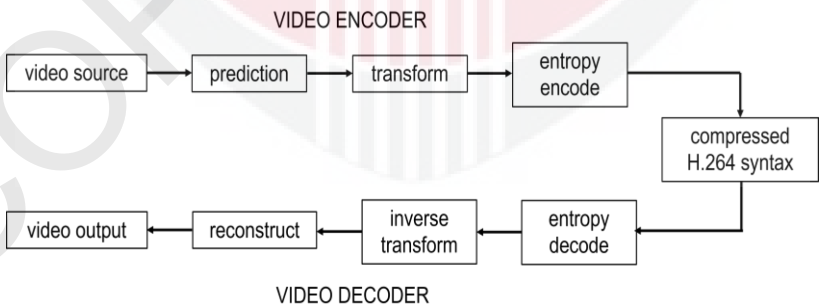


Figure 2.9 : The H.264 Video Encoding and Decoding Process [9]

Meanwhile, a decoded video sequence is produced by performing the complementary tasks of decoding, inverse transform, and reconstruction. A sequence of original video frames or fields is encoded into the H.264 format, a collection of bits that depicts the video in compressed form, as seen in Figure 2.10. It is possible to reconstitute the video sequence by decoding the compressed bitstream that is saved or sent. The decoded version generally differs from the original sequence since H.264 is a lossy compression format resulting in some visual quality lost during compression.

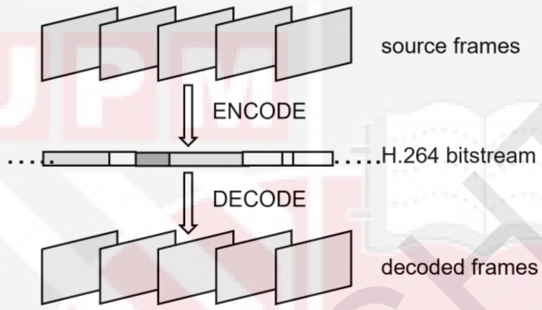


Figure 2.10 : Video Frames and Bitstream in Video Coding Process [9]

A video frame is processed by the encoder in Macroblock units, with a displayed size of 16x16 pixels. It creates a macroblock prediction using previously coded data, either from the current frame (Intra prediction) or from previously coded and transmitted frames (Inter prediction). A residual forms when the encoder subtracts the prediction from the current macroblock. Since H.264's prediction methods are more flexible than those of earlier standards, it enables accurate predictions, resulting in effective video compression [9].

This work applies an intra prediction technique to anticipate the macroblock from nearby, previously coded pixels inside the same frame, as demonstrated in Figure 2.11.

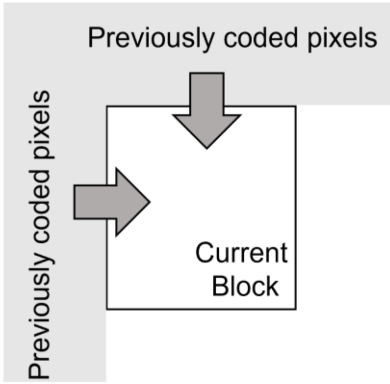


Figure 2.11 : Intra Prediction [9]

An approximation version of the Discrete Cosine Transform (DCT), known as the 4x4 or 8x8 integer transform, is used to transform a block of residual samples. Each coefficient in the transform's output is a weighting value for a regular pattern. The weighted basis patterns recreate the block of residual samples after combination. A block of transform coefficients from the transform's output is quantized by dividing each coefficient by an integer value. According to a quantization parameter (QP), quantization reduces the precision of the transform coefficients.

To create the compressed bitstream, a number of values generated during the video coding process must be encoded. These values consist of:

- Quantized transform coefficients.
- Information to allow the decoder to recreate the prediction.
- Information on the tools used for compression during encoding and the structure of the compressed data.
- Information about the entire video sequence.

The values and parameters, or syntax elements, are transformed into binary codes using variable length coding (VLC) and or without the arithmetic coding. These encoding techniques generates an efficient and compact binary representation of the data. After that, the bitstream can be sent or stored.

As in video decoder part the compressed H.264 bitstream is received and decodes each syntax element. The data is extracted by quantizing the transform coefficients, prediction data, etc. The coding process is then reversed using this information to construct a video images sequence. The re-scaled process is applied to the quantized transform coefficients, where each coefficient is scaled back to its original value by multiplying it by an integer. The original coefficients and the re-scaled coefficients are comparable but not identical. Then, to recreate each block of residual data, an inverse transform combines the standard basis patterns, weighted by the rescaled coefficients. The combination of these blocks creates a residual macroblock. The decoder then uses inter prediction from previously decoded frames to build an identical prediction to the one produced by the encoder for each macroblock. The decoder reconstructs a decoded macroblock using the prediction and the decoded residual, which may subsequently be shown as part of a video frame.

2.1.5.3 Error Resilient Video Coding Techniques

Packet loss, latency changes, and bandwidth fluctuations make it difficult to transmit video across networks prone to errors. To address these problems, several error resilience strategies have been put forth; these strategies vary in complexity, error robustness, and compression efficiency. Forward Error

Correction (FEC) is a popular method that allows error recovery without retransmission by adding redundant parity bits to the encoded stream. Despite being commonly used in contemporary video codecs like H.264/AVC, H.265/HEVC, and AV1, FEC is ineffective in networks with highly changeable conditions due to its higher bandwidth usage [89]. Automatic Repeat Request (ARQ) is another popular method that retransmits lost packets when problems are detected. Real-time adaptive video streaming technologies like WebRTC and Dynamic Adaptive Streaming over HTTP (DASH) frequently use ARQ. ARQ is inappropriate for delay-sensitive applications like live video streaming because it adds much latency [90].

Error concealment (EC) algorithms are frequently incorporated into video codecs to estimate and recover lost frames through deep learning-based reconstructions, motion estimation, or interpolation to overcome these restrictions [91]. Even though EC techniques have a low bandwidth overhead, they are not very successful in conditions with substantial packet loss when quality deterioration is severe. Scalable Video Coding (SVC), which divides a video sequence into base and enhancement layers and enables adaptive quality improvements depending on network conditions, is another extensively researched technique [92].

SVC is an appropriate option for adaptive streaming applications because it has been effectively included in H.264/SVC and H.265/SCC. Its primary disadvantage is that losing the foundation layer renders the entire video unwatchable, which has a significant impact on perceived quality.

A practical alternative for these methods, especially in lossy network settings, is Multiple Description Coding (MDC). MDC reconstructs videos without a base layer or a single stream, unlike SDC and SVC. In order to provide graceful quality decline under packet loss, the video is divided into many descriptions, each of which can be individually decoded. MDC benefits wireless networks, cognitive radio, and edge-based video streaming applications because it does not require retransmissions or excessive redundancy like FEC and ARQ. MDC has better error tolerance than classic single description coding, even though it adds more bandwidth and computational complexity, particularly when packet loss surpasses 5% to 20% [7]. Since SVC mostly depends on effectively delivering its foundation layer, MDC offers superior perceptual quality when network conditions are volatile. MDC offers a convincing solution for real-time video applications in unreliable transmission environments because of its capacity to reduce mistakes while preserving a satisfactory level of visual quality across various network conditions.

2.1.6 Related Works on Multiple Description Coding (MDC) Approach

In a mobile channel, MDC with multipath diversity can successfully reduce noise, fading, and shadowing [78]. However, limitations emerged on; (1) processing power that necessitates straightforward processing at the encoder or decoder and (2) packet loss brought on by the wireless communication environment [93]. In contrast to layered coding (LC), where there is no hierarchy among descriptions, MDC is one coding approach that generates many descriptions and can be separately decoded [94]. MDC is widely used as a source coding technique in multimedia such as images and video transmission. Table 2.4 summarized the related works on the application of the MDC for video transmission and their limitation(s).

Table 2.4 : Related Works on the Application of the MDC for Video Transmission

Reference and Year	Scopes	Proposed Approach	Advantages	Limitation (s)
[95] (2018)	MANETs	Propose novel routing protocol model using adaptive retransmission in MDC.	Proposed approach improved video quality up to 15 dB and achieved better performance than conventional FEC method.	No relay applied.
[96] (2018)	Error-prone net-works	Propose redundancy allocation scheme using visual saliency model with MDC for video transmission.	Proposed scheme improved PSNR by 2 dB.	No relay applied.
[95] (2018)	MANETs	Propose novel routing protocol model using adaptive retransmission in MDC.	Proposed approach improved video quality up to 15 dB and achieved better performance than conventional FEC method.	No relay applied.
[96] (2018)	Error-prone net-works	Propose redundancy allocation scheme using visual saliency model with MDC for video transmission.	Proposed scheme improved PSNR by 2 dB.	No relay applied.
[97] (2018)	Wireless packet net- works	Propose QoE model with HEVC-MDC based scheme for video streaming.	Proposed approach improved the PSNR by 2-3 dB.	No relay applied. Different network.
[98] (2018)	Mesh network	Propose spatial correlation transform coding of MDC scheme for video transmission.	Proposed scheme improved the PSNR and reduced the transmission delay.	No relay applied.

Table 2.4 : Continued

[99] (2018)	Wireless networks	Propose adaptive reconstruction MDC image coding with randomly offset quantizations.	Proposed scheme provides better PSNR performance than other schemes.	Image trans- mission. No relay applied.
[100] (2018)	Lossy net- works	Propose wavelet MDC based im- age coding using MOEAs.	Proposed method is robust toward mixed Gaussian impulse noise and improves the optimal side quantizers at different bitrates.	Image transmis- sion. No relay applied.
[101] (2018)	Markov model	Propose video network transmission algorithm based on unbalanced MDC.	Proposed algorithm effectively reduced the PLR and network delay compared to RED algorithm.	No relay applied.
[102] (2018)	Wireless network	Propose a spatial-frequency MDC framework with perceptual redundancy allocation for video transmission.	Proposed framework achieved better video quality com- pared to other MDC video coding methods.	No relay applied.
[103] (2018)	Wavelet transform	Propose post-processing method based optimal filtering strategy with MDC transform coding.	Proposed method achieved better re- construction image compared to other MDC with DWT method.	Image trans- mission. No relay applied.
[14] (2018)	KSVD	Propose MDC scheme with KSVD method for image coding.	Proposed scheme achieved better PSNR than other MDC methods.	Image trans- mission. No relay applied.
[17] (2019)	Vehicular com- munica- tions	Propose cross layer packet classification system for video transmission in vehicular communications.	Proposed method improved a gain in PSNR by 4.77 dB compared to the EDCA method.	No relay applied.
[104] (2019)	Error- prone network	Propose Wyner-Ziv based MDC for robust video transmission.	PSNR improved by 4.31dB compared to conventional method.	No relay applied.

Table 2.4 : Continued

[15] (2019)	Wireless network	Propose symmetrical convolutional auto-encoder based MDC framework design for image transmission.	Proposed framework improved the image reconstruction efficiency, PSNR and SSIM compared to other methods.	Image transmission. No relay applied.
[105] (2019)	Wireless network	Propose iterative decoding scheme for MDC-FEC image transmission.	Proposed scheme improved PSNR of the received image.	Image transmission. No relay applied.
[106] (2019)	network	Propose MDC image coding with balanced multi-wavelets.	Proposed method optimized multifilter banks in transform coding environment with good performance.	Image transmission. No relay applied.
[107] (2019)	network	Propose MDC scheme with compression-constrained adaptive filtering method for image signals.	Proposed scheme improved the PSNR gain compared to other similar MDC-based methods.	Image transmission. No relay applied.
[108] (2019)	Error-prone network	Propose MDC lattice vector quantization scheme for robust video transmission	Proposed scheme improved the PSNR compared to other scheme.	No relay applied.
[109] (2020)	Error-prone networks	Propose novel MDC operated at network edges for robust video transmission.	Proposed method achieved higher PSNR and error resilience performance than conventional method.	No relay applied. Different network.
[110] (2020)	UAV, MIMO-OSTBC	Propose hybrid MIMO-OSTBC architecture with MDC to transmit image for UAV in UWB system.	Proposed method has better performance compared to SDC.	Transmit image. No relay applied.
[111] (2020)	Wireless mesh network	Propose cross-layer optimization technique for video transmission in wireless mesh	Proposed technique achieved better performance in PSNR, frame delay and loss compared to	No relay applied.

Table 2.4 : Continued

		network with MDC.	existing cross layer technique.	
[92] (2020)	Error-Prone network	Propose fine grain scalable channel coded through MDC-FEC coding for video streaming.	Proposed design improved the PSNR by 1-2 dB.	No relay applied.
[112] (2020)	MANETs	Propose technique using MDC to improve multimedia applications QoS.	Proposed methods increased the PSNR by 30.84% and 18.57% in delay.	No relay applied.
[113] (2020)	multi-scale-dilated net- works	Proposed deep MDC image coding framework based on artificial neural networks for robust transmission.	Proposed method achieved higher coding efficiency compared to other neural network based MDC method.	Image trans-mission. No relay applied.
[114] (2020)	Error-prone net-works	Propose polyphase down-sampling based MDC for image transmission.	Proposed scheme improved performance at high bit rate compared to the other methods.	Image trans-mission. No relay applied.
[115] (2020)	MDC net- works	Propose deep MDC for image compression based on CAE network framework.	Proposed framework outperformed traditional MDC methods.	Image trans-mission. No relay applied.
[116] (2021)	Neural net-works, under-water trans-mission.	Propose an error-resilient coding based convolutional neural networks and MDC for un-derwater video transmission.	Proposed coding method shows better compression performance and improved transmission reliability.	No relay applied. Different network.
[117] (2021)	Wireless packet net- works	Propose framework combining video coding standard with perceptual MDC for video transmission.	The proposed scheme improved data rate reduction and perceptual PSNR performance compared to the temporally sub-sampled MDC scheme.	No relay applied. Different network.
[118] (2021)	end-to-end	Propose end-to-end distortion	Proposed model's performance	No relay applied.

Table 2.4 : Continued

	distor-tion	modelling and channel adaptive optimization for video transmission using mixed layer MDC.	outperformed the other DCT-domain model.	
[119] (2022)	Deep learning	Propose deep MDC framework for low bitrate image compression with the optimization based on MD rate-distortion minimization.	Proposed framework's image quality outperformed conventional MDC approaches.	Image. No relay applied.
[120] (2023)	Error-prone net-works	Propose a low-complexity, low-latency 2-channel MDC solution with an adaptive Instantaneous Decoder Refresh (IDR) frame period.	Proposed method achieved better resistance to high packet loss rates With lower complexity.	No relay applied.
[121] (2024)	Video codec	Propose a novel MDC video codec with bidirectional transformer for prediction.	Proposed codec achieved state-of-the-arts loss resilience performance.	Image. No relay applied.
[122] (2024)	Wireless net- works	Propose a point cloud based MDC scheme to ana-lyze compression performance.	Proposed scheme enhanced the transmission error with increasing bits perpoint by increasing the number of descriptions.	Image. No relay applied.

For the comparison of the MDC related works for video transmission, the proposed work is compared to [104]. This paper proposes a novel multiple description coding (MDC) method based on the Wyner-Ziv scheme for robust video transmission. The method encodes the motion vector (MV) field into two descriptions, which are sent over different paths. Unlike conventional approaches, it leverages the natural spatial correlation of MVs to estimate inter-description correlation without adding redundant data. The decoder uses this correlation as side information in the Wyner-Ziv scheme to enhance performance.

The results show that the proposed method balances coding efficiency and error resilience, outperforming conventional MDC techniques in objective and subjective evaluations. Next, the MDC's contributions to the relay and CR networks have been investigated. The work in [123] illustrates the MDC for source coding in the CR system to handle PU interruptions when the data flow is delay sensitive and distortion is tolerated. The study in [124] presented MDC for the CR network with a particular packetization framework under collision error. However, both studies employed only image sources.

Orthogonal frequency division multiplexing (OFDM) using MDC multicast (MDCM) was implemented in [125] and [126]. The research contrasted the MDC resource allocation strategy to the traditional multicast scheme. Instead of concentrating on video transmission performance, they addressed the resource allocation issue. In contrast, [127] used the MDC approach to develop a novel distributed system for CR networks. MDC was utilized as an error resilience strategy to reduce packet loss. The suggested technique was used in practical situations, considering sub-channel fading or PU interrupts. However, their transmission source was limited to an image.

The video transport across cognitive cellular networks is examined in [34] and [16]. Odd and even streams of the video sequence were split, and two independent descriptions were encoded. Their studies looked into the best arrangement of layered and multiple description coding without adding relays to the network. It was suggested in [18] to use MDC to increase system throughput and transmission robustness. The study only considered im- age transmission while deriving the outage probability closed-form formula to analyze the PSNR.

Lastly, in [128], the network coding (NC) is applied to relay-assisted CR networks with the MDC approach. The joint NC with MDC is revealed to improve the throughput and transmission time. However, the system is tested for image transmission only. Table 2.5 summarized the MDC approach in relay and CR networks to combat noise and delay to reduce packet loss during the transmission with their limitations.

Table 2.5 : Related Works on the MDC Approach in Relay and CR Networks

Reference and Year	Scopes	Proposed Approach	Advantages	Limitation (s)
[123] (2010)	Underlay	Propose MDC in CR network to handle PU interruptions.	The image quality improved when two descriptions are received.	No relay applied. Image transmis- sion
[124] (2012)	Underlay TDMA	Propose MDC for CR network with packetization framework.	The video quality im- proves when transmission rate increase.	No relay applied.
[125] (2012)	Underlay OFDM- based CR	Propose MDCM with resource allocation strategy to maximize the throughput of CR user.	The proposed scheme's throughput higher than conventional multicast scheme.	No relay applied.

Table 2.5 : Continued

[126] (2013)	Underlay OFDM-based CR	Propose MDCM with resource allocation strategy for OFDM-based CR systems with non-full buffer traffic.	Proposed scheme improve the SU resource allocation balancing	No relay applied.
[127] (2013	Underlay	Propose a distributed system of CR with MDC to investigate the packet drop caused by PU and subchannel fading.	PSNR improved by number of descriptions received.	No relay applied. Image transmis-sion
[129] (2015)	Underlay MC-CDMA	Propose error-free video transmission for SU.	PSNR improved by 7 dB compared to SDC.	No error conceal-ment applied.
[34] (2019)	Interweave Underlay	Video transmission over cognitive cellular by utilizing both the spectrum gaps left vacant in TV bands and the conventional licensed bands.	MDC framework increase the PSNR by 20%.	No relay applied.
[16] (2019)	Interweave Underlay	Propose improved implementation of video coding along with a DSA protocol where the sender actively chooses the best access strategy based on the current spectrum observations.	Proposed scheme increased the network capacity up to 6.3 dB.	No relay applied.
[18] (2020)	NOMA, outage proba-bility	Propose a hybrid MDC-NOMA scheme to improve system throughput and transmission robustness.	Proposed scheme outperformed the conventional NOMA	Image transmis-sion.
[128] (2021)	Overlay, NC	Propose implementation of network coding under relay model with MDC approach.	Proposed method improved the network throughput and transmission time.	Image transmis-sion.

The work in [129] is compared to our proposed scheme in terms of the MDC approach in the CR network. The paper proposes using MDC with Scalable Video Coding (SVC) to enhance error resilience. The base layer video is split into two descriptions using even and odd frames and sent to the decoder via two channels. The video performance was evaluated in this work without utilizing any error concealment at the decoder.

Simulation results indicate that MDC outperforms SDC, providing better objective and subjective video quality in underlay CR environments.

2.2 Outage Probability

Invoking the average would not make sense since it would produce a different value for each transmission if the channel did not vary quickly enough to traverse all statistical states throughout the transmission. Thus, the idea of an outage is usually included, which measures the likelihood that specific performance will not be achieved. Usually, it is possible to quantify the likelihood of an outage for channel realizations, information rates, bit, symbol, and packet errors. Since it is typically believed that fading will fluctuate sufficiently quickly while shadowing will not, averages for the former and their outages for the latter are determined. For instance, one would first determine the average packet error rate (PER) over the fading statistics in a cellular system that obeys fast fading and shadowing and then determine the packet error outage (PEO) for the determined average PER over the shadow statistics. The latter is therefore often used for cell dimensioning, which is why in real-world systems, the quantification of outages is crucial [6].

The received instantaneous SNR, γ is viewed as an RV because of noise and fading. The receiver could be unable to successfully recover the broadcast signal if γ is below a specified threshold. In this situation, where the channel's coherence time is quite long compared to the symbol interval, outage probability is used to gauge how well the system performs in slow fading. The likelihood of an outage, P_{out} is the likelihood that the received SNR, will go below a given SNR threshold, γ_{th}. The outage probability is denoted mathematically [43] as,

$$P_{out} = \int_0^{\gamma_{th}} f_\gamma(\gamma) d\gamma = F_\gamma(\gamma_{th}) \tag{2.2.1}$$

where $F_\gamma(\gamma_{th})$ is the CDF of γ evaluated at $\gamma = \gamma_{th}$.

Most related works on outage probability focus on the network with relay to improve the outage performance. In [54], the study combines cognitive relay networks with SWIPT to improve the outage performance. Power allocation strategies to decrease outage probability are proposed in [56] and [59]. The studies in [29] and [30] present a link selection scheme to improve the outage probability. The authors in [55], [58], [62], [31] and [32], the energy harvesting outage probability is investigated. The application of NOMA into relay-assisted CR networks to improve the outage performance is studied in [60] and [64]. Lastly, in [33], they proposed a scheduling method in cognitive relay networks to achieve acceptable outage performance. Table 2.6 summarized the related works on enhancing the outage performance and their limitation(s).

Table 2.6 : Related Works on the Outage Probability

Reference and Year	Scopes	Proposed Approach	Advantages	Limitation (s)
[54] (2017)	Underlay	Propose cognitive decode-and-forward (DF) relaying networks with SWIPT operation during outages.	Outage performance improves as the transmit power, energy conversion efficiency, interference threshold and fading severity parameters increase.	No MDC and video transmission applied.
[55] (2017)	Underlay	Propose cognitive decode-and-forward (DF) relaying networks with energy harvesting.	The outage performance improved by increasing the fading coefficients and the number of relays.	No MDC and video transmission applied.
[56] (2018)	Hybrid Interweave Underlay	Propose two optimal power allocation strategies for CCRNs.	Outage probability for hybrid CR out-performed the underlay CR.	No MDC and video transmission applied.
[58] (2018)	Underlay	Propose combina-tion of relay-assisted CR and wireless energy harvesting.	Outage performance decreases with the density of the secondary and distance between source and destination.	No MDC and video transmission applied.
[59] (2018)	Overlay	Propose the scheme of joint sensing time and power allocation in multi-hops and multi-channels for cognitive radio sensor network.	Maximize the energy efficient problem by analyzing the outage probability.	No MDC and video transmission applied.
[60] (2019)	Underlay	Propose application of NOMA into cooperative CR networks with SWIPT.	Outage performance improved in SWIPT NOMA compared to SWIPT OMA.	No MDC and video transmission applied.
[62] (2019)	Underlay	Propose fully energy harvested two-hop relay.	Achieved outage minimization by	No MDC and video

Table 2.6 : Continued

			~ 11.71% and ~ 12.7% gain compared to other schemes.	transmission applied.
[29] (2019)	Hybrid Interweave Underlay	Propose a combination of direct communication and buffer-aided relaying benefits.	Outage performance improved compared to the conventional link selection methods.	No MDC and video transmission applied.
[64] (2019)	Underlay	Propose cooperative NOMA systems with imperfect successive interference cancellation.	Outage probability decreases as interference constraint increases.	No MDC and video transmission applied.
[30] (2020)	Underlay	Propose novel buffer state-based relaying selection strategy for relay-assisted CR network.	The proposed system outperforms the conventional maxratio-based scheme in terms of outage.	No MDC and video transmission applied.
[31] (2020)	Underlay	Develop frame-work of wireless energy harvesting outage probability for multihop PU in relay-assisted CR network.	Optimized the primary density that minimized the existence of SU outage probability.	No MDC and video transmission applied.
[33] (2020)	Underlay	Propose a novel decentralized scheduling method for the incremental relaying-based cognitive multi-user multi-relay network.	The outage performance outperformed the benchmark schemes.	No MDC and video transmission applied.
[32] (2021)	Underlay	Develop framework in energy-harvesting cognitive radio networks with significant interferer cancellation.	The outage probability of the secondary networks with different parameters is reduced.	No MDC and video transmission applied.

For outage probability base work, the study in [29] develop a link selection scheme to improve the outage probability. The study proposes a novel transmission policy that combines direct communication with buffer-aided relaying to reduce outage probability. It modifies the hybrid interweave-underlay spectrum access policy to minimize interference from miss-detection events. The paper derives analytical expressions for outage probability and end-to-end packet delay under independent, non-identical fading channels. The simulations show that the recommended approach outperforms conventional link selection techniques, leading to reduced outage probability, improved buffer efficiency, and lowered packet latency.

2.3 Packet Transmission Time and Timeout Probability

Packet transmission time, T defined as the time taken for a packet to be arrived at the receiver after leaving the buffer. The transmission time is inversely proportional to the transmission rate generally given by,

$$T = \frac{L}{R} \tag{2.3.1}$$

where L is user mean packet length in bits and *R* is the transmission rate. If the transmission time is less than a predetermined packet timeout threshold, t_{th} a packet is regarded as successfully transferred. Otherwise, the timeout probability, $P_{timeout}$ occurs if the packet takes more time to transmit than the given transmission time. The timeout probability defined as,

$$P_{timeout} = P_r\{T > t_{th}\} \tag{2.3.2}$$

where P_R is the transmit power.

Previous research analyzed the timeout probability in the wireless network to assess the system's performance. The study in [24] investigates the energy harvesting protocols for sensor nodes to evaluate the timeout performance. In [25], the timeout probability is measured to study the impact of the transmit SNR for the NOMA system, and in [26], they present an energy harvesting scheme to evaluate the performance of the CR network via timeout probability. Energy-efficient secure video streaming with scalable video coding (SVC) is investigated in [130]. The timeout probability is measured to evaluate the trans- mission performance security. Table 2.7 summarized the related works on timeout probability and their limitation(s).

Table 2.7 : Related Works on the Timeout Probability

Reference and Year	Scopes	Proposed Approach	Advantages	Limitation (s)
[24] (2019)	WSN	Propose a wireless energy harvesting network that consists of numerous sensor nodes, each with a single antenna, and a single hybrid access point (HAP) with multiple antennas.	The timeout performance improves when the distance between HAP and sensors decrease.	No MDC, relay and video trans- mission applied.
[25] (2020)	NOMA system	Propose a secrecy outage probability and fairness of packet transmission time.	The timeout probability decrease with the increasing of the transmit SNR.	No MDC, relay and video trans- mission applied.
[26] (2021)	CR Net- work	Propose an adaptive RF energy harvest- ing with SWIPT.	The timeout probability decrease with the increasing of the energy conversion efficiency.	No MDC and video transmission applied.
[130] (2021)	UAV- enabled wireless networks	Propose an energy efficient video streaming.	The maximization of energy efficiency satisfied the secrecy timeout probability.	No MDC and relay applied.

For timeout research's work reference, the study in [26] is explored. The study proposes an adaptive energy harvesting scheme for a dual-hop CR network and evaluates its performance. It utilizes a simultaneous wireless information and power transfer (SWIPT) protocol, where data is transmitted from a secondary source (SS) to a secondary destination (SD) via a decode-and-forward (DF) relay. Findings have been provided to measure how the interference links' channel mean power and PU-Tx transmit power affect the proposed scheme's performance.

2.4 Summary and Research Gap

This chapter has reviewed the MDC approach for video transmission in relay-assisted and CR networks. A combination of cognitive radio with relay networks and MDC appears to be a promising solution to network challenges like bandwidth inefficiency and delay restriction [35]. MDC generates several descriptions, each of which can be decoded individually and used in relay-assisted networks. The generated descriptions are essential and can be routed in a different path to take advantage of network diversity. The descriptions can also be decoded independently, making the MDC useful in a network with no packet delivery priority. MDC with error concealment technique has been proven to be an effective and promising solution for improving error resilience and reducing packet loss in video distribution over various wireless networks. MDC can also be used in real-time applications like video streaming, where adequate video quality can be attained without retransmission.

In the first part of the related works, several studies have presented the relay-added into the CR networks system in various research areas. Most of the studies have measured the outage performance of the systems. However, they are not focusing on the application of MDC in their proposed system. Next, the literature has focused on the research investigating the benefits of the MDC for multimedia transmission. Most of the literature has applied the MDC technique as the video or image coding technique to exploit the path diversity of the network. However, most research focuses on the image transmission over an error-prone wireless network, not specifically over a CR network.

Besides, the issue of the lack of spectrum resources has not been discussed, as the spectrum has become the primary resource for multimedia applications. In the final part, the literature has focused on the MDC approach for multimedia transmission over the CR network. But not all studies applied the relay to their systems. All the limitations stated in this literature will be the problem statement this thesis is solving where the proposed systems are presented in detail in Chapter 3.

CHAPTER 3

METHODOLOGY

This chapter describes the proposed system design for video transmission with multiple description coding (MDC) as a video coding technique and the relay added to the CR networks, MDC-RC, to achieve the stated research objectives. The detailed procedures for each method are presented to ensure that the transmission performance and the video quality are improved with the proposed approach and technique applied for video transmission over cognitive radio (CR) networks. This research considers the proposed system model for interweave and underlay mode of CR. The chapter is organized as follows: Section 3.1 presents the proposed design for the system architecture, including the application of the MDC technique to the proposed system with H.264/AVC video codec. Section 3.2 presents the system model for the CR network's interweave mode and the outage probability expression derivation. Section 3.3 presents the system model for the underlay mode of the CR network and timeout probability derivation. Section 3.4 concludes the chapter.

3.1 The Proposed Multiple Description Coding Relay-Assisted Cognitive Radio Network (MDC-RC) System Architecture

Based on the thesis objective 1 in Chapter 1, this section describes the design procedures of a video transmission system with an MDC approach over relay-assisted CR networks. The design procedure is divided into two stages. In the first stage, we designed the system architecture for video transmission over a relay-assisted CR network.

In the second stage, the MDC technique will be applied to the video encoder and decoder at the transmitter and receiver, respectively. The multiple description source coding with H.264/AVC video encoder will generate two video descriptions and send them to the receiver via two paths. Our proposed system generates the descriptions in the temporal domain using a temporal splitting (TS) technique at the frame level. The video sequence was efficiently divided along the time axis to create odd and even video frames. As the number of descriptions rises, the compression efficiency falls because motion-compensated prediction is typically less effective. After all, the predicted frames are farther apart in time. Thus, using two separately decodable descriptions strikes a nice balance between preserving good compression efficiency and offering enhanced error recovery.

It is more complicated to determine how many paths should be used to obtain suitable path diversity. The more pathways, the better since the likelihood of an outage drops exponentially with the number of paths (this work assuming an IID model for each path). Conversely, when N is the number of pathways, the probability of an outage decreases dramatically with N. Selecting the fewest possible paths that would yield the required outage probability is advised. For instance, selecting two paths results in one of the solution that significantly lowers the outage probability. Since each independently decodable stream can be delivered over a different path, using two paths also directly links to multiple description encoding using two descriptions.

The MDC with H.264/AVC video decoder decoded the received descriptions and displayed the video. The stage details are described in Section 3.1.2, Section 3.1.3 and Section 3.1.4.

Figure 3.1 shows the proposed system architecture with the MDC approach at the transmitter and receiver parts. The Suzie (QCIF, 176×144) and Foreman (CIF, 352×288) video sequences serve as source videos for transmission. These sequences are first processed by the MDC Encoder (MDC-E), where multiple description (MD) source coding is applied using the H.264/AVC video encoder to generate two separate video descriptions. These descriptions are transmitted through two paths within the relay-assisted CR network model. At the receiver, the MD decoder with an H.264/AVC video decoder reconstructs the original video by decoding the received descriptions and restoring the video frame sequence. Subsections (3.2.1 - 3.2.4) will explain each block of the designed system architecture in detail.

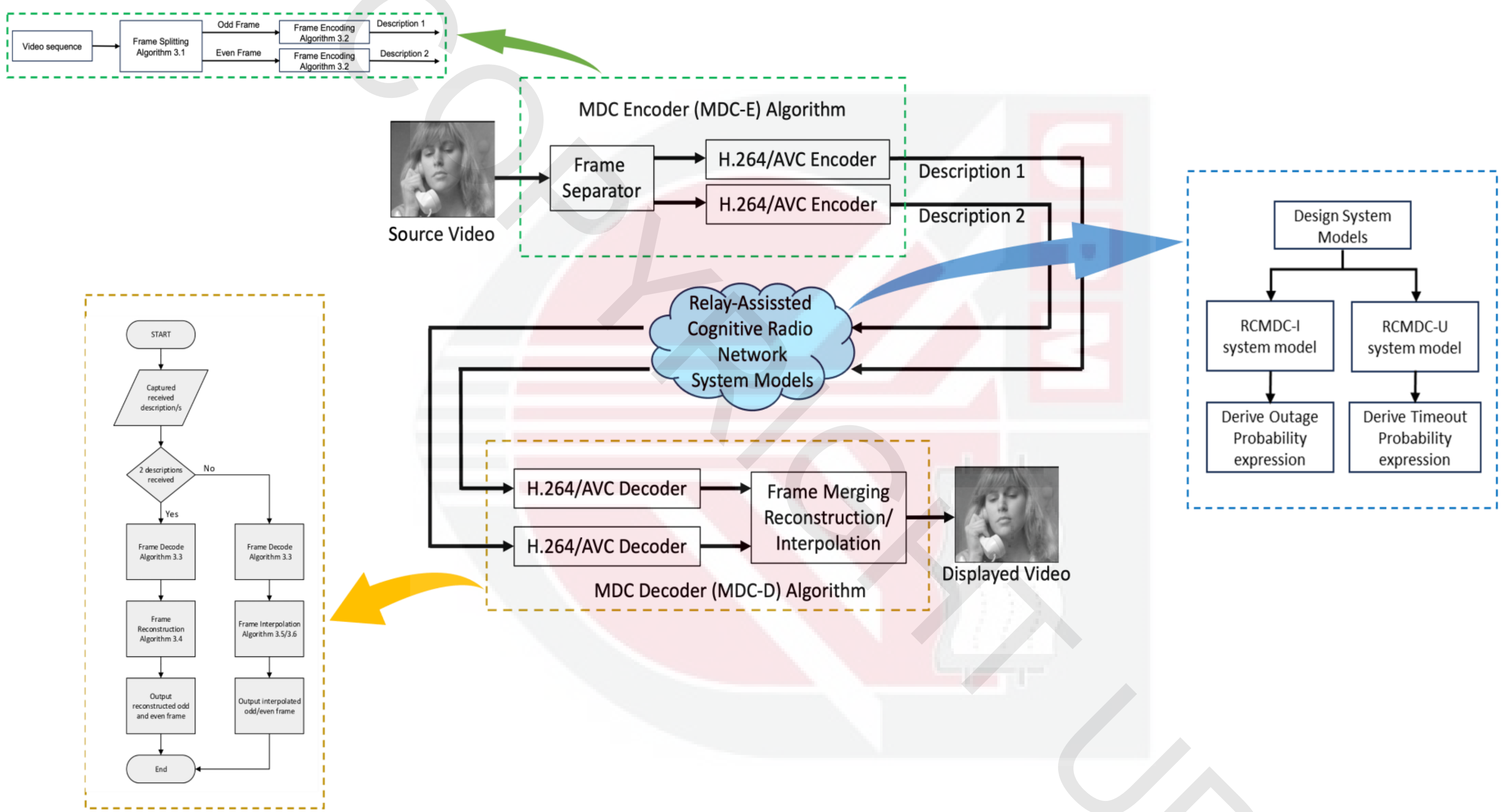


Figure 3.1 : The Proposed MDC-RC System Architecture

3.1.1 Video Sequence

As shown in Figure 3.2, Suzie and Foreman's video sequences were used as input video. The Suzie video sequence is in the quarter common intermediate format (QCIF), and the Foreman video sequence is in the common intermediate format (CIF), respectively. For QCIF, the video resolution is 176x144; for CIF, the resolution is 352x288. Details about the video format can be found in Chapter 2, section 2.1.3.

(a) Suzie sequence (b) Foreman sequence

Figure 3.2 : Video Sequence [10]

3.1.2 MDC Encoder (MDC-E)

The MDC Encoder (MDC-E) involved several processes, as shown in Figure 3.3. The transmission of the video sequence is the first step in the video encoding process. The temporal splitting MD mode is then used to divide the video sequence into odd and even frames. These frames are stored in separate files using the YUV color encoding technique to maintain the video quality. The H.264/AVC encoder is used to encode both frames, producing two different video descriptions. Both descriptions are then delivered via separate pathways in a relay-assisted network to improve resilience, while in a non-relay network, both descriptions are sent via a single transmission line. This method minimizes the possibility of data loss while guaranteeing effectual video output.

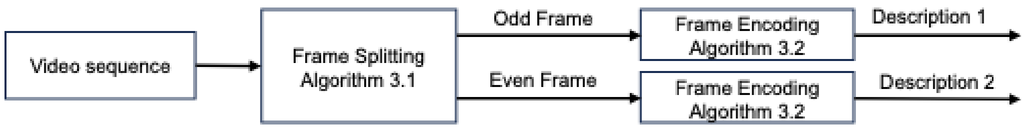


Figure 3.3 : MDC Encoder (MDC-E) Process

The step-by-step algorithms involved in the video encoding process are discussed in the subsequent subsections.

3.1.2.1 Frame Separator

Odd and even frames-based MDC system is widely used because MDC can easily produce multiple streams. This method is used in the encoding stage. In MDC, the process of generating and splitting the information into descriptions can be done in several domains, as discussed in Chapter 2, section 2.1.2. Our proposed system uses a temporal splitting (TS) algorithm to produce the descriptions in the temporal domain, where the procedure is carried out at the frame level. Odd and even video frames were produced by effectively dividing the video sequence along the time axis. Each description (odd or even frame) will be sent to the receiver via two paths. As illustrated in Figure 3.4, the original video sequence is divided into odd and even frames. The step-by-step detail of the MDC frame splitting is shown in Algorithm 3.1.

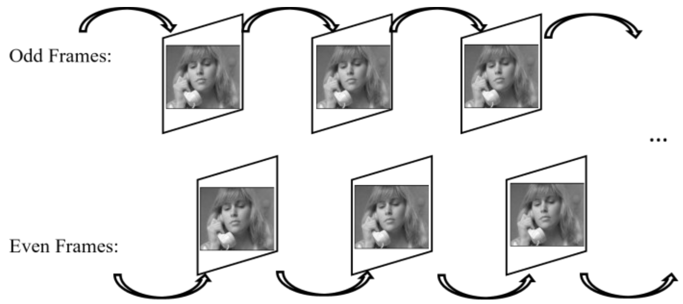


Figure 3.4 : The TS MDC Coding Method

Algorithm 3.1 Frame Splitting

$input =' video\_seq.yuv'$ ▷ Original video sequence
odd frame = 'video_seq_odd.yuv'
even frame = 'video_seq_even.yuv'
Initialise *video height, video width, frame number, N*
$framesize = videoheight * videowidth * 1.5$
$flag = 0$
$odd = []$
$even = []$
for i=0:N-1 **do**
    if flag==0 **then**
        odd=[odd;input(i*frame size+1:(i+1)*frame size)] ▷ odd frames
    else
        even=[even;input(i*frame size+1:(i+1)*frame size)] ▷ even frames
    end if
end for
Save odd frames to 'video_seq_odd.yuv'
Save even frames to 'video_seq_even.yuv'

One benefit of MDC's even and odd frames is that it is compatible with the current video coding standard because the descriptions from MDC can be decoded using the standard decoder if the descriptions are encoded using the standard encoder. In the MDC scheme, the original video sequence is split directly into odd and even frames, which is compatible with the H.264/AVC video codec.

3.1.2.2 H.264/AVC Encoder

The generated odd and even frames will be encoded into the bitstream using H.264/AVC encoder. The encoded bitstream represents the descriptions named description 1 (D1) and description 2 (D2), and next, they are sent over the network. Algorithm 3.2 explained the details of the encoding process.

Algorithm 3.2 Frame Encoding

$input =' video\_seq\_odd.yuv'$ ▷ Odd/Even frame
Initialise *video height, video width, frame start:frame end*
Convert YUV to RGB
$frameno = 1 + (frameend - framestart)$
$blocksize = []$
$QP = []$ ▷ Quantisation parameter value
Initialise *PSNR and bitrate values*
for q=1:length(QP) **do**
    Create Header
    Encode Sequence using ME ▷ motion estimation
    Determine Bitstream
    Determine PSNR
    Save Encoded bitstream
end for

In the encoding stage, the encoder will look for a block comparable to the previously encoded frame to make the prediction by considering the motion of the item in the video frame. The method is called a motion compensation technique, where frame prediction makes predictions about the following frames. The method is used to boost the effectiveness of the video encoder, as mentioned in [131]. The temporal resolution of each of the descriptions is halved from that of the original video.

The PSNR value is influenced by H.264 encoding and the MDC technique. The H.264 encoding dramatically boosts PSNR by applying efficient compression algorithms that lower the bit rate while keeping video quality. This comprises techniques such as intra-frame coding, motion estimation, and entropy coding [132]. The MDC technique increases the dependability of video transmission by supplying many descriptions of the video, enabling restoration even if some data is lost during transmission [78]. This redundancy can boost the apparent video quality, particularly in areas vulnerable to mistakes.

3.1.3 MDC Decoder (MDC-D)

In decoding, the received encoded bitstreams, D1 and D2, will be individually decoded to produce the decoded video frame (odd and even frames). Figure 3.5 shows the process involved at the MDC decoder. If both descriptions, D1 and D2, are received, the decoder will decode each description independently. The decoded descriptions will then be merged in the frame reconstruction process. If only D1 or D2 is received, the decoded frame will be interpolated to recreate the entire sequence.

The video decoding process starts with receiving the video descriptions transmitted to the decoder. Each description is then independently decoded using the H.264/AVC decoder. Error concealment techniques are used to resolve possible packet loss, improving the received video quality. If both the odd and even descriptions are successfully received, frame reconstruction is performed by merging them to restore the original video sequence. However, if only one description (odd or even) is available, frame interpolation is executed to reconstruct the missing frames, ensuring a continuous video playback experience.

3.1.3.1 H.264/AVC Decoder

The H.264/AVC video decoder will decode the received encoded bitstream at the receiver. In the decoding process, an error concealment method is applied if an error or packet loss occurs during the transmission, which affects the received bitstream. The decoded bitstream will construct a video frame, which will undergo the frame merging process before the video is displayed. The details of the decoding process are shown in Algorithm 3.3.

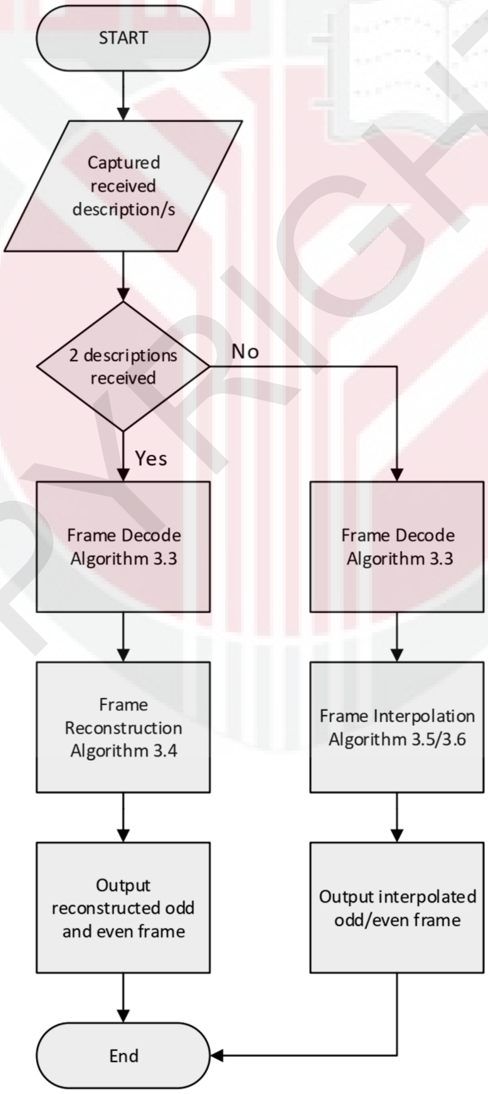


Figure 3.5 : MDC Decoder (MDC-D) Process

Due to potential transmission losses, the received video frames could be distorted. An error concealment method similar to that in [133] is used in our MDC decoder to reduce packet loss. The lost macro block (MB) is concealed using the temporal frame-copy concealment technique. The fundamental unit for motion compensated prediction in the H.264/AVC codec is the MB, corresponding to a 16x16 pixel section of a video frame. By exploiting the temporal correlation between adjacent intra-frames in two descriptions, the intra-MB is refined to make up for the missing MBs in the intra-frame.

Therefore, the lost inter-MB is concealed by using motion-compensated prediction and calculating the lost motion vector from the MB's reference.

Algorithm 3.3 Frame Decode

```
input =' bitstream.mat'                                              ▷ Encoded bitstream
Initialise video height, video width, frame start, frame end, frame number (N)
input =' video_seq_odd.yuv'                                          ▷ Odd/Even frame
Convert YUV to RGB
N = 1 + (frameend − framestart)
blocksize = []
Decode Header
for k=2:N do
    PLR= []                                                          ▷ packet loss rate
    ErrorMat=[]
    Decode Frame
    if ErrorMat=empty then
        Error=0
    else
        Launch Error concealment                                     ▷ frame-copy method
    end if
    Determine PSNR
end for
Save Decoded bitstream
```

3.1.3.2 Frame Merging

The merging process will merge the decoded bitstream based on the number of descriptions received by the decoder. In the reconstruction algorithm, the decoder interleaves the frames from descriptions 1 and 2 to reconstruct the entire sequence if both descriptions are obtained. The reconstruction process is shown in Algorithm 3.4. Meanwhile, the interpolation algorithm is applied if only one of the two descriptions is received. A slightly different algorithm is implemented depending on the description received (odd or even). The step-by-step detail of the interpolation algorithm for odd and even frame descriptions is shown in Algorithm 3.5 and Algorithm 3.6, respectively.

Algorithm 3.4 Frame Reconstruction

```
input1 = decoded_bitstream_odd.mat'                         ▷ decoded bitstream for odd frame
input2 = decoded_bitstream_even.mat'                        ▷ decoded bitstream for even frame
Convert MAT to YUV
Initialise video height, video width, frame number (N)
frame size = video height*video width*1.5
recon frame =[]
for i=0:N/2-1 do
    Write (recon frame, input1(i*frame size+1:(i+1)*frame size))    ▷ odd frames
    Write (recon frame, input2(i*frame size+1:(i+1)*frame size))    ▷ even frames
end for
Save the reconstructed frames
```

Algorithm 3.5 Frame Interpolation - Odd Frame

```
input = decoded_bitstream_odd.mat'                ▷ decoded bitstream for odd frame
output = final_odd_frame.yuv'                     ▷ location for interpolated odd frame
Convert MAT to YUV
Initialise video height, video width, frame number (N)
frame size = video height*video width*1.5
new odd frame =[]
i=0
new odd frame = [new odd frame;input(i*frame size+1:(i+1)*frame size)]
for i=0:N/2-2 do
    new odd frame = [new odd frame; input(i*frame size+1:(i+1)*frame size)]
    new odd frame = [new odd frame; input(i*frame size+1:(i+1)*frame size) + input((i+1)*frame size+1:(i+2)*frame size))/2]
end for
new odd frame = [new odd frame;input(i*frame size+1:(i+1)*frame size)]
final odd = Open (output)
Write (final odd,new odd frame)
Close (final odd)
Save the interpolated odd frames
```

Algorithm 3.6 Frame Interpolation - Even Frame

```
input = decoded_bitstream_even.mat'               ▷ decoded bitstream for even frame
output = final_even_frame.yuv'                    ▷ location for interpolated even frame
Convert MAT to YUV
Initialise video height, video width, frame number (N)
frame size = video height*video width*1.5
new even frame =[]
i=0
new even frame = [new even frame;input(i*frame size+1:(i+1)*frame size)]
for i=0:N/2-2 do
    new even frame = [new even frame; input(i*frame size+1:(i+1)*frame size)]
    new even frame = [new even frame; input(i*frame size+1:(i+1)*frame size) + input((i+1)*frame size+1:(i+2)*frame size))/2]
end for
new even frame = [new even frame;input(i*frame size+1:(i+1)*frame size)]
final even = Open (output)
Write (final even,new even frame)
Close (final even)
Save the interpolated even frames
```

It is crucial to remember that the two descriptions are individually coded so that, even if the decoder only receives a single description, it may still be decoded at a lower temporal resolution and with acceptable quality. The permissible PSNR for video transmission varies based on the application and quality standards. Typically, PSNR values are understood in the following interpretation [134]:

PSNR > 40 dB: Excellent quality with minimal distortion.

30 dB ≤ PSNR ≤ 40 dB: Good quality, acceptable for most applications.

20 dB ≤ PSNR ≤ 30 dB: Fair quality, noticeable degradation.

PSNR < 20 dB: Poor quality with significant distortion.

A PSNR value between 30 dB and 40 dB is generally deemed acceptable for video transmission and indicates good quality. Additionally, since the decoder employs the same prediction signal as the encoder for each created description, no mismatch is introduced when only one of the descriptions is received. A detailed explanation of the process of H.264/AVC video encoding and decoding is discussed in Chapter 2, subsection 2.1.3.

3.1.4 Displayed Video

The video processing workflow in a relay-assisted cognitive radio (CR) network, from frame splitting to frame merging, is depicted in Figure 3.6. First, the frame splitting technique is used to separate the original video into odd and even frames. Following independent encoding of these frames, two descriptions are produced and sent over different paths across the CR network.

The descriptions are decoded to rebuild the individual frames once they arrive at the recipient. Finally, the original video sequence is restored for display by combining the odd and even frames using the frame merging technique. The frame merging technique will recreate the video sequence based on the number of descriptions received at the receiver. The displayed video will have the original number of video frames as the video source. This method ensures a seamless and continuous video playback experience by improving transmission reliability and reducing data loss.

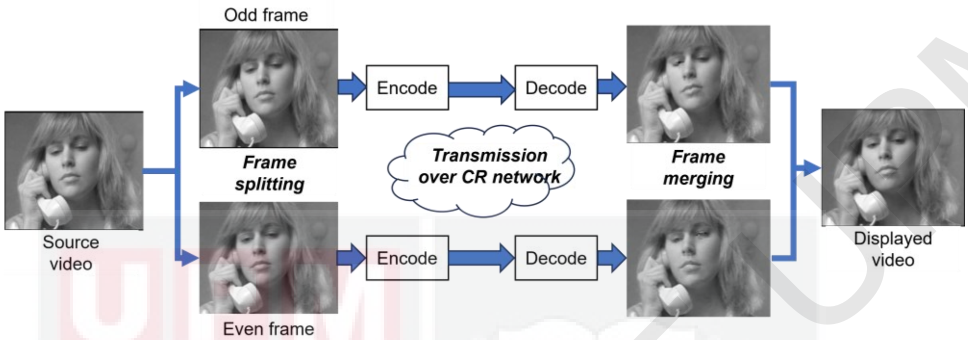


Figure 3.6 : MDC-RC Video Processing

3.2 System Model for MDC-RC Interweave (MDC-RC-I) and Outage Probability Derivation

3.2.1 MDC-RC-I System Model

This section presents the proposed design of the MDC-RC interweave mode (MDC-RC-I) and the outage probability expression derivation to address objective 2. In CR interweave mode, the PU is in idle mode and the SU can communicate with its full power while not interfering negatively with the PU. The proposed system model is depicted in Figure 3.7. A relay is added between the source and destination to utilize path diversity using MDC and multipath.

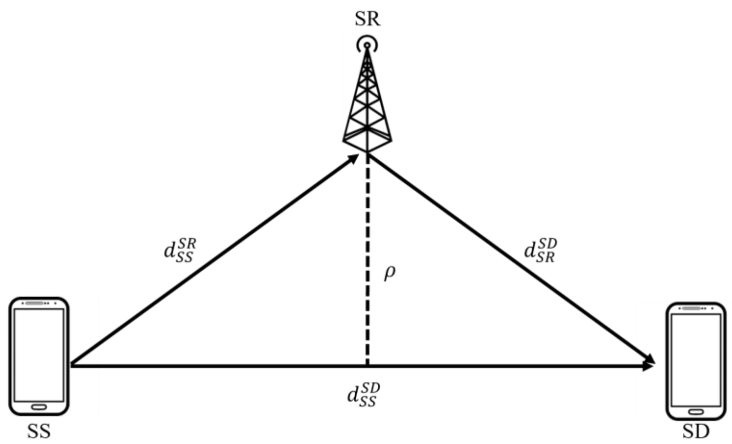


Figure 3.7 : The Proposed System Model for Interweave Mode of CR (MDC-RC-I)

The supportive relaying model (SRM) is the type of relay employed for the secondary network. The MDC technique can be applied because SRM offers two distinct pathways from the source node to the destination node. The secondary relay (SR) transmits data through the relay path from the secondary source (SS) to the secondary destination (SD). The direct path is the route that connects SS with SD. Decode and forward (DF) protocol is used in the relay path. According to this protocol, the relay will take the data from the source and transmit it to the target. In the proposed system model, the distances from SS to SR and SR to SD are denoted by the variables d_{SS}^{SR} and d_{SR}^{SD}, respectively. The distances are measured using the d_{SS}^{SD} and ρ variables applying Pythagoras' theorem to the distance between SS and SD value. The distance is calculated as follows:

$$d_{SS}^{SR} = d_{SR}^{SD} = \sqrt{\left(\frac{1}{2} d_{SS}^{SD}\right)^2 + \rho^2} \tag{3.2.1}$$

The proposed system models will be compared to the non-relay model of the interweave mode of CR network. In this model, only direct transmission is involved without assistance from the relay. The non-relay system model is shown in Figure 3.8.

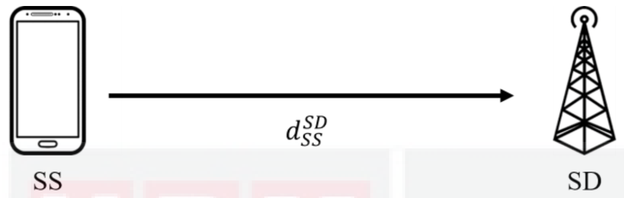


Figure 3.8 : The System Model for Non-Relay Interweave Mode of CR

3.2.2 Outage Probability

A key performance indicator in wireless communication is outage probability, which is the likelihood that the receiver's signal-to-noise ratio (SNR) will drop below a predetermined level, preventing successful transmission. This is particularly important in relay-assisted CR network communication, where cooperative relaying and dynamic spectrum access are essential for preserving dependability. This section explains the outage probability in a network affected by path loss and flat Rayleigh fading. The network model assumes that the channel experiences slowly varying fading, where the channel gain is distributed exponentially. The average power of the channel is given as $E[G_A^B] = d_A^{B-\alpha}$, where d is the distance and α is the path loss exponent. The variance of the fading process is parameterized by $1/\lambda_A^B$. The probability density function (PDF) from Equation (2.2.1) of the exponentially distributed channel gain $G_A^B = |h_A^B|^2$ is given by $f_{G_A^B}(x) = \lambda_A^B e^{-\lambda_A^B x}$.

To generalize, the parameters between two nodes, whether in one direction or the reverse, are denoted as A and B. Based on this, the channel gains and their respective PDFs are:

1. Direct Source-to-Destination (SD) Channel Gain

$$G_{SS}^{SD} = \left|h_{SS}^{SD}\right|^2 \qquad f_{G_{SS}^{SD}} = \lambda_{SS}^{SD} e^{-\lambda_{SS}^{SD} x} \tag{3.2.2}$$

2. Source-to-Relay (SR) Channel Gain

$$G_{SS}^{SR} = \left|h_{SS}^{SR}\right|^2 \qquad f_{G_{SS}^{SR}} = \lambda_{SS}^{SR} e^{-\lambda_{SS}^{SR} x} \tag{3.2.3}$$

3. Relay-to-Destination (RD) Channel Gain

$$G_{SR}^{SD} = \left|h_{SR}^{SD}\right|^2 \qquad f_{G_{SR}^{SD}} = \lambda_{SR}^{SD} e^{-\lambda_{SR}^{SD} x} \tag{3.2.4}$$

These channels are assumed to be independently and identically distributed (i.i.d), meaning their statistical characteristics remain the same across different links. The channel gains G_{SS}^{SD}, G_{SS}^{SR} and G_{SR}^{SD} all follow exponential distributions with parameters λ_{SS}^{SD}, λ_{SS}^{SR} and λ_{SR}^{SD}, respectively. Additionally, the interweave spectrum model ignores interference power and maximum transmit power constraints for simplification. This assumption helps analyze the fundamental outage probability without considering additional interference effects.

When the receiver is unable to recover the signal from the transmitter, an outage happens. It quantifies the probability that the received SNR falls below a certain threshold, rendering the transmission unsuccessful. Mathematically, an outage occurs when the mutual information, denoted as Δ, falls below a required rate threshold R, expressed as:

$$\Delta < R$$

The mutual information, Δ is given by

$$\frac{1}{2} log_2(1 + SNR) < R$$

Rearranging,

$$SNR < 2^{2R} - 1 \qquad (3.2.5)$$

This defines the SNR condition for an outage event in a relay-assisted system [48].

A. Relay-Assisted Transmission Process

For relay-assisted transmission process, the transmission occurs in two phases: The first phase covered the direct transmission from SS to SD and SS to SR. The SD and SR receive signals from the SS during the first phase. The received SNRs at the destination, $\gamma_{i_{SS}}^{SD}$ and SR, $\gamma_{i_{SS}}^{SR}$ with the transmit power of SS, P_S, are given by:

$$\gamma_{i_{SS}}^{SD} = \frac{P_S G_{SS}^{SD}}{N_0} \qquad (3.2.6)$$

$$\gamma_{i_{SS}}^{SR} = \frac{P_S G_{SS}^{SD}}{N_0} \qquad (3.2.7)$$

where N_0 is the variance of additive white Gaussian noise (AWGN).

The second phase describes the relay transmission to destination. The relay forwards the received signal to the destination in the second phase. The received SNR at the SD through the relay-assisted path, SR, ${\gamma_i}_{SR}^{SD}$ is given by:

$$ {\gamma_i}_{SR}^{SD} = \frac{P_R G_{SR}^{SD}}{N_0} \tag{3.2.8} $$

Where P_R is the transmit power of the relay, and G_{SR}^{SD} is the channel gain from the relay to the destination.

B. Outage Probability in Decode-and-Forward (DF) Relay Networks

In cooperative communication, particularly in DF protocol, outage probability is a key metric that determines the reliability of the network. An outage occurs when the received signal's mutual information falls below a given threshold, meaning that the signal cannot be successfully recovered at the receiver. For a relay-assisted CR network, the outage probability is affected by two factors, the SS to SR and the SR to SD link quality. If either of these links experiences an outage, the entire transmission fails.

In the DF protocol, an outage happens when either the SS to SR or the SR to SD channel fails [135]. The outage probability of the relay path is denoted by P_{out1}. Then, the outage probability for the source-relay-destination, SS-SR-SD path is given by:

$$ \begin{aligned} P_{out1} &= P_R\{\gamma_{SS}^{SR} < \xi\} \ or \ P_R\{\gamma_{SR}^{SD} < \xi\} \\ &= 1 - e^{-\lambda_{SS}^{SR}\theta} e^{-\lambda_{SR}^{SD}\beta} \end{aligned} \tag{3.2.9} $$

Proof: See Appendix A.1

When λ_{SS}^{SR} and λ_{SR}^{SD} are the fading parameters for the respective links. $\theta = \frac{\xi N_0}{P_S}$

and $\beta = \frac{\xi N_0}{P_R}$ is the multiplication of outage probability event with noise over source transmit power or relay transmit power, respectively.

While the outage probability for the direct path, in scenarios where direct transmission is possible from SS to SD without a relay, the outage probability is denoted as P_{out2} and the formulation is given by:

$$P_{out2} = P_R\{\gamma_{SS}^{SD} < \xi\}$$
$$= 1 - e^{-\lambda_{SS}^{SD}\theta} \quad (3.2.10)$$

Proof: See Appendix A.2

This represents the probability that the signal cannot be recovered when transmitted directly.

C. *Overall Outage Probability with Selection Combining (SC)*

In relay-assisted networks, the SC is applied as a receiver diversity technique to decode the received signals at the destination. The function of the outage probabilities for the respective paths can be used to define the total outage probability. As a result, the total outage probability is given by:

$$P_{out} = P_{out1} \times \; P_{out2}$$
$$= \left(1 - e^{-\lambda_{SS}^{SR}\theta} e^{-\lambda_{SR}^{SD}\beta}\right)\left(1 - e^{-\lambda_{SS}^{SD}\theta}\right) \quad (3.2.11)$$

This equation considers the combination of outages in both relay and direct transmission paths.

D. Comparison with Non-Relay Networks

To understand the benefit of relay-based transmission, the outage probability for the non-relay CR network model, as shown in Figure 3.8, is evaluated for comparison. In the non-relay case, only direct transmission occurs, so the outage probability is given by

$$P_{out(non-relay)} = 1 - e^{-\lambda_{SS}^{SD}\theta} \tag{3.2.12}$$

3.3 System Model for MDC-RC Underlay (MDC-RC-U) and Timeout Probability Derivation

3.3.1 MDC-RC-U System Model

For underlay mode of CR, the network system model is shown in Figure 3.9, in which the SU will share the same frequency band with the PU, but PU is now in active mode. The primary source (PS) transmits the data to the primary destination (PD) in the primary network. In the secondary network, SU transmits the data simultaneously with PU, and it assumes that PU will give interference to the secondary network. Meanwhile, the SS and SR are subjected to transmission under peak transmit power, $P_{S,peak}$ and $P_{R,peak}$, to avoid harmful interference to the PU.

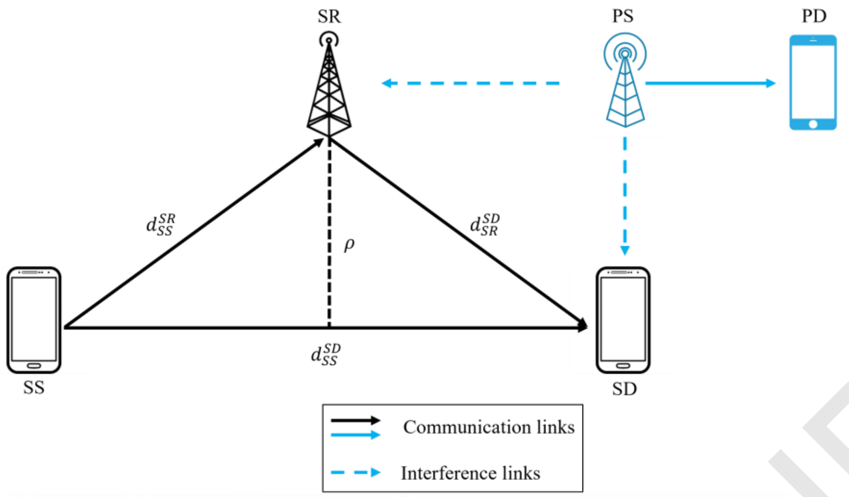


Figure 3.9 : The Proposed System Model for Underlay Mode of CR

The proposed system model will be compared to the non-relay model of the underlay mode CR network. In this model, only direct transmission is involved without assistance from the relay. For underlay mode, the system model is illustrated in Figure 3.10. The SU co-existed with the PU, but the transmission was done without giving any harmful interference to PU. As mentioned earlier, it is assumed that the PU network will interfere with the SU network.

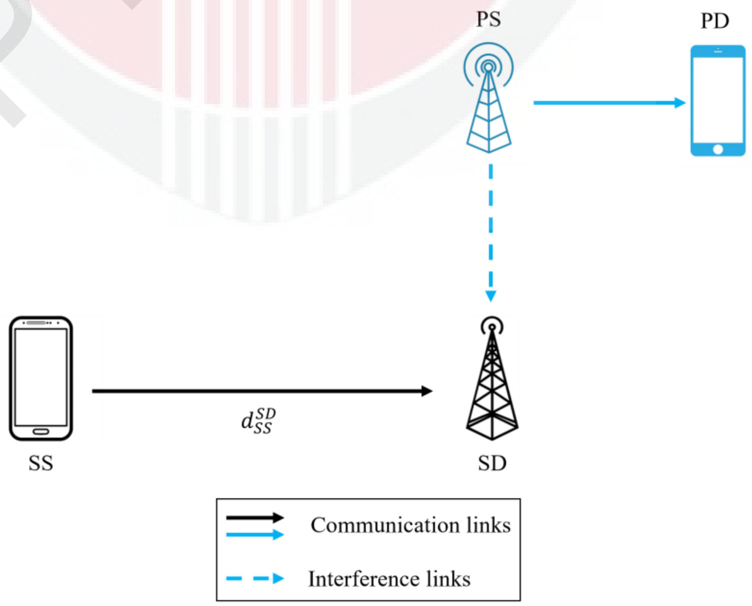


Figure 3.10 : The System Model for Non-Relay Underlay Mode of CR

3.3.2 Timeout Probability

The time taken to successfully decode the packet from SS to SD with the existence of SR is subjected to different constraints for interweave and underlay network models. Interweave spectrum sharing allows SU to transmit at maximum power because PU is idle. Meanwhile, SU must not exceed the predefined maximum transmit power at SS and SR for underlay. During transmission, SS and SR are subjected to transmit under peak transmit power, P_S^{peak} and P_R^{peak} respectively, to avoid harmful interference to the PU. The transmit power for SS and SR under constrained is given by,

$$\bar{P}_S = min\left(P_S, P_S^{peak}\right) \tag{3.3.1}$$

$$\bar{P}_R = min\left(P_R, P_R^{peak}\right) \tag{3.3.2}$$

Then the received signal is denoted as ${\gamma_u}_{SS}^{SD}$ and SR, ${\gamma_u}_{SS}^{SR}$ in the first phase considering the interference from PU source, PS and the transmit power of PS, P_P, are given by:

$${\gamma_u}_{SS}^{SD} = \frac{\bar{P}_s G_{SS}^{SD}}{P_P G_{PS}^{SD} + N_0} \tag{3.3.3}$$

$${\gamma_u}_{SS}^{SR} = \frac{\bar{P}_s G_{SS}^{SR}}{P_P G_{PS}^{SR} + N_0} \tag{3.3.4}$$

In the second phase, the source information is forwarded by the relay using transmit power of the relay, $\bar{P}_R$. The received SNR denoted as ${\gamma_u}_{SR}^{SD}$ is given by:

$$\gamma_{u_{SR}}^{SD} = \frac{\bar{P}_R G_{SR}^{SD}}{P_P G_{PS}^{SD} + N_0} \tag{3.3.5}$$

Then, the achievable rate, denoted as R_u is given by:

$$R_u = \frac{1}{2} W log_2\left(1 + \gamma_{u_{SS}}^{SD} + \gamma_{u_{SR}}^{SD}\right) \tag{3.3.6}$$

where W represent the channel bandwidth.

Finally, the packet transmission time, the time taken to successfully decode the packet from SS to SD represented by $T_{\boldsymbol{u}}$ is given by:

$$T_u = \frac{2M ln(2)}{W ln\left(1 + \gamma_{u_{SS}}^{SD} + \gamma_{u_{SR}}^{SD}\right)} \tag{3.3.7}$$

Where M denotes the packet size.

The transmission time is subjected to the timeout threshold, t_{thr} represents the moment the packet will drop after the allowed transmission time. The transmission time for underlay mode is subjected to a transmit power constraint where SU must not exceed the predefined maximum transmit power at SS and SR as formulated as follows:

$$min\ T_i$$

$$s.t\ \ T_i < t_{thr} \tag{3.3.8}$$

$$min\ T_u$$

$$s.t\ \ T_u < t_{thr} \tag{3.3.9}$$

$$0 \leq \bar{P}_S \leq P_S^{peak} \tag{3.3.10}$$

$$0 \leq \bar{P}_R \leq P_R^{peak} \tag{3.3.11}$$

Packet timeout probability occurs when the transmission time exceeds the predefined timeout threshold, t_{thr}, so the packet will drop since it cannot be successfully transmitted to the destination under the given time. Let T represent the transmission time, then the packet timeout probability is defined as:

$$P_{timeout} = P_r\{T \geq t_{thr}\} \tag{3.3.12}$$

The timeout probability for underlay mode will consider the interference caused by PU during its transmission from PS to PD on the SR and SD, as illustrated in Figure 3.9. Importantly, to prevent SU from impairing the transmission of PU, SS and SR must ensure that their transmit powers are below the peak threshold power. The packet timeout probability for SS-SR and SR-SD path are given by:

$$\begin{aligned} P_{tout,u}^{(1a)} &= P_r\{T_{1,u} \geq t_{thr}\} \\ &= \int P_r \left\{ G_{SS}^{SR} \leq \frac{k_{SU}(P_P y + N_0)}{\bar{P}_S} \right\} \frac{1}{\lambda_{PS}^{SR}} e^{-\frac{y}{\lambda_{PS}^{SR}}} \\ &= 1 - \frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_S \lambda_{SS}^{SR} + P_P \lambda_{PS}^{SR} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_S \lambda_{SS}^{SR}}} \end{aligned} \tag{3.3.13}$$

$$\begin{aligned} P_{tout,u}^{(1b)} &= P_r\{T_{2,u} \geq t_{thr}\} \\ &= \int P_r \left\{ G_{SR}^{SD} \leq \frac{k_{SU}(P_P Z + N_0)}{\bar{P}_R} \right\} \frac{1}{\lambda_{PS}^{SD}} e^{-\frac{Z}{\lambda_{PS}^{SD}}} \end{aligned}$$

$$= 1 - \frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_R \lambda_{SR}^{SD} + P_P \lambda_{PS}^{SD} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_R \lambda_{SR}^{SD}}} \tag{3.3.14}$$

The packet timeout probability for SS-SR-SD path is obtained as

$$P_{tout,u}^{(1)} = P_r\{T_{1,u} \geq t_{thr}\} \ or \ P_r\{T_{2,u} \geq t_{thr}\}$$

$$= 1 - \left(\frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_S \lambda_{SS}^{SR} + P_P \lambda_{PS}^{SR} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_S \lambda_{SS}^{SR}}}\right)\left(\frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_R \lambda_{SR}^{SD} + P_P \lambda_{PS}^{SD} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_R \lambda_{SR}^{SD}}}\right) \tag{3.3.15}$$

Proof: See Appendix B.1

While for SS-SD path, the packet timeout probability is defined as

$$P_{tout,u}^{(2)} = P_r\{T_{3,u} \geq t_{thr}\}$$

$$= \int P_r\left\{G_{SS}^{SD} \leq \frac{k_{SU}(P_P y + N_0)}{\bar{P}_S}\right\} \frac{1}{\lambda_{PS}^{SD}} e^{-\frac{y}{\lambda_{PS}^{SD}}}$$

$$= 1 - \frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_S \lambda_{SS}^{SD} + P_P \lambda_{PS}^{SD} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_S \lambda_{SS}^{SD}}} \tag{3.3.16}$$

Proof: See Appendix B.2

The SC technique is applied at the receiver. Then, the overall packet timeout probability is obtained as

$$P_{tout,u} = P_{tout,u}^{(1)} \times \ P_{tout,u}^{(2)}$$

$$= \left(1 - \left(\frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_S \lambda_{SS}^{SR} + P_P \lambda_{PS}^{SR} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_S \lambda_{SS}^{SR}}}\right)\left(\frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_R \lambda_{SR}^{SD} + P_P \lambda_{PS}^{SD} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_R \lambda_{SR}^{SD}}}\right)\right)$$

$$\left(1 - \frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_S \lambda_{SS}^{SD} + P_P \lambda_{PS}^{SD} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_S \lambda_{SS}^{SD}}}\right) \tag{3.2.17}$$

3.4 Summary

This chapter provided a detailed description of all methodologies explored in the thesis. It also gives a detailed description of the proposed system architecture, MDC-RC, the system model based on the interweave and underlay CR modes, and performance evaluation metrics for the considered CR modes. All the methodologies mentioned were used to simulate the results provided in the subsequent Chapter 4.

Section 3.1 describes the proposed system design for video transmission with MDC as a video coding technique and the relay added to the CR networks, MDC-RC, to address objective 1. The detailed procedures for MDC-RC system design stages are presented. First, the Suzie and Foreman sequences with two different video resolutions were used as input videos. Secondly, the step-by-step algorithms involved in the video encoder, MDC-E, are discussed. Then, the decoding processes by the MDC video decoder, MDC- D, involving step-by-step algorithms to decode the received frames, are discussed. Finally, the frame merging algorithm will recreate the video sequence to be displayed as an output.

In Section 3.2, the MDC-RC-I system model based on the interweave mode of CR networks is designed, and then the outage probability expression is derived to address objective 2. The proposed MDC-RC-I system model will be compared to the non-relay model of the interweave mode of the CR network. In the non-relay model, only direct transmission is involved without assistance from the relay. Outage probability expressions were derived for both the MDC-

RC-I system model and the non-relay system model.

Lastly, in Section 3.3, the MDC-RC-U system model based on the underlay mode of CR networks is designed, and then the timeout probability expression is derived to address objective 3. For the underlay mode of CR, the SU will share the same frequency band with the PU, but PU is now in active mode. The proposed system model will be compared to the non-relay model of the underlay mode CR network. In the non-relay system model, only direct transmission is involved without assistance from the relay. The SU co-existed with the PU, but the transmission was done without giving any harmful interference to the PU. Then, the timeout probability expressions were derived for MDC-RC-U and non-relay systems models.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the simulation parameters, simulation results, and performance evaluation for the proposed relay-assisted CR networks with the MDC approach for video transmission discussed in this thesis's methodology chapter. The performance of the proposed system, MDC-RC, is evaluated using a MATLAB simulator. The performance metrics, such as outage probability, timeout probability, and PSNR, are used to measure the performance of the proposed techniques and other existing methods. The results are presented in three sections based on the proposed system and two different system models according to the two modes of CR networks. The first section presents the transmission scenarios, simulation parameters for the video encoder and decoder, MDC-E and MDC-D, and the simulation results of the proposed system for addressing the thesis's first objective. The second section presents the simulation parameters and results considering the MDC-RC-I system-based interweave mode of CR networks and the outage and video performance for addressing the second and third objectives, respectively. The third section presents the simulation parameters and results for the MDC-RC-U system-based underlay mode of CR and the timeout performance to address the second and third objectives, respectively. All sections are reflected in Section 4.1, Section 4.2, and Section 4.3, respectively.

4.1 Performance Evaluations for MDC-RC System

4.1.1 Transmission Scenario

We set up the simulation for two transmission scenarios in the MDC-RC system network model, including the MDC-RC-I and MDC-RC-U system models. These scenarios refer to how the two descriptions are being transmitted. As explained in Chapter 3, Section 3.1.2, the MDC-E algorithm involves the frame separator process, where the video frames will be split into odd and even frames to produce two descriptions. These descriptions will be sent over two paths. The proposed MDC-RC systems have two paths: the relay and the direct path. Description 1 (D1), which contains odd frames, is sent through the relay path, and description 2 (D2) carries the even frames and is sent over the direct path in scenario A and vice versa in scenario B. Figure 4.1 depicts the transmission scenarios.

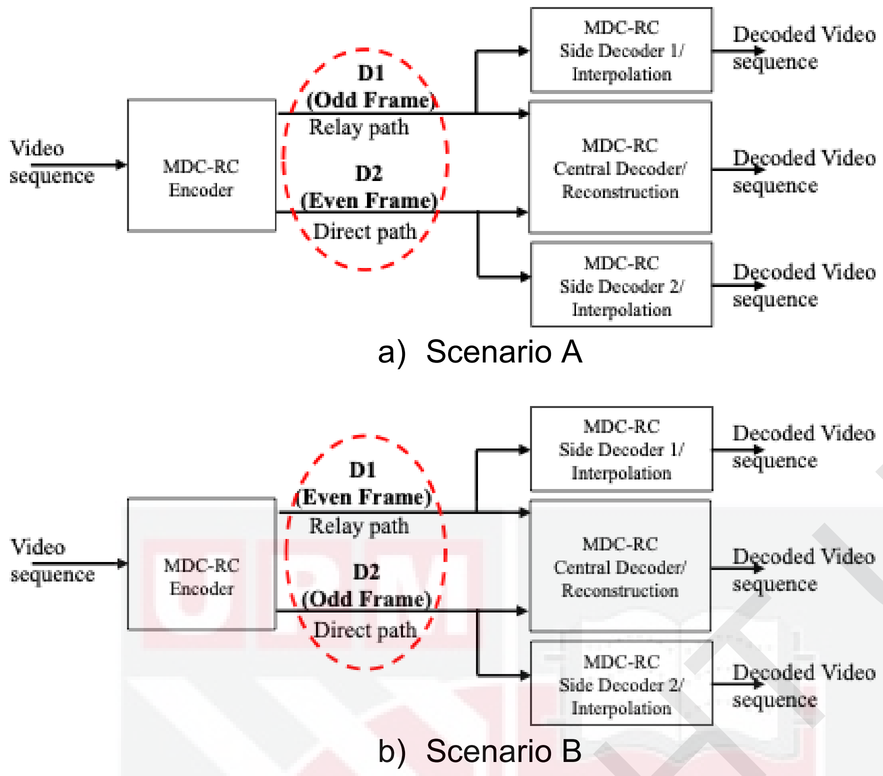


Figure 4.1 : Transmission Scenarios

4.1.2 Simulation Settings and Parameters for Video Encoding and Decoding

Table 4.1 lists the simulation parameters for video encoding and decoding. We considered two videos with different resolutions, the Suzie and Foreman video sequences in quarter common intermediate format (QCIF) and common intermediate format (CIF), respectively, as shown in Figure 3.2. Grayscale conversion of the video sequence is done for simulation purposes. Suzie and Foreman have a frame rate of 30 fps. Section 4.2 and Section 4.3 will use the same simulation setting and parameters for video encoding and decoding.

Table 4.1 : Video Coding Parameters

Parameters	Value
Input Video	_ suzie qcif.yuv & foreman cif.yuv [10]
Video width	176 & 352
Video height	144 & 288
Video codec	H.264/AVC
Quantization parameter	20
Frame format	IPPP
No. of Frame	30 frames
Error concealment	Frame-copy method [133]

4.1.3 Simulation Results

This section assesses and validates the efficiency of the proposed MDC-RC system as shown in Figure 3.1. The robustness performance measured in terms of average PSNR of the MDC technique approach in the system is compared with the classic SDC technique's algorithm used in [136].

The proposed MDC approach aims to achieve a similar performance instead of having one description received at the receiver. The results presented in this section consider the video transmission under no packet loss conditions and the transmission under different packet loss rate conditions to study the robustness of the proposed MDC-RC system. Table 4.2 shows the average PSNR without packet loss for the Suzie and Foreman video sequence. When there is no packet loss, the SDC performs slightly better than the MDC-RC system with 0.09 dB gain. This is primarily caused by the rate increment from the many descriptions utilized in the MDC-based solutions.

Table 4.2 : Average PSNR in dB for No Packet Loss Condition

Video	**2D**	**1D Odd**	**1D Even**	**SDC** [136]
Suzie	44.0444	35.9286	40.2188	44.1348
Foreman	43.4208	27.3395	32.1781	44.7122

However, when the system has a loss rate between 10% and 50%, the SDC scheme's performance quickly deteriorates even at lower packet loss percentages as shown in Figure 4.2 and Figure 4.3. SDC may become more vulnerable to deterioration of quality when packet loss occurs because no redundant information is accessible if a packet is dropped during transmission, which could result in potential errors when the signal is reconstructed. Figure 4.2 and Figure 4.3 show the effect of the packet loss on PSNR for different packet loss percentages for Suzie and Foreman video sequences, respectively. The results show that the proposed MDC-RC outperforms SDC by a 4 dB average, which indicates that the MDC-RC provides better performance for both video sequences under various packet loss rates.

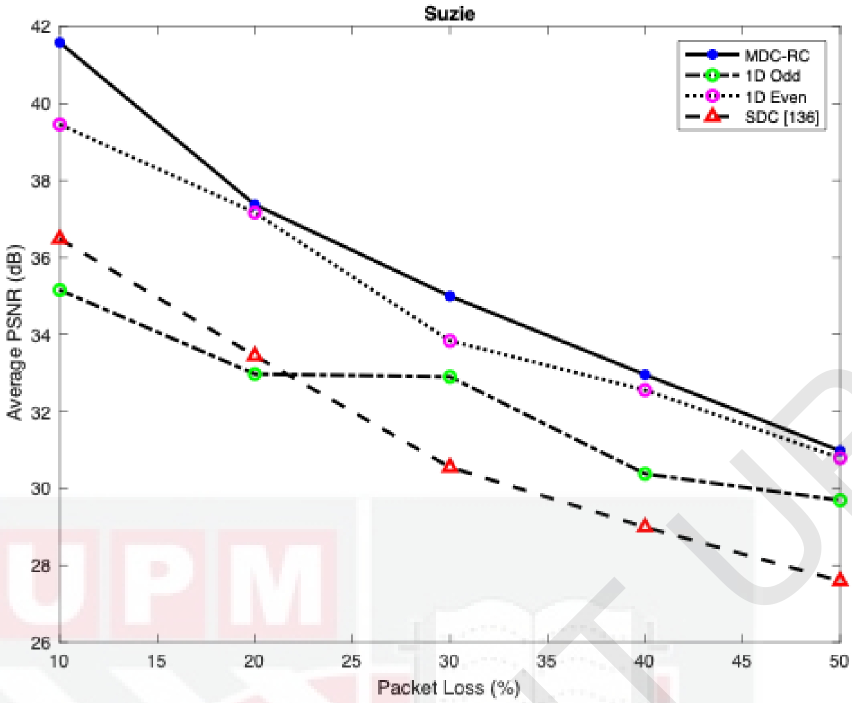


Figure 4.2 : PSNR Performance at a Different PLR for Suzie Sequence

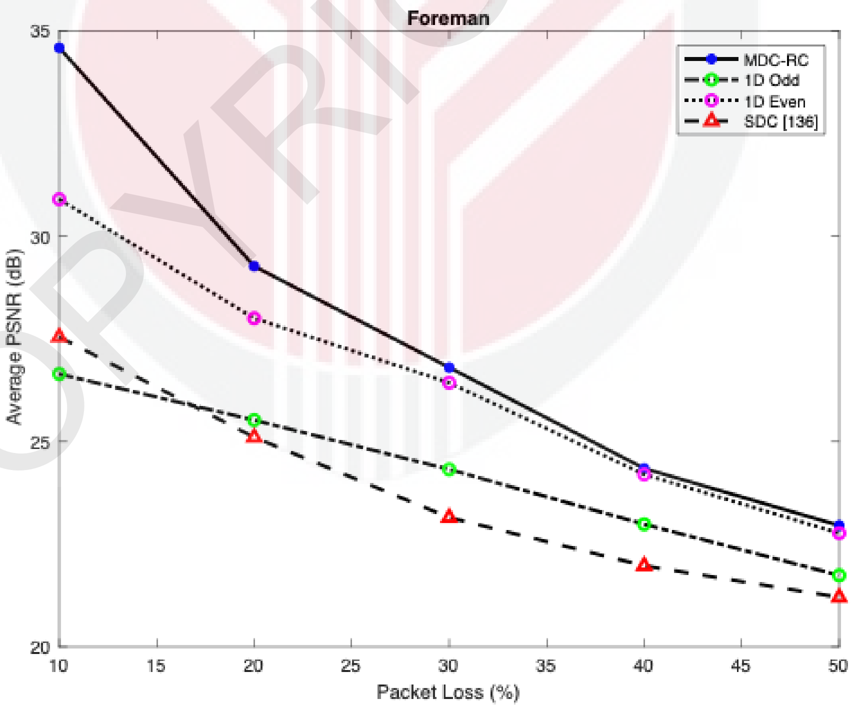


Figure 4.3 : PSNR Performance at a Different PLR for Foreman Sequence

MDC technique can enhance the robustness by redundantly encoding the data over multiple descriptions. Figure 4.4 shows a decoded frame at frame 30 of Suzie sequence for MDC-RC system, 1D Odd and Even interpolated frame and SDC scheme with 20% packet loss. An increase in the visual quality with the increase in the description received can be observed from the decoded frame of the proposed MDC-RC system when two descriptions are received and 1D Odd and Even interpolated decoded frames when only one description is received. The comparison of the visual quality can also be easily observed between the MDC-RC decoded frame and the SDC scheme decoded frame. Similar visual quality improvement can be observed for the Foreman sequence in Figure 4.5 when 10% packet loss is considered.

Figure 4.4 : Decoded Suzie Frame after 20% Packet Loss

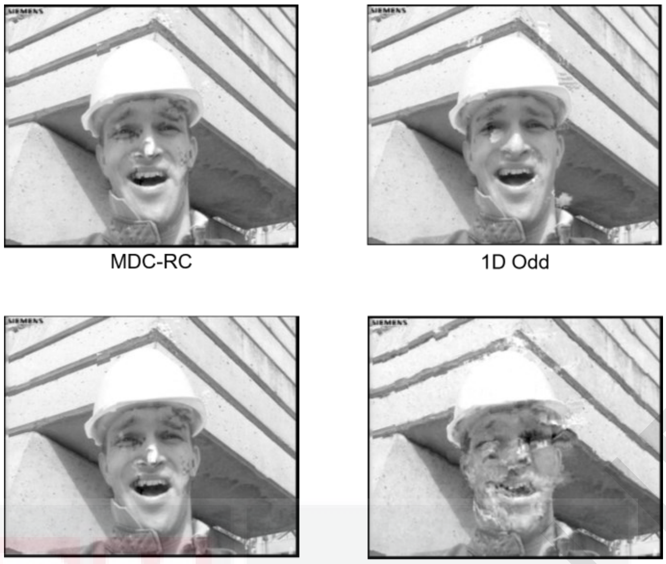


Figure 4.5 : Decoded Foreman Frame after 10% Packet Loss

4.2 Performance Evaluation for MDC-RC-I in Interweave CR Networks

In this section, the outage performance and video performance for proposed MDC-RC- I system model shown in Figure 3.7 is assessed and validated. The proposed MDC-RC-I system is based on the interweave mode of CR networks. An outage probability expression is derived, and the measured probability is used to analyze the video quality received at the receiver. The video quality also evaluated based on the number of descriptions received. The outage performance of the proposed system will be compared to the non-relay network and the video performance is compared to the classic SDC scheme.

4.2.1 Simulation Parameters for MDC-RC-I

In the first set of simulation results, the outage performance of the system model, MDC-RC-I proposed in Section 3.2.1 is verified. The simulation parameter as in [49] used to measure the outage probability of MDC-RC-I system is shown in Table 4.3. The parameter values used in a measurement of outage probability vs. transmit power of the SS. The outage performance was evaluated based on; 1) the varying distance between SS and SD, d_{SS}^{SD}, 2) the varying distance between SS to SD and SR, denoted as ρ.

Table 4.3 : Simulation Parameter of MDC-RC-I System

Parameters	Value
Path loss exponent, α	4 [49]
Noise variance, N_0	10^{-13}[49]
Transmit power of SS, P_S	0.01 W to 0.1 W [49]
Transmit power of SR, P_R	0.2 W [49]
Threshold rate, R	1 [49]

4.2.2 Outage Performance

The outage performance for transmission over interweave mode of CR using the MDC-RC-I system model is presented in this section. The total outage probability is computed based on the equation (3.2.11). Firstly, the outage probability is evaluated when the distance between SS and SD is set to 100 m, 200 m, 300 m, and 400 m. The ρ is fixed at 150 m.

The outage performance is shown in Figure 4.6. The outage probability is displayed as a function of the transmit power of SS, P_S. The graph shows that the probability of an outage has risen as the source to destination distance has increased. Meanwhile, when the channel gain decreases with increasing distance from SS to SD, the probability of an outage will increase.

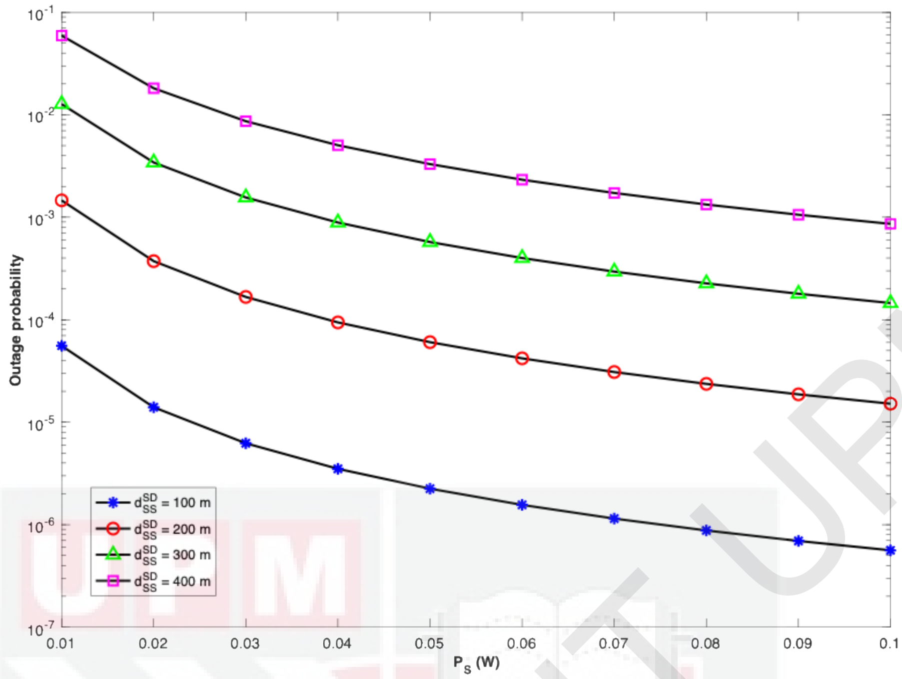


Figure 4.6 : MDC-RC-I Outage Performance at a Different Distance of SS to SD

Secondly, the outage evaluation was simulated when the ρ value was set to 50 m, 100 m, 150 m, and 200 m, with the d_{SS}^{SD} fixed at 300 m. Figure 4.7 shows the simulation result. As the distance between the source to relay, d_{SS}^{SR} and relay to the destination, d_{SR}^{SD} was proportional to the ρ, there has been an increase in the outage probability when the ρ distance is increased.

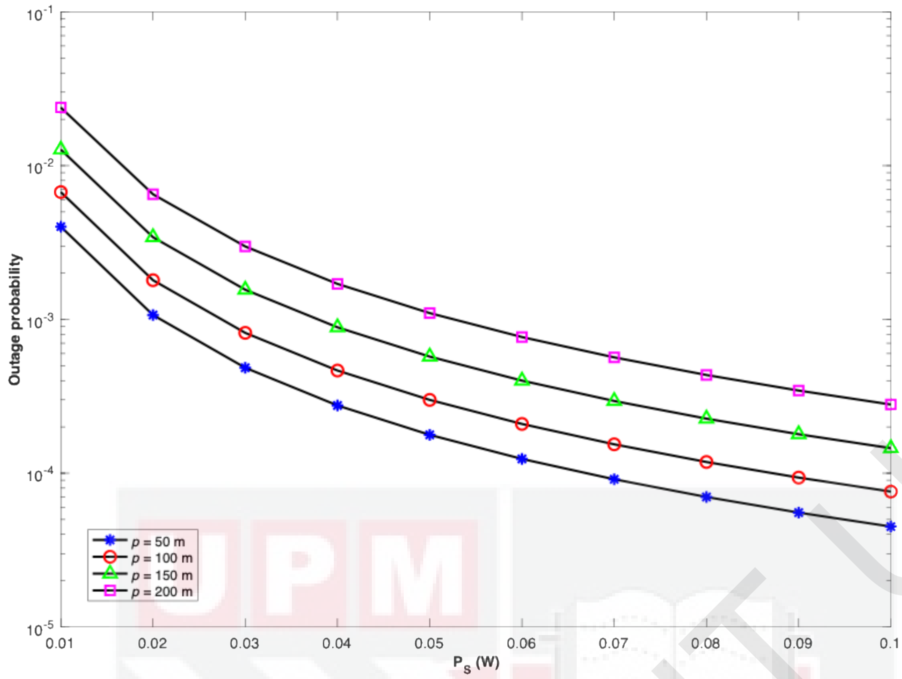


Figure 4.7 : MDC-RC-I Outage Performance for Different ρ Value

Then, we contrasted the outage performance of a relay network with a non-relay network at various SS to SD distances. Figure 4.8 displays the results of the comparison. The outage probability for the descriptions transmitted across the non-relay network, as determined by equation (3.2.12), was higher than that of a network with a relay. Over a non-relay network, the MDC-RC-I improved outage probability by 9%. Transmission in a non-relay network solely depends on the path between SS and SD, where path loss and fading effects negatively impact the quality of the data received. When the transmission distance is increased, however, adding a relay can enhance the quality of the received data.

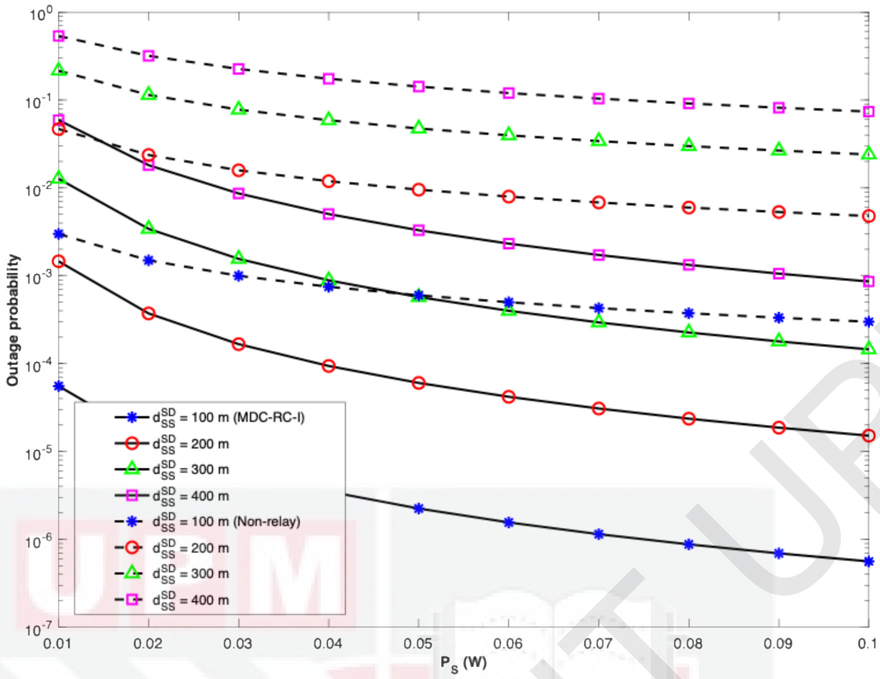


Figure 4.8 : Comparing Outage Performance of RC-MDC and Non-Relay Network at a Different Distance of SS to SD

4.2.3 Video Quality Based on Outage Performance

The quality of the decoded video received at the destination was assessed for the proposed MDC-RC-I system using the PSNR as a performance indicator in the second set of simulation results. In this set, first, a simulation of PSNR performance using various d_{SS}^{SD} was conducted. The results for the decoded Suzie sequence for transmission scenario A and B are shown in Figures 4.9 and 4.10, respectively. While for Foreman sequence, the results are shown in Figures 4.11 and 4.12, respectively. The findings indicate the PSNR of the reconstructed and interpolated decoded sequence reflecting both descriptions (2D) and one description (1D even or 1D odd) received.

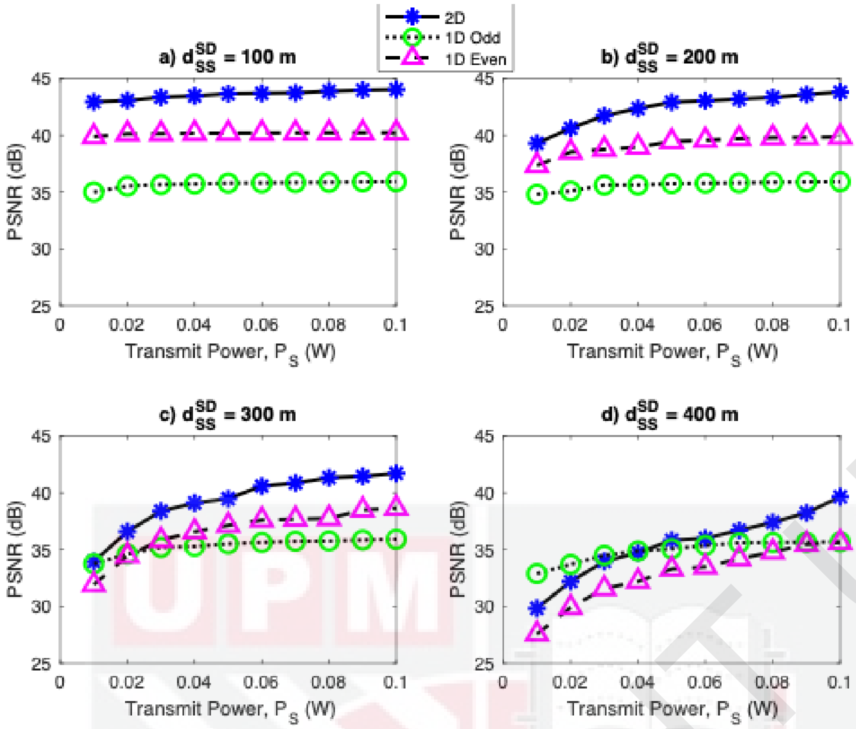


Figure 4.9 : MDC-RC-I PSNR Performance of Suzie Sequence at a Different Distance of SS to SD for Scenario A

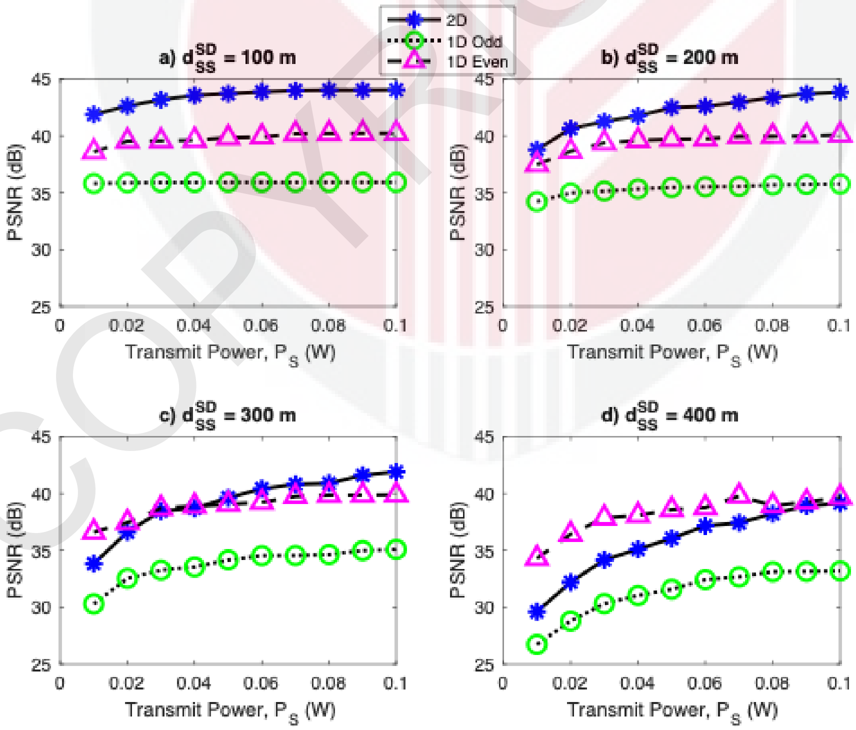


Figure 4.10 : MDC-RC-I PSNR Performance of Suzie Sequence at a Different Distance of SS to SD for Scenario B

Figure 4.9 presents the PSNR performance of the MDC-RC-I for the Suzie sequence under varying distances between the SS and SD in Scenario A. The results indicate that the PSNR performance is influenced by both the transmission distance and the encoding scheme. When d_{SS}^{SD} is small (e.g., 100 m in Figure 4.9a), all schemes maintain relatively high PSNR values, with the 2D MDC scheme consistently achieving the best performance. As the distance increases to 200 m (Figure 4.9b) and 300 m (Figure 4.9c), the PSNR for the 1D MDC (Odd and Even) schemes declines more significantly compared to the 2D MDC scheme, which remains more resilient to increasing distance. At the largest distance (400 m in Figure 4.9d), the degradation in PSNR is most pronounced, particularly for 1D Odd and 1D Even schemes, indicating their vulnerability to increased transmission distance due to higher packet loss and weaker signal strength.

Additionally, the impact of transmit power P_S on PSNR performance is evident across all distances. At lower P_S, the PSNR values remain relatively low, especially at greater distances. As P_S increases, an improvement in PSNR is observed across all encoding schemes, though the rate of improvement diminishes at larger distances, particularly for 1D MDC schemes. This implies that while boosting transmit power can help offset some of the effects of signal attenuation, it is ultimately insufficient to counteract the performance deterioration brought on by distance. Because of its improved error resilience and redundancy in encoding, the 2D MDC method continuously performs better than its 1D counterparts across all power levels and distances.

These results emphasize how crucial it is to use the best encoding technique in addition to relay-assisted transmission in order to improve the dependability of video communication in cognitive radio networks.

Figure 4.10 shows the MDC-RC-I scheme's PSNR performance for the Suzie sequence for varying distances between the SS and SD in Scenario B. The outcomes show how encoding strategies and transmission distance affect PSNR performance. Scenario B shows a slightly different performance pattern than Scenario A (Figure 4.9). While the 1D MDC (Odd and Even) schemes perform marginally worse but still offer respectable video quality, the 2D MDC scheme retains the highest PSNR values at a short distance (Figure 4.10a). The PSNR performance for 2D and 1D Even encoding is constant at distances of 200 m (Figure 4.10b) and 300 m (Figure 4.10c), whereas 1D Odd degrades more noticeably.

A clear trend appears at the most significant distance d_{SS}^{SD} = 400 m in Figure 4.10d). Here, the 1D Even method performs similarly to 2D MDC at greater transmit power levels, unlike Scenario A, where 2D MDC routinely beats 1D encoding. This implies that a better relay-assisted transmission approach increases the error robustness of 1D Even encoding, which is advantageous for Scenario B. The effect of increased transmit power P_S is noticeable at all distances since greater P_S always results in better PSNR values. Nevertheless, the rate of PSNR gain slows down with increasing distance, especially for the 1D Odd scheme, which is still the most susceptible to performance degradation due to distance. The findings show that Scenario B gains from a more successful relay cooperation tactic that lessens the adverse effects of growing SS-SD distance.

The 1D Even scheme in Scenario B shows unexpected durability, especially at larger P_S, while 2D MDC is still the most dependable scheme. According to the comparison of circumstances A and B, 1D MDC-based video transmission may be considerably more resilient by optimizing relay cooperation, making it a feasible substitute in some deployment circumstances.

Using the MDC-RC-I technique, Figure 4.11 shows the PSNR performance of the Foreman video sequence in Scenario A at different distances between the SS and the secondary destination (SD). The findings show how transmission distance, encoding techniques (2D and 1D), and transmit power, P_S affect video quality. With a PSNR of 45 dB at higher P_S, the 2D MDC scheme performs noticeably better than the 1D Odd and 1D Even schemes at a shorter distance (d_{SS}^{SD} = 100 m, Figure 4.11a). On the other hand, the very constant PSNR of the 1D encoding techniques indicates that they are not very resilient to rising transmission power. This pattern suggests that single description encoding cannot sustain quality even at a favorable distance, but cooperative relay support helps the 2D MDC approach.

All schemes show a progressive drop in PSNR as the distance grows to 200 m (Figure 4.11b) and 300 m (Figure 4.11c). While the 1D schemes show only slight gains, the 2D MDC scheme remains the most robust, with a consistent increase in PSNR as P_S grows. In Scenario A, 1D Odd and 1D Even encoding is less effective for long-distance transmissions due to their lower PSNR, which emphasizes their greater sensitivity to growing route loss. The PSNR loss is most noticeable at the greatest distance (d_{SS}^{SD} = 400 m, Figure 4.11d), especially for the 1D schemes, which stabilize at about 22–25 dB irrespective of P_S.

Although the 2D MDC scheme continues to show an improving trend with P_S, its PSNR is still below 35 dB, showing a considerable decline in performance due to weaker cooperative relay effects and greater path loss. This implies that Scenario A, especially for single description encoding, suffers from a severe deterioration in quality at greater distances due to the absence of an efficient relay scheme to reduce losses.

The PSNR values for the Foreman sequence are lower at all distances than in Figure 4.9 (Suzie sequence in Scenario A). This is explained by the Foreman sequence's greater motion complexity, which leaves it more vulnerable to transmission losses and compression artifacts. The results highlight that the effectiveness of MDC-based transmission is greatly influenced by the video content features, with low-motion sequences (like Suzie) retaining higher quality than high-motion sequences (as Foreman).

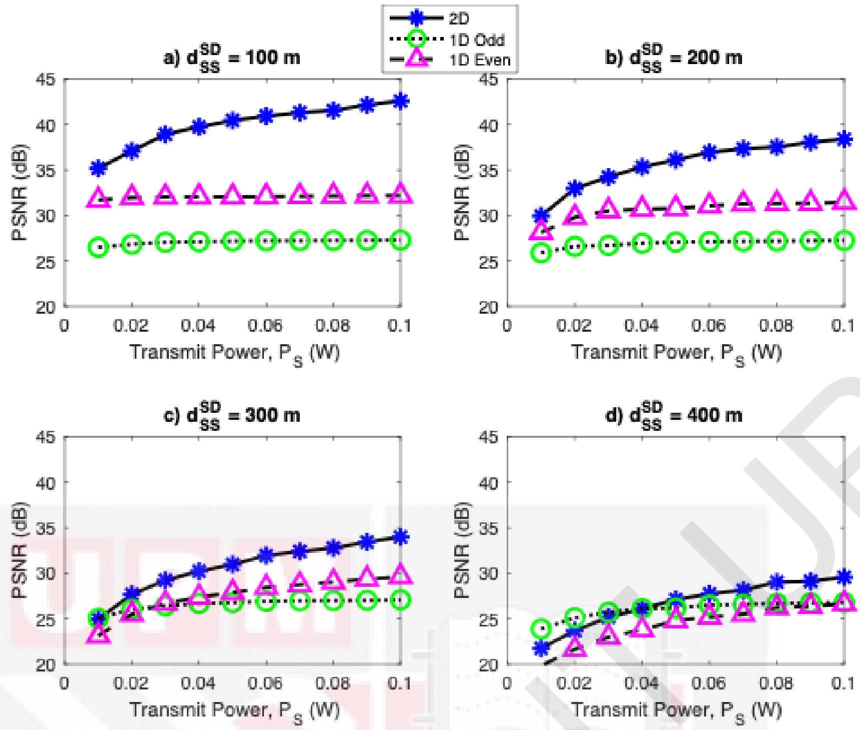


Figure 4.11 : MDC-RC-I PSNR Performance of Foreman Sequence at a Different Distance of SS to SD for Scenario A

The PSNR performance of the Foreman video sequence for Scenario B, in which the trans- mission takes place at different distances between the SS and the SD, is shown in Figure 4.12. The MDC-RC-I scheme's performance is assessed using a range of transmit power P_S and encoding techniques (2D, 1D Odd, and 1D Even). The 2D MDC technique consistently beats the 1D encoding schemes at a shorter transmission distance (d_{SS}^{SD}= 100 m, Figure 4.12a), with a PSNR of 40 dB at greater P_S. The 1D encoding schemes (Odd and Even) show better PSNR performance than in Scenario A, indicating that Scenario B's relay cooperation mechanism is more successful in reducing losses than Scenario A's.

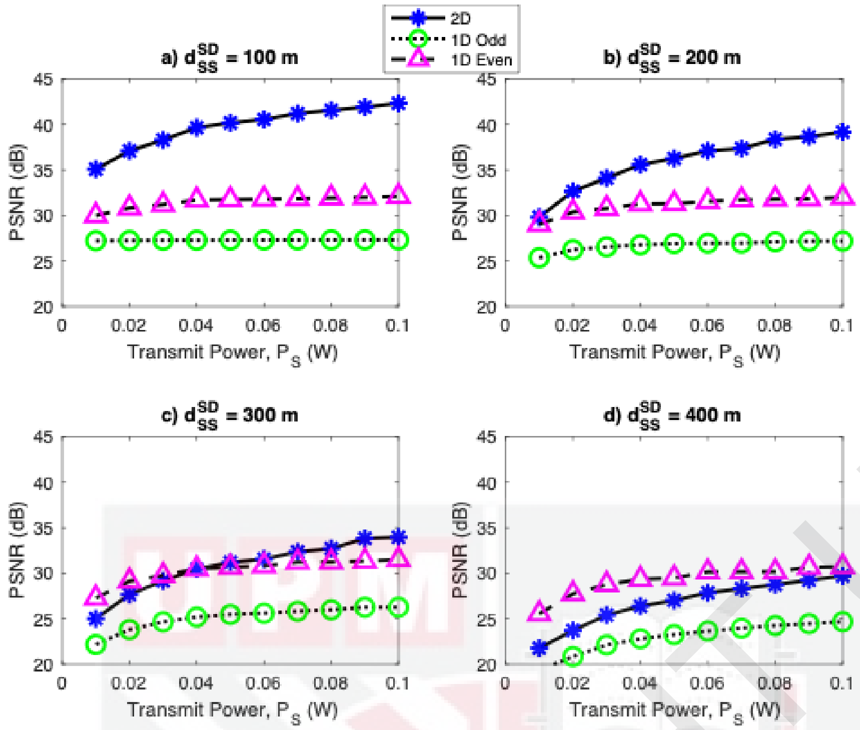


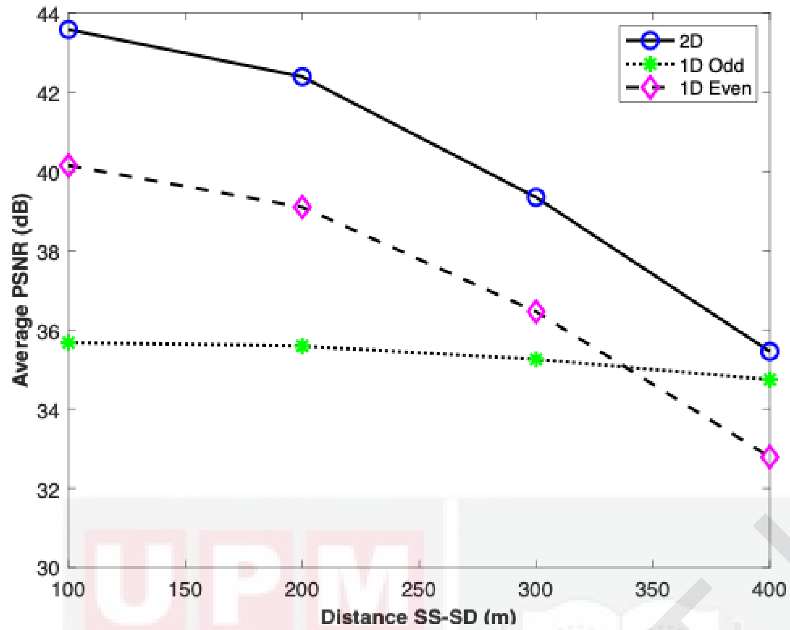
Figure 4.12 : MDC-RC-I PSNR Performance of Foreman Sequence at a Different Distance of SS to SD for Scenario B

The 2D technique maintains a rising PSNR trend with P_S when the distance grows to 200 m (Figure 4.12b) and 300 m (Figure 4.12c), confirming its resilience in improving video quality. However, beyond 30 dB, the 1D Odd and 1D Even schemes show only modest gains, suggesting a limited capacity to utilize higher gearbox power efficiently. The difference between the 2D and 1D schemes at greater distances becomes more noticeable, emphasizing the advantage of 2D MDC encoding in managing transmission defects over longer distances.

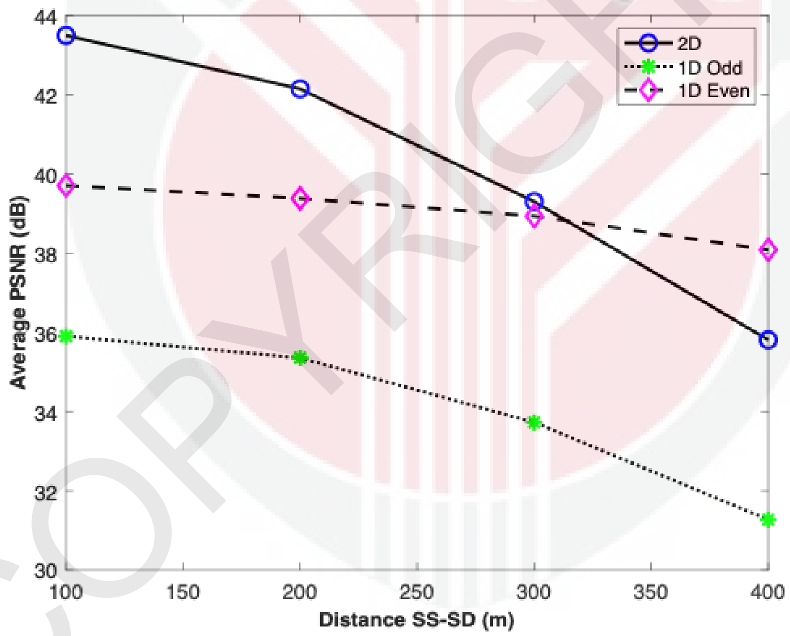
While PSNR degradation is noticeable at all schemes at the longest distance (d_{SS}^{SD} = 400 m, Figure 4.12d), a significant distinction from Scenario A is that the 1D Even scheme maintains a relatively stable PSNR (30 dB) across the transmit power range. In contrast, the 2D scheme does not show a PSNR increase as steeply as in the previous distances. For the identical transmission conditions, Scenario B regularly yields higher PSNR values, especially for 1D encoding methods, when compared to Figure 4.11 (Foreman sequence in Scenario A). This suggests that Scenario B's relay arrangement is more suited to preserving video quality across longer transmission distances.

The acceptable video quality was produced if the receiver received one description, a set of even or odd frames when either the relay or direct path failed. The video quality will improve if both descriptions are obtained at the location. As the outage probability for the relay path is lower than that of the direct path at d_{SS}^{SD} = 400 m in Scenario B, the PSNR of one description (1D) broadcast through the relay way is marginally greater than that of two descriptions (2D) received at the receiver.

The overall PSNR performance comparison for 2D and 1D at the various d_{SS}^{SD} is shown in Figures 4.13 and 4.14.

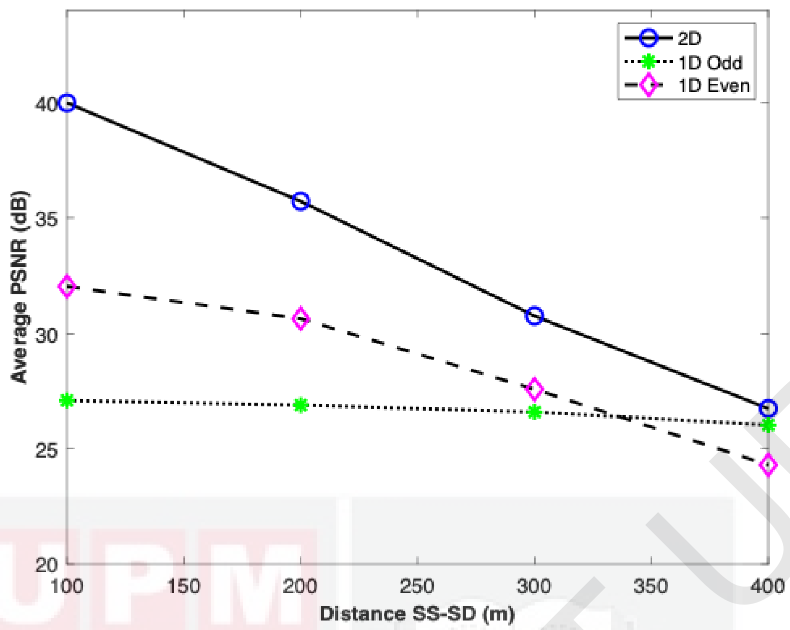


a) **PSNR comparison for Scenario A**

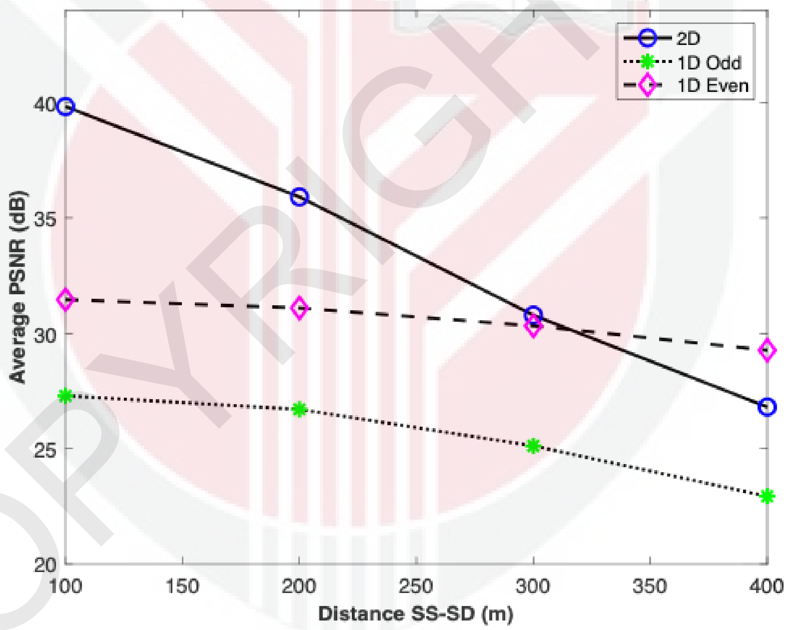


b) **PSNR comparison for Scenario B**

Figure 4.13 : PSNR Performance Comparison over Distance of MDC-RC-I for Suzie Sequence



a) **PSNR comparison for Scenario A**



b) **PSNR comparison for Scenario B**

Figure 4.14 : PSNR Performance Comparison over Distance of MDC-RC-I for Foreman Sequence

The PSNR performance of the MDC-RC-I technique for the Suzie sequence at different distances between the SS and the SD is shown in Figure 4.13. Because of the larger packet loss rate and more network impairments, PSNR naturally drops with increasing distance. Because of the additional spatial redundancy that improves the quality of the reconstructed frames, the 2D scheme routinely performs better at shorter distances (100–300 m) than both the 1D Even and 1D Odd schemes. Beyond 300 m, however, an odd pattern is shown where the 1D Even scheme outperforms the 2D scheme in terms of PSNR, resulting in the 1D line crossing the 2D line at long ranges.

The nature of frame dependencies and error propagation in motion-compensated video coding are responsible for this situation. In contrast to sequences like Foreman, the Suzie sequence mostly consists of a talking head with comparatively little physical action. Even indexed frames (1D Even) are more stable and show less motion dependency in this setting, making the reconstruction procedure more robust in heavy packet loss. On the other hand, because the 1D Odd scheme depends on earlier frames, it maintains a lower PSNR over all distances, making it more prone to distortion and error propagation.

The redundancy in the 2D scheme improves performance at shorter distances. However, the 2D scheme is negatively impacted by the growing packet loss rate as the distance beyond 300m, leading to a more noticeable deterioration in PSNR. Due to its reliance on both temporal and spatial redundancy, the 2D scheme is more susceptible to burst faults, which can result in a substantial reduction in quality when a considerable amount of the transmitted data is lost.

On the other hand, the 1D Even scheme outperforms the 2D scheme beyond 300m and maintains more stability because of its reduced motion complexity and dependence on inter-frame dependencies. This result implies that, in comparison to the 2D scheme, the 1D Even scheme can offer more robustness in extremely lossy situations for low-motion video sequences like Suzie. This emphasizes the significance of adaptive multiple description coding (MDC) techniques, which optimize perceived video quality in relay-assisted cognitive radio networks by dynamically adjusting transmission parameters based on network conditions and video characteristics.

The PSNR performance of the MDC-RC-I technique for the Foreman sequence at different separations between the SS and SD is shown in Figure 4.14. As anticipated, the relay-assisted cognitive radio network experiences greater route loss and interference as the transmission distance rises, resulting in a drop in the overall PSNR. The 2D transmission technique benefits from spatial redundancy in both dimensions and achieves the best PSNR at shorter distances (100–300 m). On the other hand, because of the loss of redundancy from discarded frames, the 1D Odd and 1D Even schemes show lower PSNR values at shorter distances. At distances longer than 300 meters, however, an odd pattern is shown where the 1D Even system outperforms the 2D scheme regarding PSNR.

The frame dependency properties of the Foreman sequence are responsible for this behavior. The sequence has much motion, especially in odd frames when motion correction from earlier frames is crucial. As a result, the 1D Odd scheme's performance is limited at longer distances because mistakes propagate more strongly through motion-predicted frames, maintaining a comparatively constant PSNR trend. The 1D Even system, on the other hand, has fewer error propagation effects because it uses frames with comparatively less motion. The 1D Even system eventually outperforms the 2D scheme because of its decreased reliance on earlier frames, which increases its resistance to packet losses over longer distances.

Moreover, this trend is influenced by packet loss recovery techniques and error propagation. The 2D technique can more successfully restore missing data at shorter distances because of redundancy. However, as errors affect both dimensions and propagate over numerous frames, the impact of losing some of the sent data in 2D coding increases with distance and packet loss frequency. On the other hand, because it depends less on previous frames, the 1D Even scheme counteracts this effect, resulting in a more progressive decline and, ultimately, a PSNR advantage over the 2D scheme. These results point to a critical trade-off in multiple description coding for wireless video transmission, redundancy against error resilience. Even though 2D transmission performs better at shorter distances, its vulnerability to error propagation results in a noticeable decline in performance as distance rises. Because of its decreased inter-frame reliance, the 1D Even scheme eventually shows higher resilience at longer distances.

The average PSNR of the Suzie and Foreman sequences from 10 trials for Scenario A and Scenario B are shown in Tables 4.4 and 4.5, respectively.

The overall average PSNR increased by 17% for the Suzie sequence and 27% dB for the Foreman sequence at the variations of d_{SS}^{SD} when both descriptions received as opposed to receiving just one. The highest increment of PSNR is 8 dB for Suzie and 13 dB for Foreman at d_{SS}^{SD} = 100 m.

Table 4.4 : Average PSNR of MDC-RC-I at Variations of d_{SS}^{SD} for Scenario A

d_{SS}^{SD} (m)	Suzie - PSNR (dB)			Foreman - PSNR (dB)		
	2D received	1D odd received	1D even received	2D received	1D odd received	1D even received
100	43.5817	35.7069	40.1465	39.9942	27.0924	32.0379
200	42.3906	35.6180	39.0991	35.6888	26.8938	30.6399
300	39.3468	35.3246	36.4598	30.7593	26.5916	27.5803
400	35.4540	34.8949	32.7895	26.7436	26.0312	24.2998

Table 4.5 : Average PSNR of MDC-RC-I at Variations of d_{SS}^{SD} for Scenario B

d_{SS}^{SD} (m)	Suzie - PSNR (dB)			Foreman - PSNR (dB)		
	2D received	1D odd received	1D even received	2D received	1D odd received	1D even received
100	43.4963	35.9003	39.7061	39.7061	39.8340	27.2959
200	42.1461	35.3474	39.3803	39.3803	35.9165	26.7071
300	39.2998	33.7277	38.9367	38.9367	30.7911	25.1243
400	35.8102	31.2722	38.0833	38.0833	26.8098	22.9394

The PSNR of the MDC-RC-I was then compared with the non-relay network. The odd and even frames are interleaved and sent over a direct path in a non-relay network. The results of the PSNR at variation of SS-SD and the comparison over distance for the Suzie sequence are displayed in Figures 4.15 and 4.16, respectively. For Foreman sequence, the results are displayed in Figures 4.17 and 4.18, respectively.

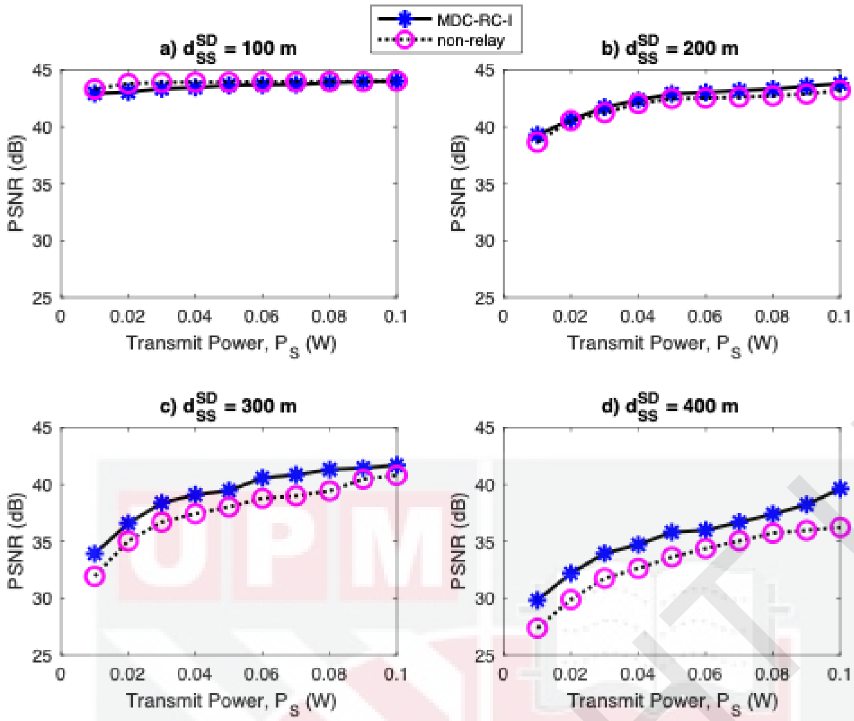


Figure 4.15 : PSNR of MDC-RC-I and Non-relay Network at Variation of SS-SD for Suzie Sequence

Figure 4.15 shows the PSNR performance of MDC-RC-I and a non-relay network for the Suzie sequence at various transmit power levels, P_S and source-to-destination, d_{SS}^{SD} distances. Since greater power levels result in better signal quality and less packet loss, it is seen that PSNR rises with increasing transmit power throughout all subfigures (a–d).

Furthermore, a more noticeable performance difference between MDC-RC-I and the non-relay network is noticeable as the distance between the SS and the SD grows from 100 to 400 meters. The PSNR values for MDC-RC-I and the non-relay technique are almost the same for shorter distances (100m and 200m, subfigures a and b), indicating no improvement with the relay-assisted approach. This is because the direct transmission line is nonetheless comparatively dependable over shorter transmission distances, guaranteeing low packet loss even in the absence of relay help. As a result, under these situations, the relay's contribution to MDC-RC-I is minimal, leaving the two systems barely different.

However, the performance difference between MDC-RC-I and the non-relay scheme grows with increasing distance (300m and 400m, subfigures c and d), especially at lower transmit power levels. This demonstrates how well relay-assisted transmission works to preserve superior video quality across longer distances, where the direct transmission line degrades significantly due to increasing packet errors and path loss. By offering a different path, the relay node helps to minimize these impairments, improving the resilience of video delivery and raising PSNR values in MDC-RC-I relative to the non-relay network.

Even at greater distances, the overall disparity between MDC-RC-I and the non-relay network is still negligible. This is because the Suzie sequence is more immune to packet losses because it contains low-motion material. Furthermore, even in non-relay scenarios, the error concealment features of MDC ensure a gentle deterioration of video quality by compensating for missing data and lessening the impact of packet losses.

Consequently, the relative benefits are low even if MDC-RC-I offers a discernible advantage at larger distances, highlighting the significance of network conditions and content characteristics in influencing the efficacy of relay-assisted transmission in cognitive radio networks. As a function of SS-SD distance for the Suzie sequence, the PSNR performance of MDC-RC-I and a non-relay network is compared in Figure 4.16.

Because of increased route loss, attenuation, and packet mistakes, it is expected that PSNR will drop with increasing distance. The efficacy of relay-assisted transmission in reducing the deterioration brought on by longer communication links is demonstrated by the MDC-RC-I scheme, which routinely outperforms the non-relay network at greater distances. Interestingly, the non-relay network performs better in terms of PSNR at 100 meters than the relay-assisted MDC-RC-I scheme.

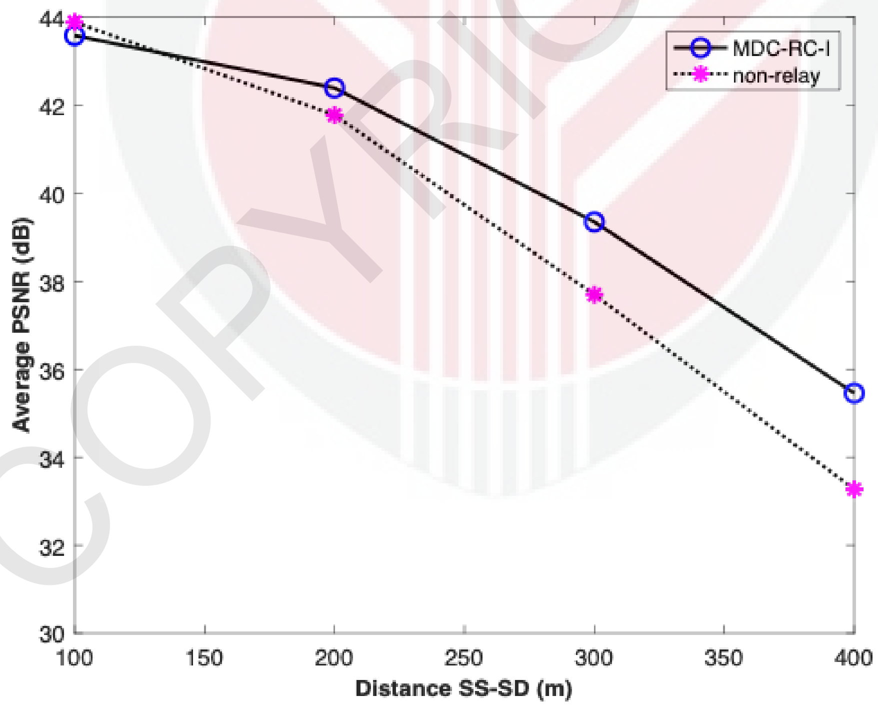


Figure 4.16 : PSNR Performance Comparison over Distance of MDC-RC-I and Non-relay Network for Suzie Sequence

This phenomenon is explained by the extra transmission overhead and possible delays that the relay node in MDC-RC-I introduces. The direct transmission path in the non-relay network is very dependable at a small distance of 100 m, which leads to low packet loss and an effective transmission process. Although relays are helpful over longer distances, they add processing and transmission time to MDC-RC-I, which may cause minor differences in packet arrival times and buffering effects at the receiver. Also, relay-assisted transmission may not yield considerable benefits when the direct link is already substantial due to the additional forwarding involved.

Beyond 100 meters, path loss and signal degradation have a greater effect on the non-relay network, which causes the PSNR to drop more precipitously. On the other hand, MDC-RC-I maintains a more progressive fall since the relay may compensate for the higher losses in the direct connection by offering an alternate communication path. The benefit of employing relay-assisted transmission for video streaming in cognitive radio networks is further supported by the fact that the MDC-RC-I network continuously outperforms the non-relay scheme at longer distances. The PSNR performance of the non-relay network and MDC- RC-I over various SS-SD distances for the Foreman sequence, taking into account changes in transmit power, is shown in Figure 4.17.

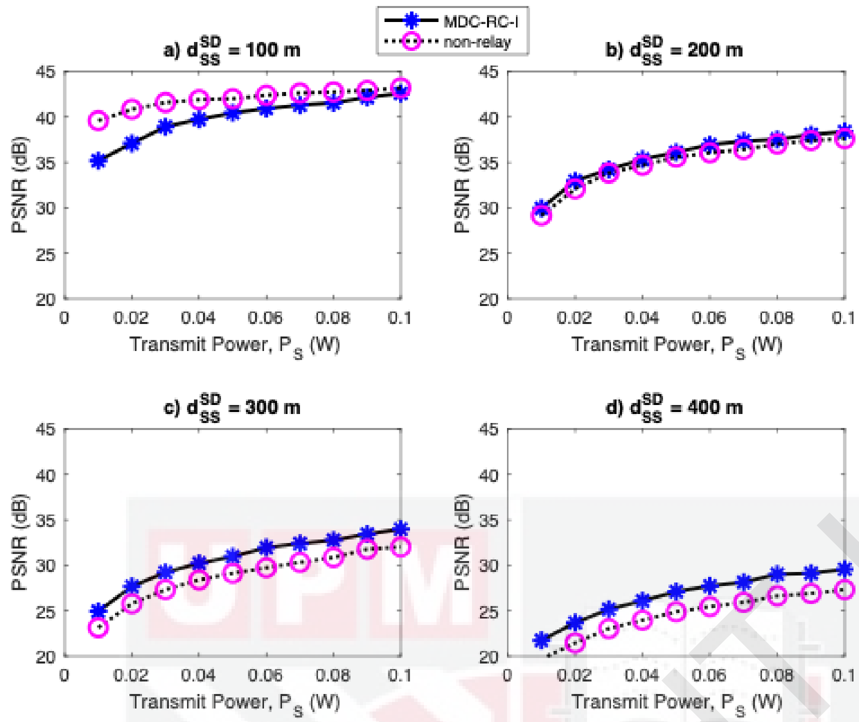


Figure 4.17 : PSNR of MDC-RC-I and Non-relay Network at Variation of SS-SD for Foreman Sequence

The overall pattern indicates that for both methods, the PSNR improves as the transmit power rises. This makes sense because more transmission power improves the quality of the received signal, lowers packet loss, and improves the quality of the decoded video. Additionally, because route loss and attenuation have a stronger impact on video transmission dependability, a decrease in PSNR is seen when the SS-SD distance grows.

The slight PSNR difference between the MDC-RC-I and the non-relay network, especially at shorter ranges like 100 and 200 meters, is one of the main findings of this study. Both transmission techniques operate similarly at these distances because the direct link between the source and the destination is still strong. Because the direct transmission line is already dependable and eliminates the need for an extra forwarding node, the relay in MDC-RC-I does not substantially improve performance.

This is consistent with the hypothesis that relay-assisted transmission offers more pronounced benefits in situations with greater transmission defects. The MDC-RC-I scheme shows a slight advantage over the non-relay network as the distance climbs to 300 and 400 meters. The relay node in MDC-RC-I helps maintain better transmission quality by providing an alternate path with stronger signal strength, whereas direct transmission experiences higher packet loss and more mistakes at longer distances. Nonetheless, the disparity is still negligible, indicating that the Foreman sequence is resilient to packet loss, most likely due to its more straightforward motion than other video sequences.

The same performance seen between the two methods across various power levels results from the redundancy that multiple description coding adds, which also lessens the impact of transmission faults. When transmitting the Foreman sequence, the average PSNR performance for both the MDC-RC-I and non-relay networks as a function of SS-SD distance is shown in Figure 4.18. As anticipated, when the SS-SD distance grows, the PSNR performance deteriorates. This is because increased route loss and attenuation affect the received signal quality. By employing relay-assisted transmission, the MDC-RC-I scheme continuously outperforms the non-relay network across greater distances, proving its efficacy in reducing the negative impacts of signal deterioration.

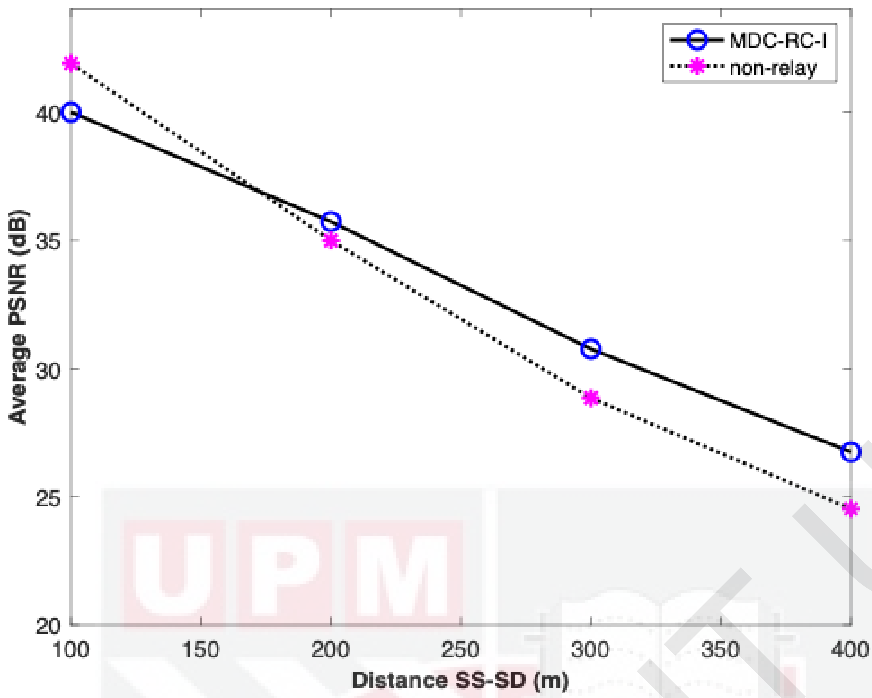


Figure 4.18 : PSNR Performance Comparison over Distance of MDC-RC-I and Non-relay Network for Foreman Sequence

The data shows that, for a short SS-SD distance of 100 meters, the non-relay network performs better in terms of PSNR than the MDC-RC-I scheme. At close range, the signal maintains its strength, guaranteeing flawless transmission quality free from distortion or interference. In the relay-assisted situation, adding a second transmission hop could result in processing delays, increased relay node noise, and possible packet buffering, all of which could lower PSNR performance. The benefits of relay aid are not entirely realized since the direct transmission line is already dependable at this short distance; instead, the additional relay processing overhead has a minor negative influence on the overall quality of the video. The performance trend moves toward MDC-RC-I as the SS-SD distance rises because the relay node offers a backup link, contributing to a more dependable transmission.

The relay-assisted method is more advantageous because the direct transmission path's signal deterioration increases with distance. The growing performance difference between the two methods at 300 and 400 meter ranges, where MDC-RC-I maintains a higher PSNR because of enhanced link dependability, makes this clear. In difficult wireless situations where direct transmission suffers from higher attenuation and packet loss, the results show that relay-assisted transmission becomes more helpful as the transmission distance increases, even though it may not be advantageous at short distances.

Compared to the non-relay network, the PSNR using MDC-RC-I improves by 9% for the Foreman sequence and 6% for the Suzie sequence. The average PSNR values in dB are compared in Table 4.6.

Table 4.6 : Average PSNR of MDC-RC-I and Non-relay Network

d_{SS}^{SD} (m)	Suzie - PSNR (dB)		Foreman - PSNR (dB)	
	MDC-RC-I	non-relay	MDC-RC-I	non-relay
100	43.5817	43.8850	39.9949	41.8925
200	42.3906	41.7747	35.6888	34.9924
300	39.3468	37.6940	30.7593	28.8531
400	35.4540	33.2717	26.7436	24.5303

The findings indicate that a network with relay assistance performs better than a network without a relay. Signal degradation occurs with large-scale transmission because data efficiency declines as SS and SD are separated by more distance. It is possible to achieve better transmission quality and sufficient signal coverage by having a relay in the center.

Even with a slight improvement, the MDC-RC-I remains favorable since it ensures that at least one description is received through the relay link when the direct path experiences an outage. This redundancy boosts the reliability of video transmission, preventing a complete loss of information.

The video performance also compared the MDC-RC-I with the system that applied the SDC approach. The algorithm used for SDC is as in [8]. The odd and even frames transmitted over the direct path are contained in the single description for SDC. Figures 4.19 and 4.20 show the PSNR results of MDC-RC-I and SDC at variations of SS-SD and the PSNR performance over distance, respectively for Suzie sequence and for Foreman sequence, the results shown in Figure 4.21 and 4.22 The results reveal that the MDC-RC-I outperformed SDC by 4% and 2% improvement for the Suzie and Foreman sequences, respectively. Even with a slight improvement, the MDC-RC-I still benefits from getting the description via a relay path compared to just one description transmitted over a single path if an outage happens in the direct path. The PSNR in dB for both sequences are summarized in Table 4.7.

Table 4.7 : Average PSNR of MDC-RC-I and SDC

d_{SS}^{SD} (m)	Suzie - PSNR (dB)		Foreman - PSNR (dB)	
	MDC-RC-I	SDC	MDC-RC-I	SDC
100	43.5817	43.9412	39.9942	43.5050
200	42.3906	42.2720	35.6888	36.7810
300	39.3468	38.5089	30.7593	30.7525
400	35.4540	34.0973	26.7436	26.1736

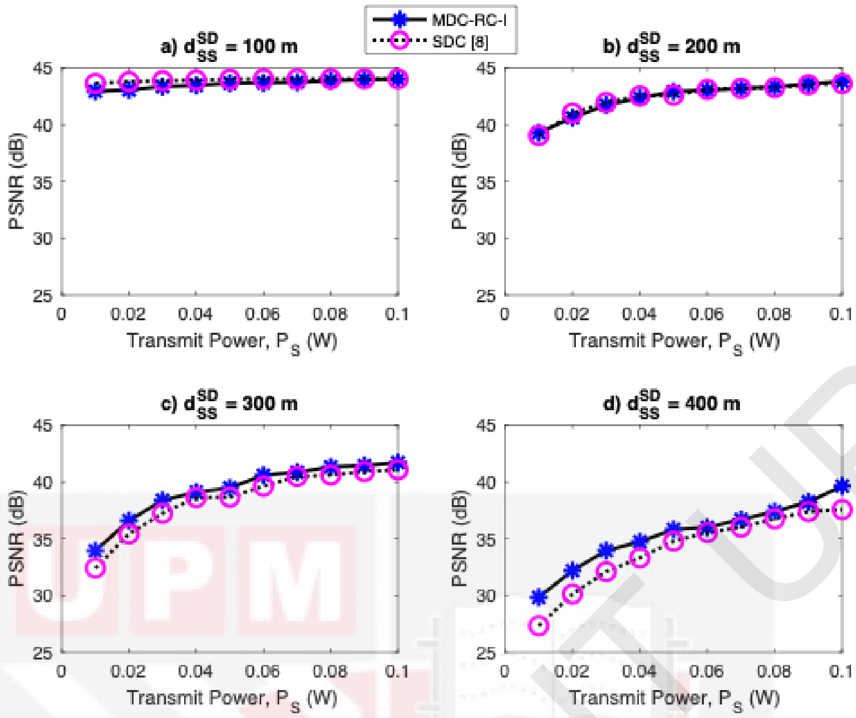


Figure 4.19 : PSNR of MDC-RC-I and SDC at Variation of SS-SD for Suzie Sequence

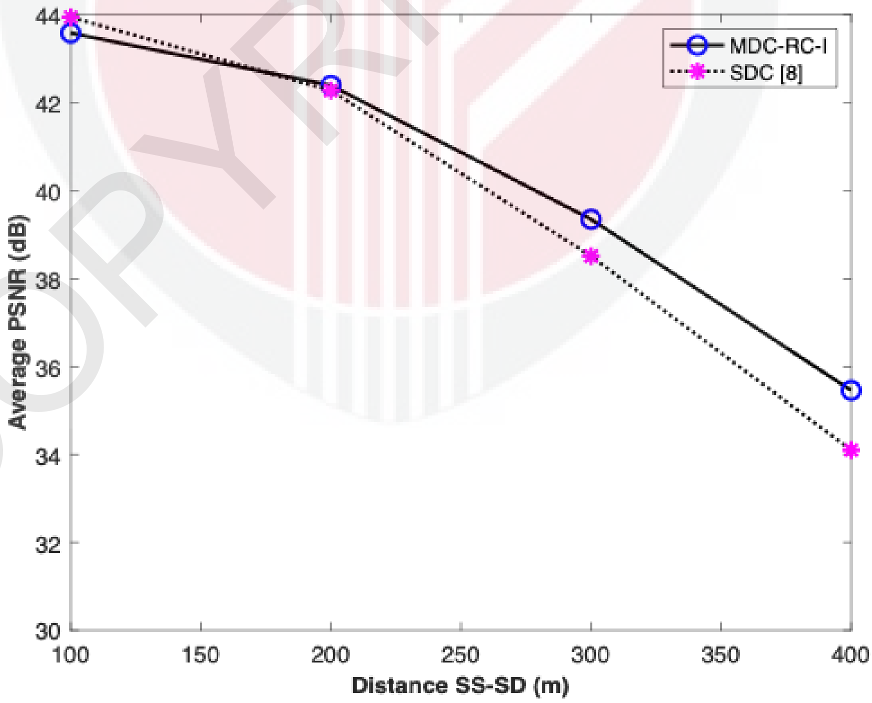


Figure 4.20 : PSNR Performance Comparison over Distance of MDC-RC-I and SDC for Suzie Sequence

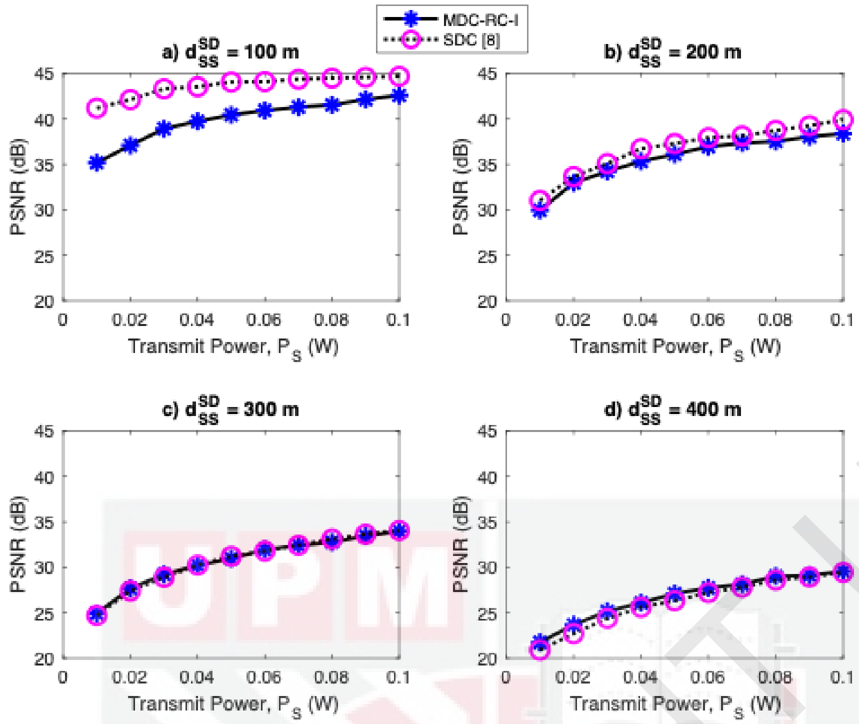


Figure 4.21 : PSNR of MDC-RC-I and SDC at Variation of SS-SD for Foreman Sequence

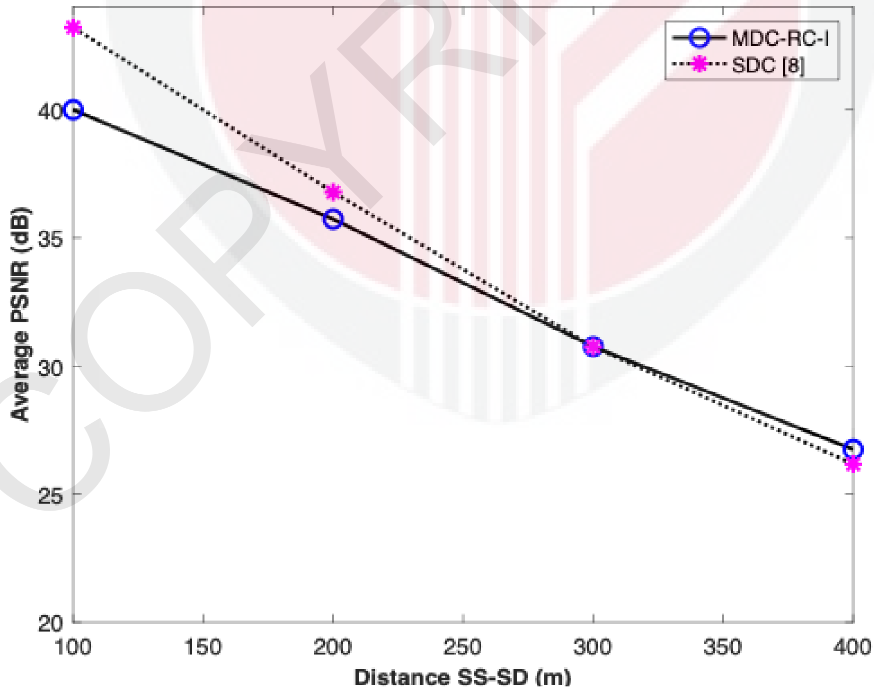


Figure 4.22 : PSNR Performance Comparison over Distance of MDC-RC-I and SDC for Foreman Sequence

4.3 Performance Evaluation for MDC-RC-U in Underlay CR Networks

This section presents the timeout and video performance for proposed MDC-RC-U system model shown in Figure 3.9. The proposed MDC-RC-U system is based on the underlay mode of CR networks. The timeout probability expression is derived, and the measured probability is used to analyze the received video quality. The timeout performance will be compared to the non-relay network and the video quality is then compared to the SDC technique.

4.3.1 Simulation Parameters for Underlay mode of CR Networks

In underlay mode of CR network, the SU is co-existed with the PU. The SS and SR in secondary network are subjected to transmit under peak power transmit to avoid interference to the PU. The transmission performance of the SU via MDC-RC-U will consider the interference from the PU. The PU interference in the proposed MDC-RC-U system model is assumed comes from the primary source, PS. Table 4.8 shows the simulation parameter values as in used in the first set of simulation results to measure the timeout probability of MDC-RC-U system.

Table 4.8 : Simulation Parameter of MDC-RC-U System for Underlay Mode of CR

Parameters	Value
Path loss exponent, α	4 [137]
Noise variance, N_0	1 [137]
Transmit power of SS, P_S	1 W to 10 W
Transmit power of SR, P_R	1 W to 10 W
Transmit power of PS, P_P	10 W
Peak transmit power of SS, P_S^{peak}	7 W
Peak transmit power of SR, P_R^{peak}	7 W
Channel mean power of SS-SR, SR- SD and SS-SD, Ω_{SS}^{SR}, Ω_{SR}^{SD} and Ω_{SS}^{SD}	2
Channel mean power of PS-SR and PS-SD, Ω_{PS}^{SR} and Ω_{PS}^{SD}	1, 2 and 3
Bandwidth, W	5 MHz [137]
Threshold time of SU, t_{thr}	2 ms

4.3.2 Timeout Performance

In this subsection, we analyze the timeout performance of the MDC-RC-U systems in the underlay mode of CR networks. The timeout probability results are plotted at different channel mean power. From the observation of Figure 4.23, decreasing the channel mean power leads to a decrease in the timeout probability. While increasing the SS transmit power will improve the timeout probability. Figure 4.24 compares the timeout performance of MDC-RC-U with non-relay model. As expected, the MDC-RC-U model improves the timeout performance by 6%.

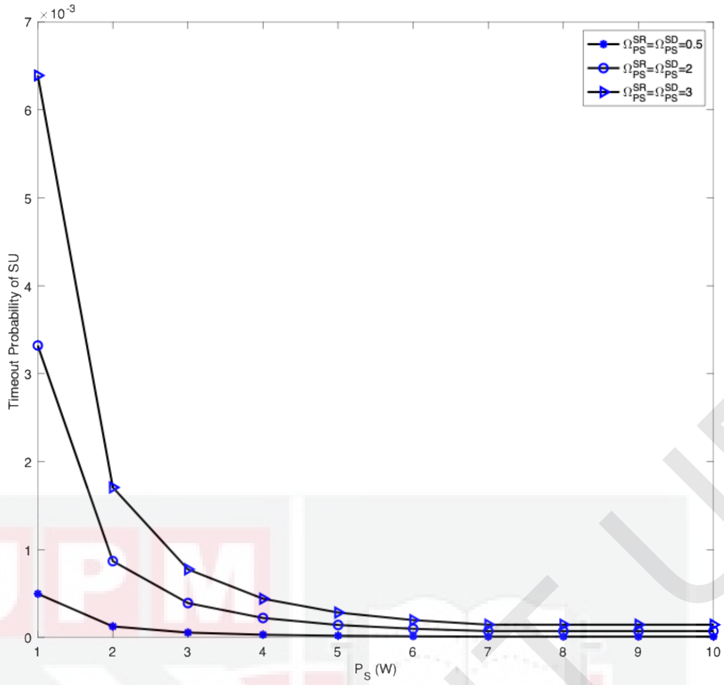


Figure 4.23 : MDC-RC-U Timeout Performance for Different Channel Mean Power

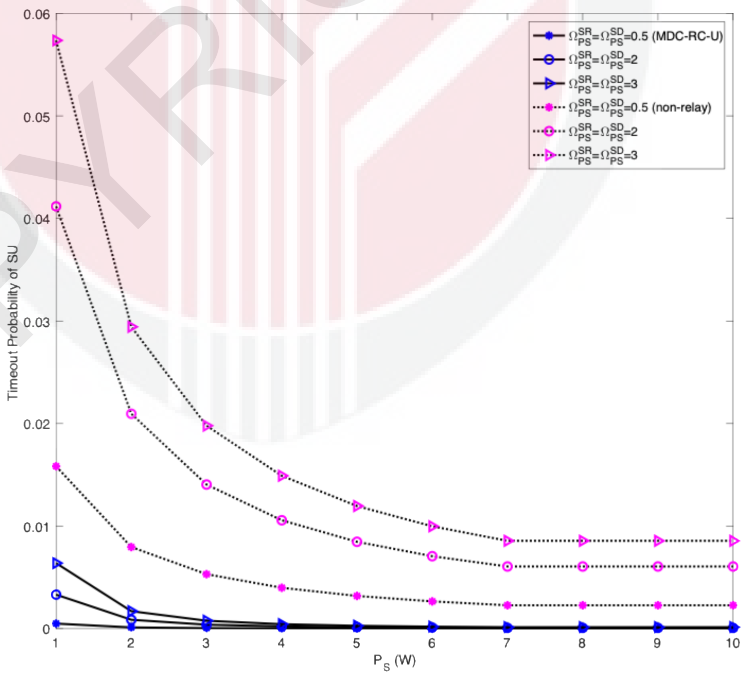


Figure 4.24 : Comparing Timeout Performance of MDC-RC-U and Non-relay Network at a Different Channel Mean Power

4.3.3 Video Quality Based on Timeout Performance

A simulation and analysis results of PSNR performance using different channel mean power of PU interference link towards SR and SD, Ω_{PS}^{SR} and Ω_{PS}^{SD} for MDC-RC-U is presented in this subsection. Figures 4.25 and 4.26 show the PSNR of the decoded Suzie sequence for scenario A and B, respectively. While for Foreman sequence, the results are shown in Figures 4.27 and 4.28. According to the trends, the overall PSNR rises as the transmit power rises because of improved connection quality, which lowers packet losses and improves the quality of the received video. Because it has more redundancy and better error tolerance than the 1D Odd and 1D Even schemes, the 2D transmission system maintains a higher PSNR. However, after a certain transmit power level, the PSNR improvement becomes negligible, indicating a saturation effect where the underlying channel impairments prevent further power increases from yielding appreciable benefits.

Figure 4.26(c) shows a noticeable decrease in PSNR for the 2D system, which is caused by the combined effects of timeout probability and channel mean power. While overall transmission reliability improves with increasing channel mean power, the likelihood of excessive delays from retransmissions also increases. When channel conditions change, the timeout probability, a measure of the chance that a packet will surpass its delay threshold, becomes more noticeable. Both descriptions are essential for high-quality reconstruction in the case of the 2D scheme. The adequate received quality drastically deteriorates, and the PSNR drops if one description is delayed over the tolerable threshold due to retransmissions or deep fading.

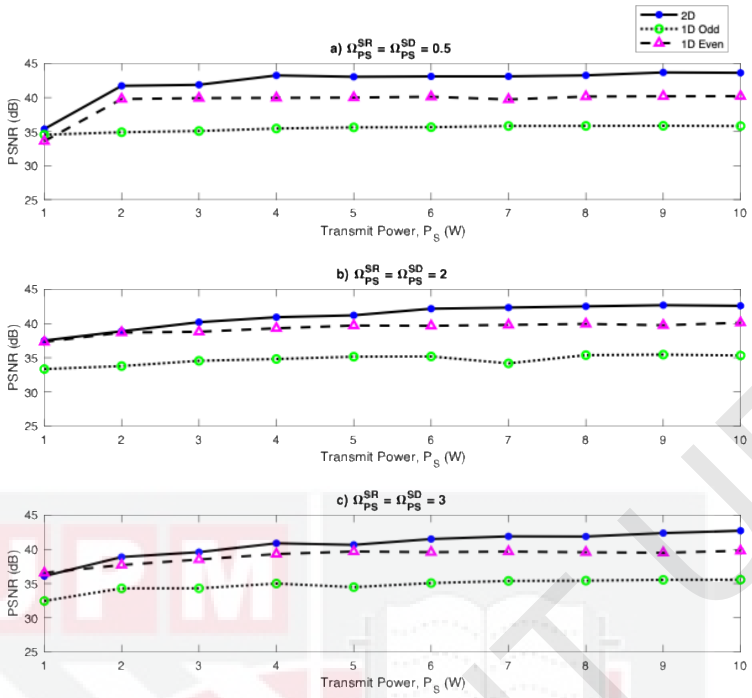


Figure 4.25 : MDC-RC-U PSNR Performance of Suzie Sequence at a Different Channel Mean Power for Scenario A

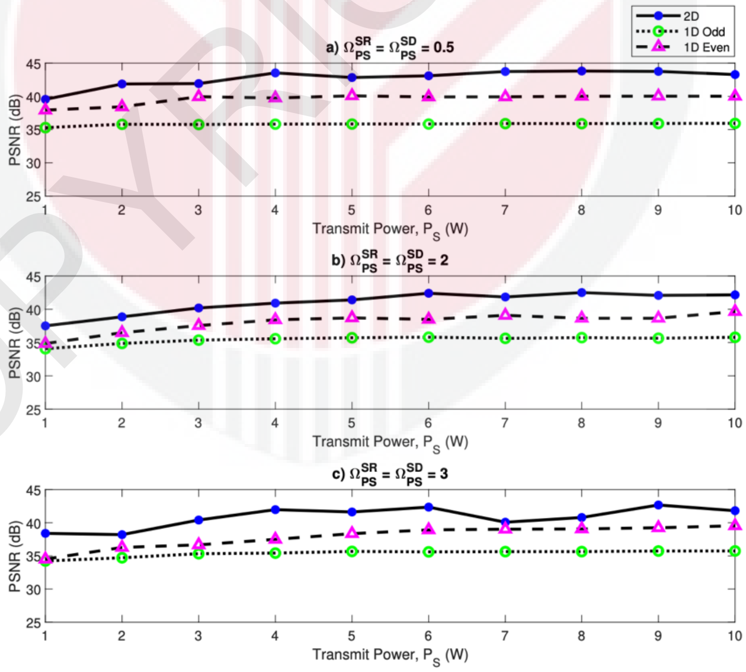


Figure 4.26 : MDC-RC-U PSNR Performance of Suzie Sequence at a Different Channel Mean Power for Scenario B

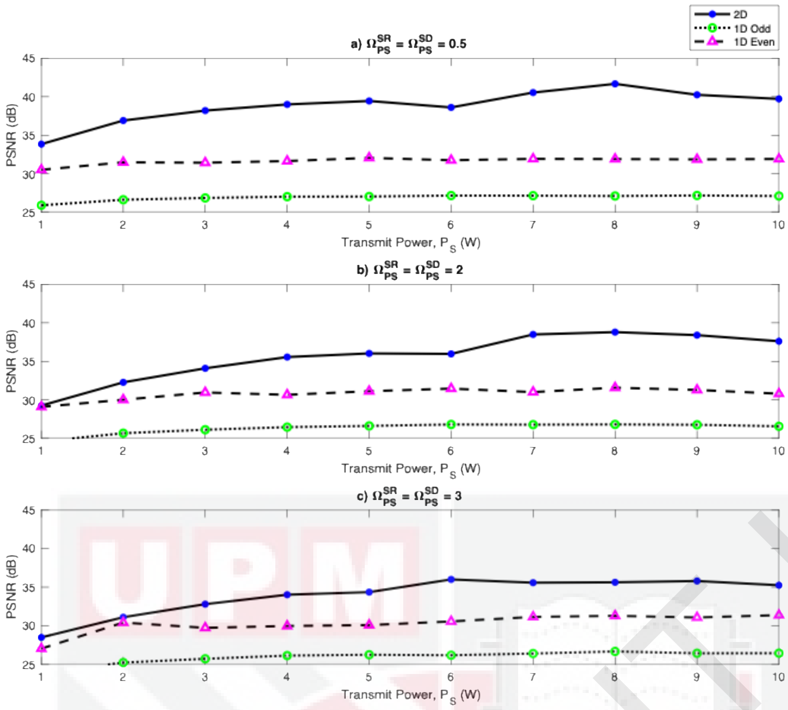


Figure 4.27 : MDC-RC-U PSNR Performance of Foreman Sequence at a Different Channel Mean Power for Scenario A

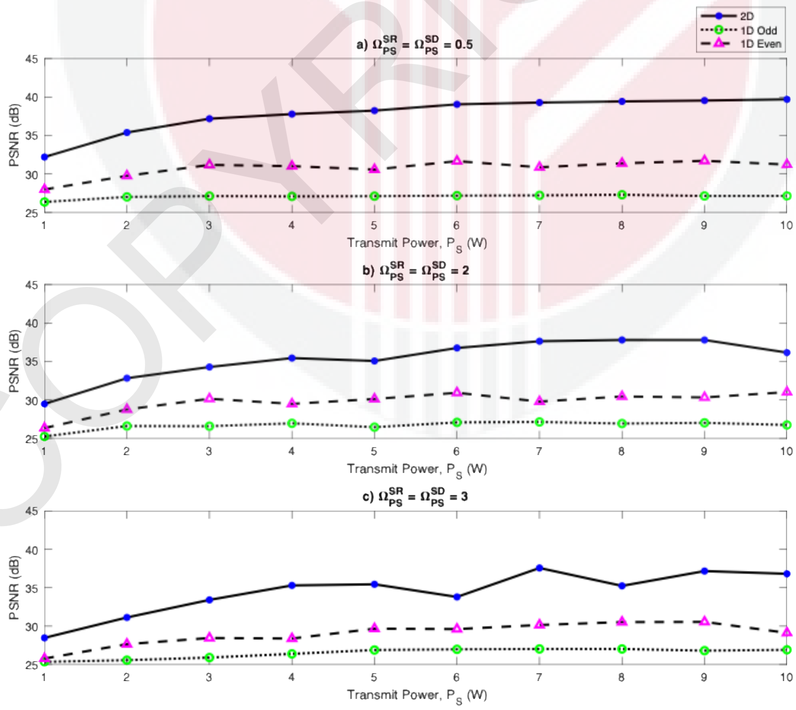
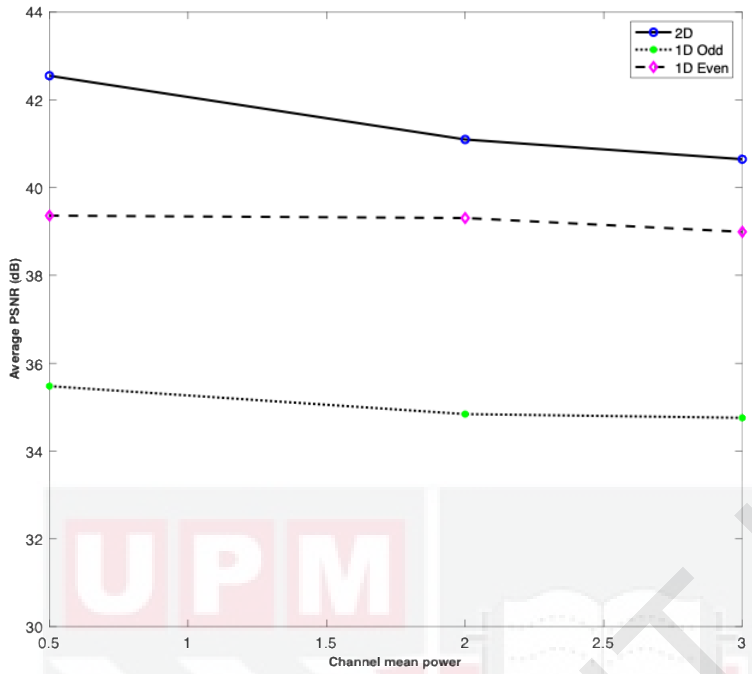


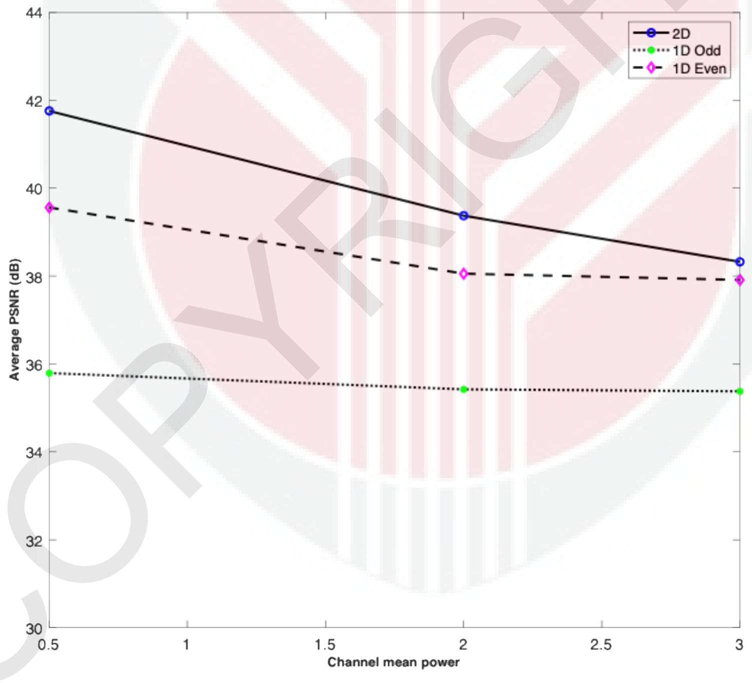
Figure 4.28 : MDC-RC-U PSNR Performance of Foreman Sequence at a Different Channel Mean Power for Scenario B

The trade-off between delay limitations and dependability becomes crucial in high channel mean power settings, intensifying this effect. The findings highlight how crucial it is to balance timeout restrictions and power distribution in relay-assisted networks to preserve video quality under various channel situations. The findings also indicate that the PSNR of the reconstructed and interpolated decoded sequence reflecting both descriptions (2D) and one description (1D even or 1D odd) received and measured for Scenario A and Scenario B as shown in Figure 4.1. The acceptable video quality was produced if the receiver received one description, a set of even or odd frames when either the relay or direct path failed. The video quality will improve if both descriptions are obtained at the location. The overall PSNR performance comparison over channel mean power for 2D and 1D are shown in Figures 4.29 and 4.30 for Suzie and Foreman sequences, respectively.

The average PSNR of the Suzie and Foreman sequences from 10 trials for scenario A and scenario B are shown in Tables 4.9 and 4.10, respectively. The overall average PSNR increased by 17% for the Suzie sequence and 31% for the Foreman sequence at the different channel mean power when both descriptions received as opposed to receiving just one. The highest increment of PSNR is 7 dB for Suzie and 12 dB for Foreman at Ω_{PS}^{SR} = Ω_{PS}^{SD} = 0.5. It can be observed that, the PSNR value dropped as channel mean power increase.

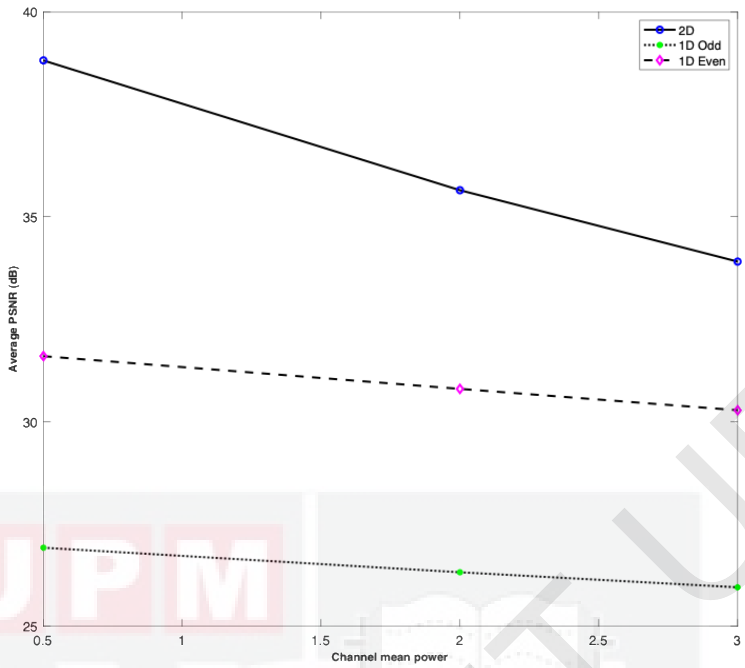


a) **PSNR comparison for Scenario A**

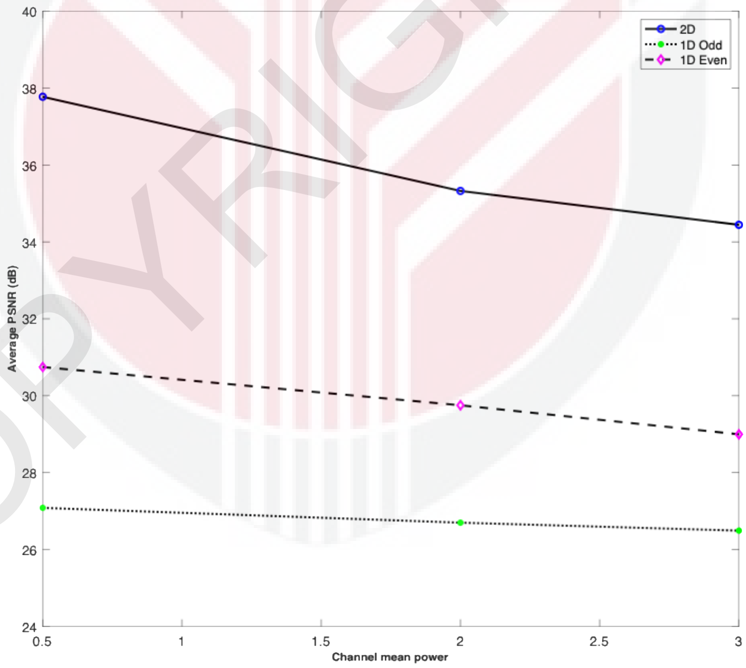


b) **PSNR comparison for Scenario B**

Figure 4.29 : PSNR Performance Comparison over Different Channel Mean Power of MDC-RC-U for Suzie Sequence



a) PSNR comparison for Scenario A



a. PSNR comparison for Scenario B

Figure 4.30 : PSNR Performance Comparison over Different Channel Mean Power of MDC-RC-U for Foreman Sequence

Table 4.9 : Average PSNR of MDC-RC-U at Different Channel Mean Power for Scenario A

$\Omega_{PS}^{SR} = \Omega_{PS}^{SD}$	Suzie - PSNR (dB)			Foreman - PSNR (dB)		
	2D received	1D odd received	1D even received	2D received	1D odd received	1D even received
0.5	42.5462	35.4789	39.3603	38.8152	26.9193	331.5950
2	41.0944	34.8419	39.3060	35.6457	26.3200	30.7964
3	40.6448	34.757	38.9908	33.9033	25.9526	30.2753

Table 4.10 : Average PSNR of MDC-RC-U At Different Channel Mean Power for Scenario B

$\Omega_{PS}^{SR} = \Omega_{PS}^{SD}$	Suzie - PSNR (dB)			Foreman - PSNR (dB)		
	2D received	1D odd received	1D even received	2D received	1D odd received	1D even received
0.5	42.5462	35.4789	39.3603	38.8152	26.9193	331.5950
2	41.0944	34.8419	39.3060	35.6457	26.3200	30.7964
3	40.6448	34.757	38.9908	33.9033	25.9526	30.2753

The PSNR of the MDC-RC-U was then compared with the non-relay network. The odd and even frames are interleaved and sent over a direct path in a non-relay network. The results of the PSNR for the Suzie sequence are displayed in Figure 4.31 and the PSNR performance comparison over channel mean power is shown in Figure 4.32. For Foreman sequence, the results are displayed in Figures 4.33 and 4.34.

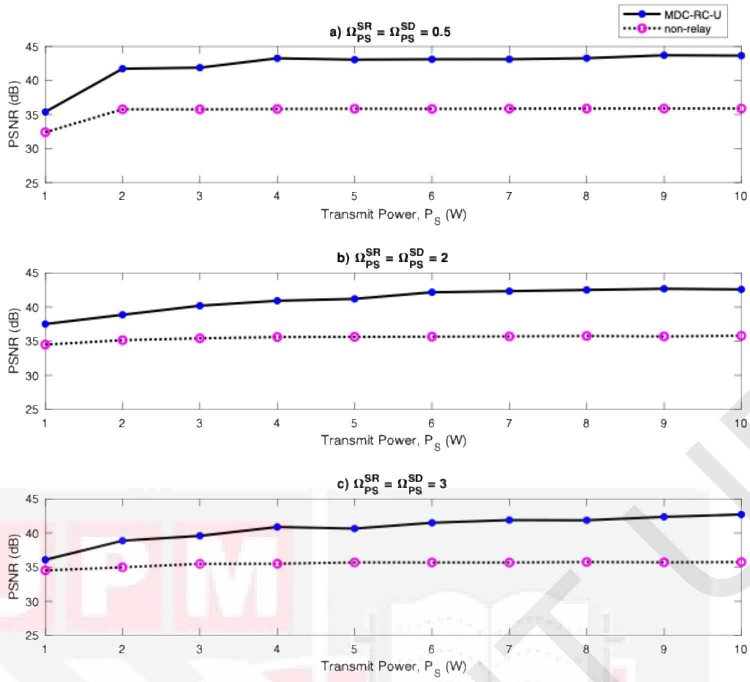


Figure 4.31 : PSNR of MDC-RC-U and Non-relay Network at a Different Channel Mean Power for Suzie Sequence

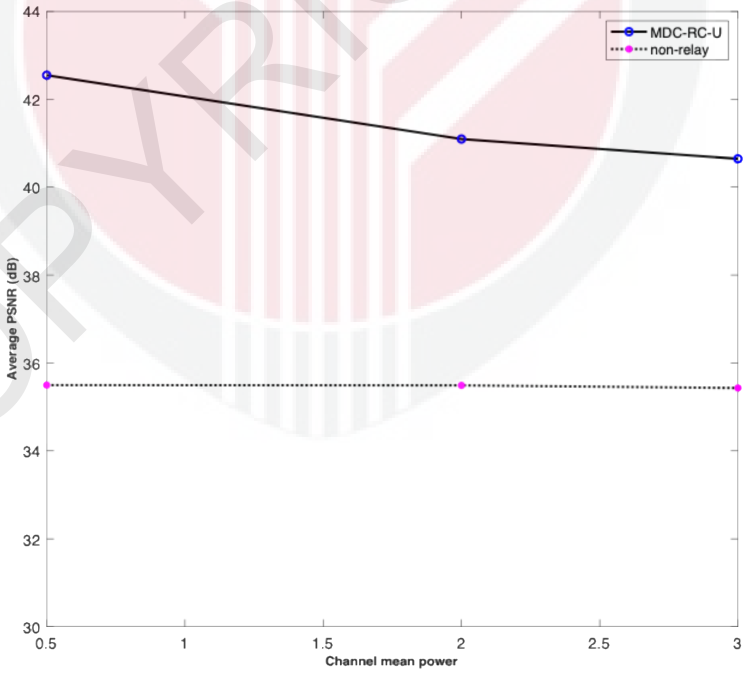


Figure 4.32 : PSNR Performance Comparison over Different Channel Mean Power of MDC-RC-U and Non-relay Network for Suzie Sequence

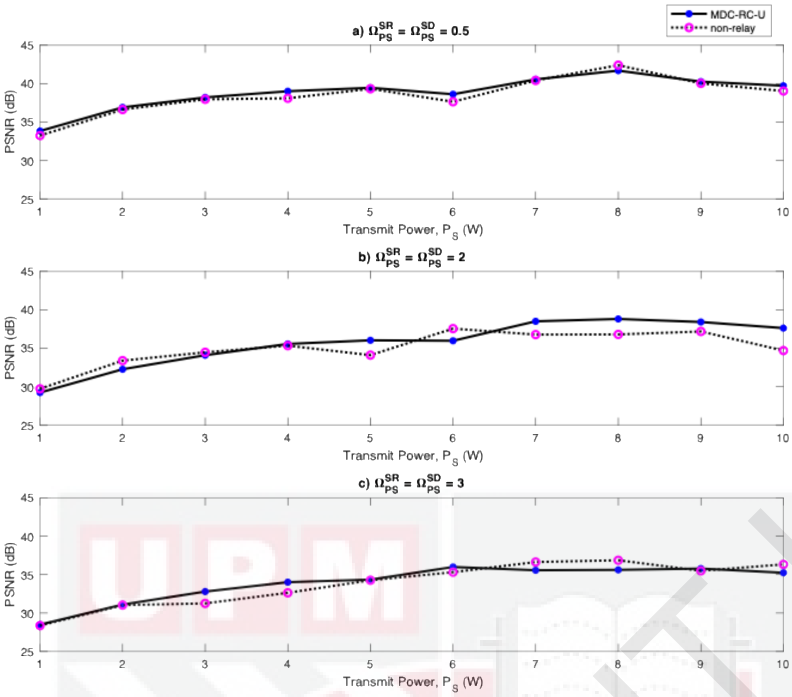


Figure 4.33 : PSNR of MDC-RC-U and Non-relay Network at a Different Channel Mean Power for Foreman Sequence

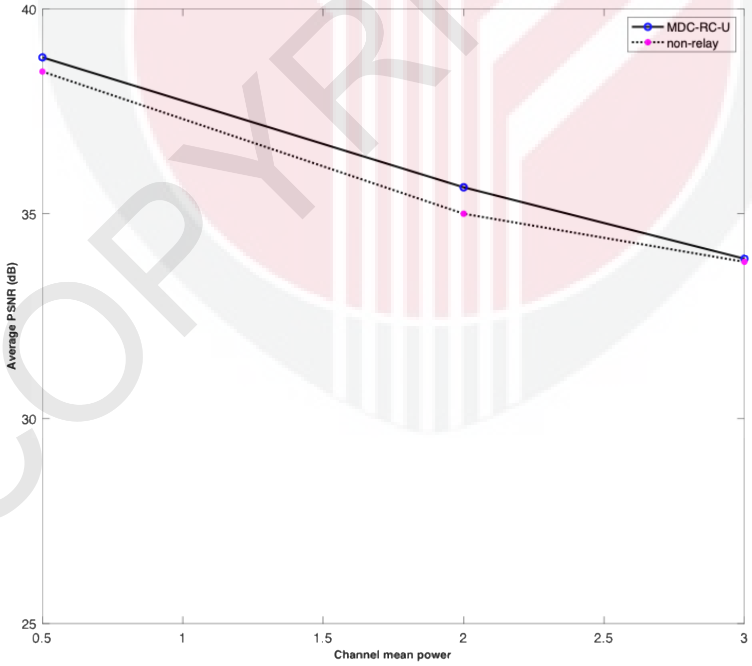


Figure 4.34 : PSNR Performance Comparison over Different Channel Mean Power of MDC-RC-U and Non-relay Network for Foreman Sequence

As can be seen, Figure 4.33 shows that PSNR values rise with increasing transmit power levels. Because the Foreman segment has comparatively fewer high-motion moments and less intricate spatial information than the Suzie sequence, the two approaches have little performance difference. The advantages of relay-assisted transmission are more noticeable for video sequences with higher motion dynamics because MDC is especially advantageous in situations with high-motion material and sudden scene changes. On the other hand, the relay network's benefit is less noticeable for sequences like Foreman, where motion fluctuations are moderate. Additionally, both transmission methods increase PSNR overall by benefiting from stronger received signals at higher transmit power levels. This effect further reduces the discernible performance difference between relay and non-relay networks.

Figure 4.34 shows that PSNR performance decreases with increasing channel mean power. Higher fading and interference effects linked to higher channel mean power cause this deterioration, which adversely influences the quality of the received signal. The performance gap between the MDC-RC-U and non-relay networks is minimal despite differences in transmit and channel mean power. Additionally, the findings show that the performance trend exhibits a consistent pattern across all tested channel mean power values, indicating that fading effects are felt proportionately in both network architectures. In this instance, the relay node's contribution to performance improvement is less noticeable because it functions under the same channel circumstances as the direct transmission.

These results support the fact that MDC-RC-U's efficacy is strongly influenced by the features of the video sequence and the degree of channel impairments, with more difficult transmission scenarios and intricate video material producing a more pronounced performance boost.

Compared to the non-relay network, the PSNR using MDC-RC-U improves by 15% for the Suzie sequence and 1% for the Foreman sequence. The average PSNR values in dB are compared in Table 4.11. The findings indicate that a network with relay assistance performs better than a network without a relay. Signal degradation occurs with large-scale transmission because data efficiency declines as SS and SD are separated without any power boosting in between. It is possible to achieve better transmission quality and sufficient signal coverage by having a relay in the center.

Table 4.11 : Average PSNR of MDC-RC-U and Non-relay Network at Different Channel Mean Power

$\Omega_{PS}^{SR} = \Omega_{PS}^{SD}$	Suzie - PSNR (dB)		Foreman - PSNR (dB)	
	MDC-RC-U	non-relay	MDC-RC-U	non-relay
0.5	42.5462	35.4960	38.8152	38.4686
2	41.0944	35.4903	35.6457	35.0006
3	40.6448	35.4305	33.9033	33.8258

Finally, the video performance of the MDC-RC-U is compared with the SDC technique in [127]. Figures 4.35 and 4.36 show the PSNR results and the PSNR performance com parison over channel mean power, respectively, for the Suzie sequence. While for the Foreman sequence, the results are shown in Figures 4.37 and 4.38. As the signal intensity is increased, Figures 4.35 and 4.37 shows that the PSNR values rise with transmit power, indicating better video quality. However, the difference between MDC-RC-U and SDC was not significant in every tested case. Both transmission systems show a progressive drop in PSNR as the channel mean power rises in Figures 4.36 and 4.38, where the PSNR is assessed across a range of channel mean power values. The increased influence of noise and fading explains this.

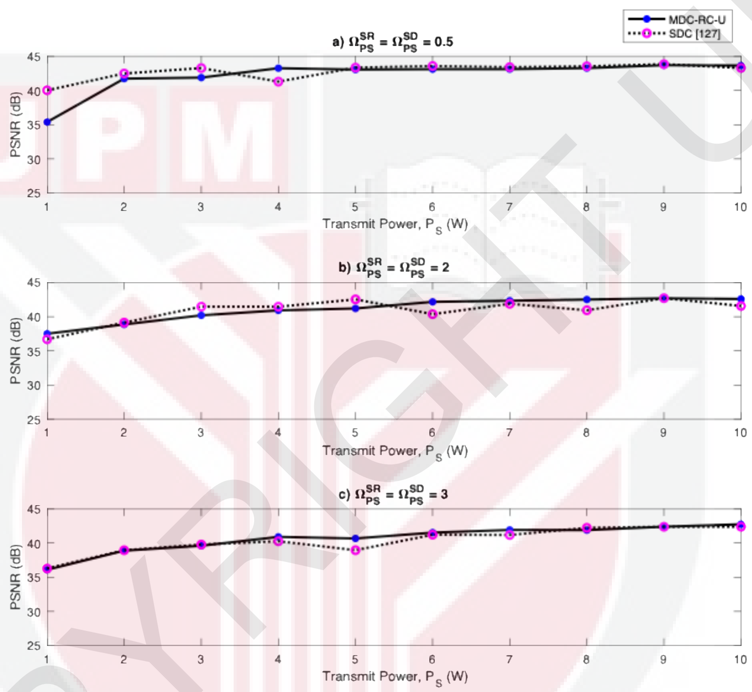


Figure 4.35 : PSNR of MDC-RC-U and SDC at a Different Channel Mean Power for Suzie Sequence

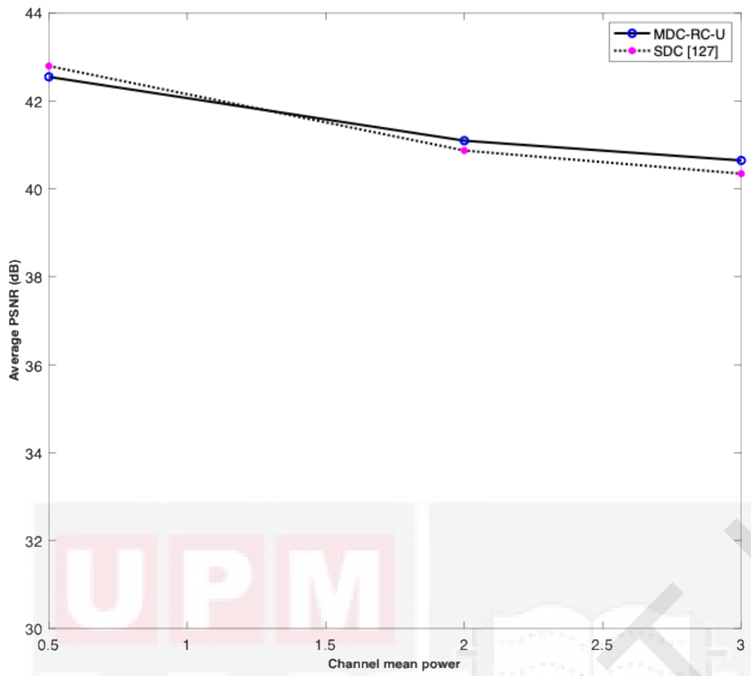


Figure 4.36 : PSNR Performance Comparison over Different Channel Mean Power of MDC-RC-U and SDC for Suzie Sequence

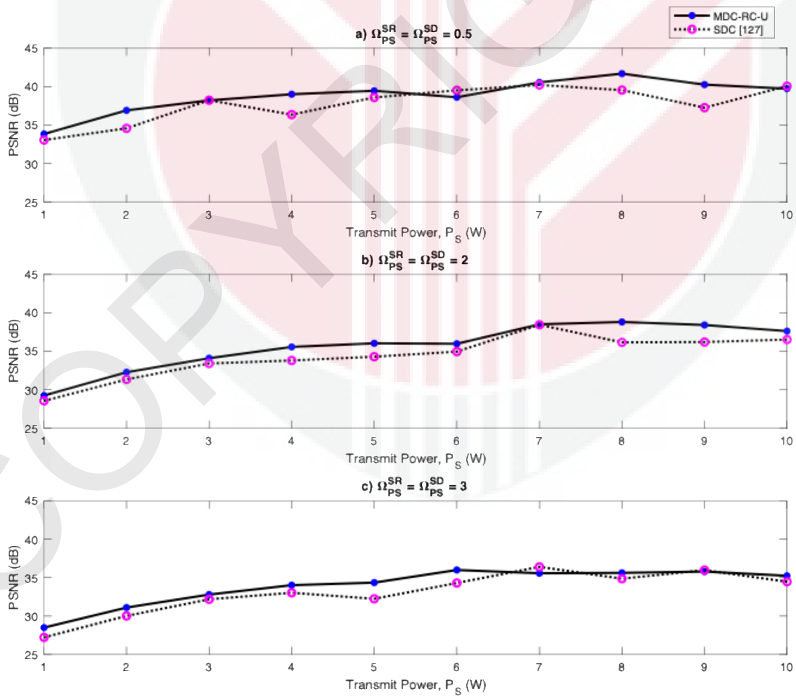


Figure 4.37 : PSNR of MDC-RC-U and SDC at a Different Channel Mean Power for Foreman Sequence

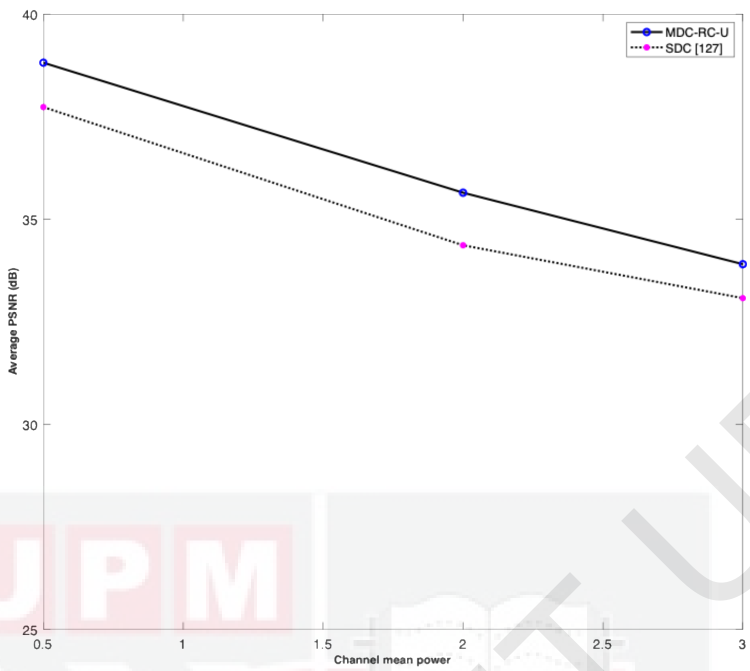


Figure 4.38 : PSNR Performance Comparison over Different Channel Mean Power of MDC-RC-U and SDC for Foreman Sequence

The results indicate that the MDC-RC-U outperformed SDC by 0.2% and 3% improvement for the Suzie and Foreman sequences, respectively. The PSNR in dB is summarized in Table 4.12. Even with the slight improvement compared to SDC, The MDC-RC-U still benefits from getting the description from one path if the other path fails, compared to a single description transmitted over a single path. On the other hand, in future works, the MDC can be applied to the Scalable Video Coding (SVC) scheme, which offers several layers of description at various resolutions or quality levels. Higher resolution can improve the video quality received at the receiver.

The features of the Suzie sequence account for the smallest variation between MDC-RC-U and SDC. Most of the material in this sequence is low-motion, where MDC's ability to reduce packet losses is less important. The Suzie sequence does not significantly deteriorate with network impairments, unlike high-motion sequences, where MDC offers improved robustness against frame loss and motion abnormalities. As a result, MDC-RC-U offers less of an advantage over SDC. Additionally, when transmit power increases, the signal intensities of both transmission systems get stronger, leading to a convergence in performance. Low-motion video scenarios already benefit from SDC's effectiveness. The benefit of MDC-RC-U is, therefore, minimal. The trend indicates that network conditions and video properties should be considered when selecting a transmission strategy. While the benefits of MDC become increasingly apparent in high-motion video broadcasts, its complexity may not offer a significant advantage over SDC for low-motion sequences like Suzie.

Table 4.12 : Average PSNR of MDC-RC-U and SDC at Different Channel Mean Power

$\Omega_{PS}^{SR} = \Omega_{PS}^{SD}$	Suzie - PSNR (dB)		Foreman - PSNR (dB)	
	MDC-RC-U	SDC	MDC-RC-U	SDC
0.5	42.5462	42.7924	38.8152	37.7336
2	41.0944	40.8705	35.6457	34.3648
3	40.6448	40.3446	33.9033	33.0759

4.4 Summary

This chapter demonstrated the simulation results by providing the performance evaluation of the outage, timeout and video quality for the proposed MDC-RC system. The improvement percentage is calculated based on the average difference between the results of the comparison techniques. First, the efficiency of the proposed MDC-RC systems to improve the error resilience by exploiting the path diversity is assessed and validated. The results presented considers the packet loss rate condition to measure the robustness performance.

The results indicate that receiving two descriptions instead of one in a no-packet-loss scenario significantly improves performance by 20% and 45% for the Suzie and Foreman sequences, respectively. The high motion complexity, where more descriptions provide more detailed information, is the reason for this notable improvement, especially for the Foreman sequence, which improves reconstruction quality. On the other hand, the Suzie sequence, which has less motion complexity, gains less from the extra description because the impact of missing data is lessened because of the small frame-to-frame fluctuations.

Under packet loss conditions, the performance gain when receiving two descriptions is lower, with improvements of 10% for Suzie and 13% for Foreman. This implies that although several descriptions aid in reducing losses, the degree of duplication they contribute limits their success. Because of its many scene changes, the Foreman sequence is still more susceptible to missing packets, which explains why it still gains more from an extra description. However, the smaller improvement compared to the no-loss scenario highlights that network impairments still degrade quality despite the advantages of MDC. When compared to MDC-RC, SDC performs slightly better in a no-loss environment, with a marginal improvement of 0.2% for Suzie and 3% for Foreman. This is due to SDC's higher compression efficiency, which avoids redundancy and maintains quality when all packets are received correctly. However, MDC-RC demonstrates significant improvements under packet loss conditions over SDC, with a 12% gain for Suzie and a 15% gain for Foreman. This demonstrates how resilient MDC-RC is in lossy settings, where its capacity to split up video data among several pathways guarantees a more dependable transmission. These results confirm that MDC-RC is a better option for error prone networks with greater packet loss rates, guaranteeing more consistent video quality.

Secondly, the results of the outage performance for the proposed model, MDC-RC-I were investigated. The performance evaluation considered the proposed system model under interweave mode of CR networks and the probability derived in chapter 3 for MDC-RC-I and non-relay system models. The effects of the different distance of SS to SD and the different ρ values have been considered in analyzing the outage performance. The results show that the MDC-RC-I scheme is beneficial in increasing transmission reliability and improving outage probability by 9% compared to a non-relay network. This is due to the relay-assisted technique, which offers an extra transmission path and lowers the possibility of total signal loss. An outage occurs in a non-relay system when there is severe interference or deep fading in the direct link, which drastically lowers the quality of the video.

However, if the direct path fails, the relay node in MDC-RC-I ensures that some data is still received. By strengthening the signal, a higher transmit power frequently reduces the chance of an outage; nevertheless, excessive power consumption can lead to interference and energy waste. Therefore, MDC-RC-I helps to optimize this trade-off by using the relay to maintain enhanced performance even at moderate transmit power levels. Since frequent outages lead to missing data, frame freezes, and decreased video quality, the effect of outage probability on video performance is also investigated. The findings demonstrate that MDC-RC-I offers a more robust transmission system than non-relay networks, especially in complex wireless settings, guaranteeing better video quality even during network outages.

From the measurement of the outage probability, the video performance is evaluated. The video quality is analyzed considering the number of descriptions received at the destination. The overall average PSNR increased by 17% for the Suzie sequence and 27% dB for the Foreman sequence at the variations of SS-SD when both descriptions received as opposed to receiving just one. This highlights the role of the number of descriptions in maintaining video quality. When only one description is provided, the video reconstruction is based on insufficient data, which results in a lower PSNR and a loss of visual features. However, if both descriptions are received, the decoder can use them together to recreate the video more precisely, which improves the quality significantly. The video performance of the proposed system is then compared with the non-relay network system and the system with SDC approach [8].

Compared to the non-relay network, the PSNR using MDC-RC-I improves by 6% for the Suzie sequence and 9% for the Foreman sequence. However, the non-relay network achieves better PSNR for short SS-SD distances as the direct transmission remains strong and distortion-free. At short distances, the benefits of relay assistance are limited due to additional processing delays, relay node noise, and buffering, which slightly reduce video quality. MDC-RC-I compensates for signal deterioration over the direct path by offering a dependable backup connection, which makes it more effective as the SS-SD distance rises. This benefit is most apparent at 300 and 400 meters when MDC-RC-I's enhanced connection stability allows it to sustain greater PSNR. According to the results, relay help may not be required for short-range communication. However, it becomes crucial for long-distance transmissions when performance is impacted by attenuation and packet loss.

For the comparison between the MDC-RC-I and SDC, the proposed model outperformed SDC by 4% and 2% improvement for the Suzie and Foreman sequences, respectively. Despite the modest gains, MDC-RC-I enhances outage performance compared to SDC by ensuring that at least one description is received via the relay path when the direct link fails. In SDC, the entire video stream is transmitted over a single path, making it highly susceptible to outages. If the direct link experiences deep fading or signal blockage, SDC suffers a complete loss of video data, leading to severe quality degradation or playback failure.

This chapter further demonstrated the proposed system model, MDC-RC-U simulation results to analyze the timeout performance. The timeout performance evaluation considered the proposed system model under underlay mode of CR networks. In the performance evaluation, the effects of the interference from the PU were investigated. Then, the proposed system performance was compared to the system without a relay. Over a non-relay network, the MDC-RC-U has improved the timeout performance by 6%. By offering a backup data line, the relay-assisted technology greatly improves video transmission reliability by lowering the possibility of prolonged delays brought on by lost or delayed packets. Even under difficult network situations, video data can be reconstructed thanks to the MDC-RC-U technique, which combines several descriptions and uses a relay. The efficacy of this methodology is further supported by the timeout probability-based evaluation of video performance since lower timeout probabilities signify better user experience and higher-quality videos.

Lastly, the video performance based on the timeout performance of the proposed system is evaluated. The same analysis as in the evaluation of the video performance based on outage is presented but at the consideration of the interference effects from the PU. The overall average PSNR increased by 17% for the Suzie sequence and 31% for the Foreman sequence at the different channel mean power when both descriptions received as opposed to receiving just one. Given that the quantity of received descriptions directly impacts the precision of video reconstruction, this demonstrates how well Multiple Description Coding (MDC) improves video quality.

The decoder uses less information to reconstruct the video when just one description is provided, which lowers the visual quality. Nevertheless, the system may integrate the complementary information after receiving both descriptions, producing a more thorough and superior video reconstruction.

Compared to the non-relay network, the PSNR using MDC-RC-U improves by 15% for the Suzie sequence and 1% for the Foreman sequence. The improvement was observed due to the benefit of the relay-assisted system in handling packet losses and transmission delays. Furthermore, the motion complexity of the video material and the secondary transmission path's efficiency determine how well relay help works. For the comparison between the MDC-RC-U and SDC, the proposed model outperformed SDC by 0.2% and 3% improvement for the Suzie and Foreman sequences, respectively. The trade-offs between motion complexity, compression efficiency, and video transmission redundancy can explain MDC's slight improvement over SDC. On a steady network with low packet loss, MDC's redundancy loses some of its effectiveness despite adding many descriptions to increase error resilience. Because MDC divides the video into multiple descriptions, each description only provides a fraction of the video, which somewhat reduces compression efficiency when compared to SDC, which sends a single, high-quality description.

CHAPTER 5

CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

This thesis examined the video source coding technique, multiple description coding (MDC) approach for video transmission over relay-assisted cognitive radio (CR) networks. The thesis gives an overview of MDC as a tool for error resiliency for video transmission and to exploit the path diversity benefits. Concluding remarks and possible future work recommendations presented in this chapter.

5.1 Conclusion

The original driving force behind the creation of MDC was the requirement for high network reliability in order to enhance the mechanisms for handling outages. An effective method to give transmission networks robustness is to use a multiple path. In relay networks, a relay and direct path were used to accomplish path diversity. By dividing the data between two separate paths, the network's robustness could be increased instead of using only single path. As a result, communication would normally be done with high quality, and when a path failed, the other path would provide uninterrupted communication with a lower but still adequate quality. With this as a direction, this thesis explored the MDC technique approach in relay network to improve the outage and timeout performance also achieving the acceptable video quality.

A new system design named MDC-RC was proposed to improve the video transmission performance. The system architecture is constructed with the application of the MDC source coding technique at the video encoder and decoder.

Starting with the design of the proposed relay-assisted network architecture, MDC-RC, this study focused on the two modes of CR networks, interweave and underlay relay-assisted system model development. In the interweave mode of the relay-assisted model, MDC-RC-I, the primary user (PU) is idle, and in the underlay mode system model, MDC-RC-U, the secondary user (SU) co-exists with the PU. In this model, there is a presence of interference from primary source (PS) to secondary destination (SD) and secondary relay (SR). In the MDC approach, the video source is split into odd and even frames and encoded into two descriptions. These descriptions are sent via two paths in the proposed design relay-assisted model. During the transmission, the outage and timeout probability are evaluated and analyzed. The evaluated probabilities were then used to estimate the peak signal-to-noise ratio (PSNR) of the received video.

In the first stage, a video transmission system using a combination of the MDC and a relay-assisted CR network is designed to take advantage of path diversity. Additionally, the video's encoding and decoding method is developed using the MDC approach. Subsequently, the proposed system, MDC-RC, is evaluated to examine the video performance. The simulation results show that the proposed MDC-RC has addressed the first objective, improving error resilience by exploiting path diversity.

Upon analyzing the transmission results without any packet loss, it was seen that the performance of the Suzie sequence increased by 20% and the Foreman sequence improved by 45% when two descriptions were received, compared to receiving only one description. The transmission performance with packet loss conditions showed an improvement of up to 10% and 13% for the Suzie and Foreman sequences, respectively. Subsequently, a comparison is made between the performance of the MDC-RC systems and the single description coding (SDC) approach.

Under ideal conditions with no packet loss, the SDC outperforms the MDC-RC system by a margin of 0.2% and 3% for the Suzie and Foreman sequences, respectively. In the absence of packet loss, SDC outperforms MDC because of its higher compression efficiency and absence of redundancy. By encoding the video as a single description, SDC maximizes video quality. In contrast, MDC splits the video into multiple descriptions, each containing only a portion of the original information.

MDC includes redundancy across descriptions to maintain robustness against packet loss, which becomes unneeded in a lossless case and leads to poor compression. One of the key reasons for the decreased performance of MDC in a lossless scenario is the redundancy overhead. Since MDC repeats portions of the video data to achieve error resilience, it sacrifices overall compression performance when no data loss occurs. Additionally, the bit allocation approach in MDC leads each description to operate at a lower bit rate than an equivalent SDC stream, leading to coarser quantization and higher distortion. This effect is visible in the PSNR values, where SDC achieves the greatest quality, followed by 2D MDC, but 1D Odd and 1D Even exhibit

substantial degradation. Since all packets arrive successfully in a lossless environment, MDC's error resistance benefits are unnecessary, and redundancy becomes a disadvantage. SDC, employing the bandwidth for a single high-quality stream, retains finer quantization and better video reconstruction. The result shows that SDC consistently produces the best PSNR because it avoids the quality loss associated with MDC's bitstream splitting and redundancy.

Therefore, while MDC is effective in error-prone networks, SDC remains the ideal solution in a lossless environment due to its ability to preserve video quality without additional overhead. However, in the presence of packet loss, the MDC-RC systems exhibited enhancements of 12% and 15% for the Suzie and Foreman sequences, respectively. In a lossy environment, MDC performs better than SDC due to its ability to tolerate packet loss well. MDC distributes video data over numerous independent descriptions so that even if some descriptions are lost, the remaining ones can still reconstruct a degraded but with acceptable video quality. The redundancy in MDC helps maintain continuity and lowers the implications of losing data, making it well-suited for networks with unpredictable packet loss.

In contrast, SDC relies simply on getting the complete descriptions for successful video reconstruction. SDC meets considerable deterioration if packets are missing, leading to visual distortions, frame freezes, or playback failure. Since SDC does not feature redundancy, any lost data results in a visible drop in quality, making it less resilient to transmission faults.

While slightly less efficient on a perfect network due to its redundant encoding, MDC proved useful in unstable conditions. Dispersing information across various channels raises the possibility of successful reconstruction, even when some packets are missing. This makes MDC the best choice for video transmission in error-prone contexts when preserving acceptable video quality is more critical than obtaining the highest compression efficiency.

Then, in the second stage, the MDC-RC-I system model was designed for transmitting videos over a relay-assisted CR network, using an interweave mode when the PU does not utilize the channel. The outage probability expression will be deduced using the system model to address the second objective, and the performance of the outage and video will be assessed in the objective 3. An analysis has been conducted to evaluate the impact of varying distances between SS and SD and varied ρ values on the outage performance. Next, the outcomes of the suggested method were contrasted with those of the traditional system without a relay. The MDC-RC-I has reduced the outage probability by 9% on a non-relay network. An investigation has also been conducted on the outage performance concerning the transmit power of the SS. The video performance is assessed based on the evaluation of the outage probability. The video quality is assessed based on the number of descriptions received at the destination. The average (PSNR) for the Suzie sequence increased by 17% and for the Foreman sequence by 27 % when both descriptions were received, compared to getting only one.

The video performance of the proposed system is subsequently evaluated against both the non-relay network system and the system utilizing the SDC technique [7]. The MDC-RC-I method enhances the PSNR by 6% for the Suzie sequence and 9% for the Foreman sequence in comparison to the non-relay network. The non-relay network achieves better PSNR for short SS-SD distances than the MDC-RC-I scheme, as the direct transmission remains strong and distortion-free.

In contrast, the relay-assisted approach introduces additional processing delays, relay node noise, and buffering, slightly reducing video quality. Since the direct link is already reliable at short distances, the benefits of relay assistance are not fully realized. However, as the SS-SD distance increases, MDC-RC-I outperforms direct transmission by providing a more reliable backup link. The relay-assisted method becomes increasingly beneficial as signal degradation over the direct path worsens with distance. This trend is evident at 300 and 400 meters, where MDC-RC-I maintains higher PSNR due to improved link stability. The results indicate that while relay assistance may not be necessary for short distances, it becomes crucial in challenging wireless environments where attenuation and packet loss are significant.

The suggested model demonstrated better performance in comparing the MDC-RC-I and SDC, achieving a 4% and 2% improvement for the Suzie and

Foreman sequences, respectively. Even with a modest improvement, the MDC-RC-I scheme enhances outage performance compared to SDC by ensuring that at least one description is received through the relay path when the direct link experiences an outage.

In SDC, the entire video stream is transmitted as a single description over a single path, making it highly vulnerable to outages. If the direct path experiences deep fading or signal blockage, SDC suffers a complete loss of video data, resulting in severe degradation or playback failure. In contrast, MDC-RC-I distributes the video into multiple descriptions and utilizes a relay-assisted link, reducing the probability of a total outage. Even if the direct transmission fails, the relay provides an alternative path for at least a partial reconstruction of the video.

This redundancy significantly improves outage performance by maintaining a usable video stream under challenging network conditions. While SDC may achieve higher quality in an ideal, lossless scenario, MDC-RC-I proves more resilient in lossy environments, ensuring more reliable video delivery in the presence of unpredictable transmission impairments.

Next, in the third stage, the MDC-RC-U system model is developed to transmit video using the underlay mode of a cognitive radio network. In this mode, primary users (PUs) are present, and secondary users (SUs) must avoid causing any detrimental interference to the PUs. The term for the timeout probability will be derived to quantify the performance of timeout and video to address the second and the third objectives, respectively. The performance evaluation examined the impact of interference caused by the primary user (PU).

The MDC-RC-U has enhanced the timeout performance by 6% over a non-relay network. Compared to a non-relay network, the MDC-RC-U demonstrated a 6% improvement in timeout performance, demonstrating how well it works to cut down on transmission delays. The relay-assisted technique, which provides a backup data transmission line and lowers the possibility of extended waiting times because of lost or delayed packets, is primarily responsible for this improvement. Combining numerous descriptions and utilizing a relay ensures that video data can still be reconstructed even when some packets incur delays.

The video performance is then assessed based on the timeout probability of the proposed system model, which examines how often packets fail to arrive within the required time restrictions. Lower timeout probabilities indicate improved system dependability and user satisfaction, highlighting the benefits of the MDC-RC-U approach.

Finally, the video performance is examined based on the timeout probability of the proposed system model. The average peak signal-to-noise ratio (PSNR) for the Suzie sequence increased by 17%, and for the Foreman sequence increased by 31% when both descriptions were received, compared to only one. This illustrates how well MDC enhances video quality, since the number of incoming descriptions directly affects the accuracy of video reconstruction. When only one description is given, the decoder uses less information to recreate the video, resulting in a lower visual quality. However, after getting both descriptions, the system might incorporate the complimentary information to create a better and more comprehensive video reconstruction.

Compared to the non-relay network, the PSNR using the MDC-RC-U scheme shows a 15% improvement for the Suzie sequence and a 1% improvement for the Foreman sequence. The significant gain for the Suzie sequence can be attributed to its relatively lower motion complexity, which makes it more sensitive to packet losses and delays. These issues are effectively resolved, and video quality is enhanced by the relay-assisted approach, which provides an alternative transmission path. The Foreman portion, on the other hand, barely marginally becomes better while having more sophisticated action and numerous scene changes.

Since predictive coding techniques may still partially compensate for the missing data, the impact of lost packets is lessened because of the higher inter-frame fluctuations caused by the increased motion. Furthermore, Foreman's quick movements could result in more frequent modifications to the relay path's efficiency, which would reduce the total gain made possible by MDC-RC-U. As a result, while the relay-assisted scheme significantly benefits low-motion sequences, its impact is less pronounced for high-motion content.

The MDC-RC-U system model shows only a slight improvement over SDC, with a 0.2% increase for the Suzie sequence and a 3% increase for the Foreman sequence. The minimal gain for the Suzie sequence is primarily due to its low-motion characteristics compared to Foreman with high-motion characteristic, which make it less sensitive to packet loss and delay. The trade-offs between motion complexity, compression efficiency, and redundancy in video transmission account for MDC's marginal improvement over SDC.

Although MDC adds numerous descriptions to improve error resilience, its redundancy loses some of its usefulness on a stable network that experiences little packet loss. Compared to SDC, which sends a single, high-quality stream, MDC somewhat reduces compression efficiency because each description only conveys a portion of the video since it splits it up into many descriptions.

5.2 Recommendation for Future Works

This thesis presented the performance of the proposed system with MDC as the video source coding technique. The proposed system is designed to satisfy the MDC technique and indirectly exploit the path diversity. Based on the performance of the MDC itself in the multimedia transmission, some future works recommendation can be discussed.

MDC for High Efficiency Video Coding: The next-generation coding standard, High Efficiency Video Coding (HEVC), has implemented innovative coding structures in its test model. These structures include the utilization of larger coding units and transform blocks. Coding units with dimensions larger than 16 by 16 and smaller than or equal to 64 by 64 provide significant reductions in bit rate, but their coding complexity increases significantly. It is necessary to develop new MDC schemes to enhance coding efficiency and error resilience due to the introduction of novel spatial and temporal prediction dependencies by these coding units. For example, one can assess novel information-based methods that are redundant and have different quality adjustments for HEVC structures.

MDC for 3D video: Multi-view video coding involves representing a video scenario using many views that contain overlapping information. Presently, research focuses on enhancing coding efficiency and 3D rendering, encompassing video-depth representation and view synthesis. Exploring multi-view video transmission is necessary to provide error robustness for this novel video format, characterized by its intricate prediction relationships. MDC can make a critical determination to ensure error resilience in the streaming of 3D video. This can be achieved by minimizing the reliance on predictions. It is feasible to merge multiple quality representations to improve decoding quality, which introduces new challenges in assessing the perceived quality of 3D video material.

REFERENCES

[1] M. Wien, “High efficiency video coding,” *Coding Tools and specification*, vol. 24, 2015.

[2] Y. Wang, S. Wenger, J. Wen, and A. K. Katsaggelos, “Error resilient video coding techniques,” *IEEE Signal Processing Magazine*, vol. 17, no. 4, pp. 61–82, 2000.

[3] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, “Next generation/dynamic spectrum access/cognitive radio wireless networks: A survey,” *Comput. Netw.*, vol. 50, no. 13, pp. 2127–2159, 2006.

[4] I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury, “Crahns: Cognitive radio ad hoc networks,” *AD hoc networks*, vol. 7, no. 5, pp. 810–836, 2009.

[5] H. M. Farag and E. M. Mohamed, “Soft decision cooperative spectrum sensing with noise uncertainty reduction,” *Pervasive and Mobile Computing*, vol. 35, pp. 146– 164, 2017.

[6] M. Dohler and Y. Li, *Cooperative communications: hardware, channel and PHY*. John Wiley & Sons, 2010.

[7] M. Kazemi, S. Shirmohammadi, and K. H. Sadeghi, “A review of multiple description coding techniques for error-resilient video delivery,” *Multimedia Systems*, vol. 20, no. 3, pp. 283–309, 2014.

[8] M. Kazemi, R. Iqbal, and S. Shirmohammadi, “Joint intra and multiple description coding for packet loss resilient video transmission,” *IEEE Trans. Multimedia*, vol. 20, no. 4, pp. 781–795, 2017.

[9] I. E. Richardson, *The H. 264 advanced video compression standard*. John Wiley & Sons, 2011.

[10] Xiph.org, “Xiph.org : Derf’s test media collection,” 1994. Last accessed 6 February 2020.

[11] E. Hossain, D. Niyato, and Z. Han, *Dynamic spectrum access and management in cognitive radio networks*. Cambridge University Press, 2009.

[12] D. Hu, S. Mao, Y. T. Hou, and J. H. Reed, “Scalable video multicast in cognitive radio networks,” *IEEE J. Sel. Areas Commun.*, vol. 28, no. 3, pp. 334–344, 2010.

[13] M. Ibnkahla, *Cooperative cognitive radio networks: The complete spectrum cycle*. CRC Press, 2018.

[14] G. Sun, L. Meng, L. Liu, Y. Tan, J. Zhang, and H. Zhang, “Ksvd-based multiple description image coding,” *IEEE Access*, vol. 7, pp. 1962–

1972, 2018.

[15] H. Li, L. Meng, J. Zhang, Y. Tan, Y. Ren, and H. Zhang, "Multiple description coding based on convolutional auto-encoder," *IEEE Access*, vol. 7, pp. 26013–26021, 2019.

[16] A. Chaoub and E. Ibn-Elhaj, "A multiple description scalable coding scheme for adaptive video streaming over next generation cellular networks," *Digital Signal Processing*, vol. 91, pp. 77–90, 2019.

[17] M. A. Labiod, M. Gharbi, F.-X. Coudoux, P. Corlay, and N. Doghmane, "Cross-layer scheme for low latency multiple description video streaming over vehicular ad-hoc networks (vanets)," *AEU- Int. J. of Electron. And Commun.*, vol. 104, pp. 23–34, 2019.

[18] T. Tang, A. Wang, S. Muhaidat, S. Li, M. Li, and J. Liang, "Mdc-noma: Multiple description coding-based nonorthogonal multiple access for image transmission," *IEEE Syst. J.*, 2020.

[19] A. Goldsmith, *Wireless communications*. Cambridge university press, 2005.

[20] A. P. Snow, "Network reliability: the concurrent challenges of innovation, competition, and complexity," *IEEE Transactions on Reliability*, vol. 50, no. 1, pp. 38–40, 2001.

[21] V. Vassiliou, P. Antoniou, I. Giannakou, and A. Pitsillides, "Requirements for the transmission of streaming video in mobile wireless networks," in *International Conference on Artificial Neural Networks*, pp. 528–537, Springer, 2006.

[22] I. Lee and L. Guan, "Reliable video communication with multi-path streaming using mdc," in *2005 IEEE International Conference on Multimedia and Expo*, pp. 4–pp, IEEE, 2005.

[23] D. Das and S. Das, "A survey on spectrum occupancy measurement for cognitive radio," *Wireless Personal Communications*, vol. 85, no. 4, pp. 2581–2598, 2015.

[24] H. Tran, J. *ρA*kerberg, M. Bjharvesting: an analysis of wireless sensor networks for reliable communication," *Wireless Networks*, vol. 25, pp. 185–199, 2019.

[25] T. P. Huu, T. N. Thi-Thanh, C. Nguyen-Yen, H. Tran, V. N. Dinh, *et al.*, "Secrecy outage probability and fairness of packet transmission time in a noma system," *IEEE Access*, vol. 8, pp. 79637–79649, 2020.

[26] S. Mondal, S. Roy, and S. Kundu, "Performance analysis of a cognitive radio network with adaptive rf energy harvesting," *International Journal of Electronics Letters*, vol. 9, no. 1, pp. 114–127, 2021.

[27] B. Wang and K. R. Liu, "Advances in cognitive radio networks: A survey," *IEEE Journal of selected topics in signal processing*, vol. 5, no. 1, pp. 5–23, 2010.

[28] B. Ali, J. Mirza, J. Zhang, G. Zheng, S. Saleem, and K.-K. Wong, "Full-duplex amplify-and-forward relay selection in cooperative cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 68, no. 6, pp. 6142–6146, 2019.

[29] O. M. Kandelusy and N. J. Kirsch, "Buffer-aided relaying with direct link transmission and spectrum sharing," *IEEE Trans. Cogn. Commun. Netw.*, vol. 6, no. 2, pp. 631–644, 2019.

[30] R. Zhang, R. Nakai, K. Sezaki, and S. Sugiura, "Generalized buffer-state-based relay selection in cooperative cognitive radio networks," *IEEE Access*, vol. 8, pp. 11644– 11657, 2020.

[31] O. A. Amodu, M. Othman, N. K. Noordin, and I. Ahmad, "Outage analysis of energy-harvesting-based relay-assisted random underlay cognitive radio networks with multihop primary transmissions," *IEEE Syst. J.*, 2020.

[32] O. A. Amodu, M. Othman, N. K. Noordin, and I. Ahmad, "Outage minimization of energy harvesting-based relay-assisted random underlay cognitive radio networks with interference cancellation," *IEEE Access*, 2021.

[33] O. M. Kandelusy and N. J. Kirsch, "Cognitive multi-user multi-relay network: A decentralized scheduling technique," *IEEE Trans. Cogn. Commun. Netw.*, 2020.

[34] A. Chaoub, F. Z. Ennaoui, and E. Ibn-Elhaj, "Reliable rate-adaptive video transmission over cognitive cellular networks using multiple description scalable coding," *Telecommunication Syst.*, vol. 71, no. 3, pp. 321–338, 2019.

[35] J. Balam and J. D. Gibson, "Path diversity and multiple descriptions with rate dependent packet losses," in *Proc. Of the Information Theory and Applications Workshop*, 2006.

[36] J. Mitola and G. Q. Maguire, "Cognitive radio: making software radios more personal," *IEEE personal communications*, vol. 6, no. 4, pp. 13–18, 1999.

[37] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE journal on selected areas in communications*, vol. 23, no. 2, pp. 201–220, 2005.

[38] H.-P. Shiang and M. Van Der Schaar, "Queuing-based dynamic channel selection for heterogeneous multimedia applications over cognitive radio networks," *IEEE Transactions on multimedia*, vol. 10,

no. 5, pp. 896–909, 2008.

[39] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, “A survey on spectrum management in cognitive radio networks,” *IEEE Communications magazine*, vol. 46, no. 4, pp. 40–48, 2008.

[40] Q. Zaho and B. Sadler, “A survey of dynamic spectrum access: Signal processing, networking and regulatory policy,” *IEEE Signal Processing Magazine*, vol. 55, no. 5, pp. 2294–2309, 2007.

[41] M. Matinmikko, H. Okkonen, M. Palola, S. Yrjola, P. Ahokangas, and M. Mustonen, “Spectrum sharing using licensed shared access: the concept and its workflow for lte-advanced networks,” *IEEE Wireless Communications*, vol. 21, no. 2, pp. 72–79, 2014.

[42] K. B. Letaief and W. Zhang, “Cooperative communications for cognitive radio networks,” *Proceedings of the IEEE*, vol. 97, no. 5, pp. 878–893, 2009.

[43] A. Nosratinia, T. E. Hunter, and A. Hedayat, “Cooperative communication in wireless networks,” *IEEE communications Magazine*, vol. 42, no. 10, pp. 74–80, 2004.

[44] G. Kramer, M. Gastpar, and P. Gupta, “Cooperative strategies and capacity theorems for relay networks,” *IEEE Transactions on Information Theory*, vol. 51, no. 9, pp. 3037–3063, 2005.

[45] J. N. Laneman, D. N. Tse, and G. W. Wornell, “Cooperative diversity in wireless networks: Efficient protocols and outage behavior,” *IEEE Transactions on Information theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[46] S. Nazir, V. Stankovic, H. Attar, L. Stankovic, and S. Cheng, “Relay-assisted rateless layered multiple description video delivery,” *IEEE J. Sel. Areas Commun.*, vol. 31, no. 8, pp. 1629–1637, 2012.

[47] Z. Yan, X. Zhang, and W. Wang, “Outage performance of relay assisted hybrid overlay/underlay cognitive radio systems,” in *2011 IEEE Wireless Commun. And Netw. Conf.*, pp. 1920–1925, 2011.

[48] K. Ho-Van, “Exact outage probability of underlay cognitive cooperative networks over Rayleigh fading channels,” *Wireless Personal Commun.*, vol. 70, no. 2, pp. 1001–1009, 2013.

[49] J. Zou, H. Xiong, D. Wang, and C. W. Chen, “Optimal power allocation for hybrid overlay/underlay spectrum sharing in multiband cognitive radio networks,” *IEEE Trans. Veh. Technol.*, vol. 62, no. 4, pp. 1827–1837, 2012.

[50] A. Kaushik, M. R. Raza, and F. K. Jondral, “On the deployment of cognitive relay as underlay systems,” in *2014 9th Int. Conf. on Cognitive*

Radio Oriented Wireless Netw. And Commun. (CROWNCOM), pp. 329–334, 2014.

[51] Y. Zou, J. Zhu, and B. Zheng, "Outage analysis of multi-relay selection for cognitive radio with imperfect spectrum sensing," in *2014 IEEE Global Conf. on Signal and Information Processing (GlobalSIP)*, pp. 1262–1266, 2014.

[52] N. Ibrahim, A. Sali, M. Mohamad, and S. Hashim, "Outage performance in relay- assisted overlay cognitive radio networks," in *2015 IEEE 12th Malaysia Int. Conf. on Commun. (MICC)*, pp. 119–123, 2015.

[53] A. El Shafie, T. Khattab, and A. S. Salem, "Relay-assisted primary and secondary transmissions in cognitive radio networks," *IEEE Access*, vol. 4, pp. 6386–6400, 2016.

[54] Y. Cheng, J. Yang, J. Ding, K. P. Peppas, and P. T. Mathiopoulos, "Outage performance analysis of underlay cognitive df relaying network with swipt in nakagami-m fading environment," in *2017 IEEE/CIC Int. Conf. on Commun. In China (ICCC)*, pp. 1–5, 2017.

[55] C. Yiyun and Y. Jing, "Outage analysis of cognitive energy harvesting relaying networks with opportunistic relay selection over nakagami-m fading channel," in *2017 13th IEEE Int. Conf. on Electron. Measurement & Instruments (ICEMI)*, pp. 463– 469, 2017.

[56] T. M. C. Chu and H.-J. Zepernick, "Optimal power allocation for hybrid cognitive cooperative radio networks with imperfect spectrum sensing," *IEEE Access*, vol. 6, pp. 10365–10380, 2018.

[57] M. A. Rahman, Y. Lee, and I. Koo, "Joint relay selection and power allocation through a genetic algorithm for secure cooperative cognitive radio networks," *Sensors*, vol. 18, no. 11, p. 3934, 2018.

[58] Z. Yan, S. Chen, X. Zhang, and H.-L. Liu, "Outage performance analysis of wireless energy harvesting relay-assisted random underlay cognitive networks," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2691–2699, 2018.

[59] B. Han, M. Zeng, Q. Guo, H. Jiang, Q. Zhang, and L. Feng, "Energy-efficient sensing and transmission for multi-hop relay cognitive radio sensor networks," *China Communications*, vol. 15, no. 9, pp. 106–117, 2018.

[60] Y. Yu, Z. Yang, Y. Wu, J. A. Hussein, W.-K. Jia, and Z. Dong, "Outage performance of NOMA in cooperative cognitive radio networks with SWIPT," *IEEE Access*, vol. 7, pp. 117308–117317, 2019.

[61] S. Lavanya and M. A. Bhagyaveni, "EVM based rate maximized relay selection for cooperative cognitive radio networks," *AEU-International Journal of Electronics and Communications*, vol. 104, pp. 86–90, 2019.

[62] A. Banerjee and S. P. Maity, "On outage minimization in relay assisted cognitive radio networks with energy harvesting," *Ad Hoc Networks*, vol. 82, pp. 46–55, 2019.

[63] L. Zhang, Y. Yang, X. Li, J. Chen, and Y. Chi, "Effective capacity in cognitive radio networks with relay and primary user emulator," *China Communications*, vol. 16, no. 11, pp. 130–145, 2019.

[64] G. Im and J. H. Lee, "Outage probability for cooperative NOMA systems with imperfect SIC in cognitive radio networks," *IEEE Communications Letters*, vol. 23, no. 4, pp. 692–695, 2019.

[65] L. Zhang, R. Senanayake, S. Atapattu, and J. Evans, "Relay assisted underlay cognitive radio networks with multiple users," in *2022 IEEE 33rd Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, pp. 1153–1158, IEEE, 2022.

[66] C. Hu, Q. Li, Q. Zhang, and J. Qin, "Security optimization for an AF MIMO two-way relay-assisted cognitive radio nonorthogonal multiple access networks with SWIPT," *IEEE Transactions on Information Forensics and Security*, vol. 17, pp. 1481–1496, 2022.

[67] Y. Zhang, J. Hou, and X. Zhao, "Secure V2V communications in relay-assisted cognitive radio vehicular networks with imperfect CSI," *IEEE Transactions on Intelligent Vehicles*, 2023.

[68] L. Kong, Y. Zou, and B. Li, "Security and reliability tradeoff of UAV relays assisted cognitive transmissions with hardware impairments," *IEEE Internet of Things Journal*, 2023.

[69] D. Sahu, S. Maurya, M. Bansal, and D. Kumar, "Deep learning based relay selection and precoders design for IoT cognitive relay networks," *Physical Communication*, vol. 61, p. 102195, 2023.

[70] J. Yao, M. Jin, T. Wu, Q. Li, and K.-K. Wong, "Joint optimization for over-the-air computation in AF relay-assisted cognitive radio networks," *IEEE Transactions on Vehicular Technology*, 2024.

[71] P. Ghosh, S. Dhar Roy, and S. Kundu, "Outage of cooperative NOMA with an energy harvesting relay in an underlay cognitive radio network," *International Journal of Communication Systems*, vol. 37, no. 8, p. e5749, 2024.

[72] A. Gersho, "The channel splitting problem and modulo-pcm coding," *Bell Labs Memo for Record (not archived)*, 1979.

[73] V. K. Goyal, "Multiple description coding: Compression meets the network," *IEEE Signal processing magazine*, vol. 18, no. 5, pp. 74–93, 2001.

[74] N. Jayant, E. Chen, J. Johnston, S. Quackenbush, S. Dorward, K. Thompson, R. Cupo, J. Wang, C. Sundberg, and N. Seshadri, “The AT&T in-band adjacent channel system for digital audio broadcasting,” in *Proc. Int. Symp. Digital Audio Broadcasting*, pp. 254–267, 1994.

[75] N. Jayant, “Subsampling of a DPCM speech channel to provide two “self-contained” half-rate channels,” *Bell System Technical Journal*, vol. 60, no. 4, pp. 501–509, 1981.

[76] R. Balan, I. Daubechies, and V. Vaishampayan, “The analysis and design of windowed fourier frame based multiple description source coding schemes,” *IEEE Transactions on information Theory*, vol. 46, no. 7, pp. 2491–2536, 2000.

[77] Z. Ling and I. Lee, “Adaptive multi-path video streaming,” in *Eighth IEEE International Symposium on Multimedia (ISM’06)*, pp. 399–406, IEEE, 2006.

[78] J. G. Apostolopoulos, “Reliable video communication over lossy packet networks using multiple state encoding and path diversity,” in *Visual Communications and Image Processing 2001*, vol. 4310, pp. 392–409, 2000.

[79] R. Kibria and J. Kim, “H. 264/AVC-based multiple description coding for wireless video transmission,” in *Proceedings of the 12th WSEAS international conference on Communications*, pp. 429–432, 2008.

[80] T. Tillo and G. Olmo, “Low complexity pre postprocessing multiple description coding for video streaming,” in *Proceedings. 2004 International Conference on Information and Communication Technologies: From Theory to Applications, 2004.*, pp. 519–520, IEEE, 2004.

[81] T. Tillo, E. Baccaglini, and G. Olmo, “Multiple descriptions based on multirate coding for jpeg 2000 and h. 264/avc,” *IEEE Transactions on Image Processing*, vol. 19, no. 7, pp. 1756–1767, 2010.

[82] I. Radulovic, P. Frossard, Y.-K. Wang, M. M. Hannuksela, and A. Hallapuro, “Multiple description video coding with h. 264/avc redundant pictures,” *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 20, no. 1, pp. 144–148, 2009.

[83] H. Bai, Y. Zhao, and C. Zhu, “Multiple description video coding using adaptive temporal sub-sampling,” in *2007 IEEE International Conference on Multimedia and Expo*, pp. 1331–1334, IEEE, 2007.

[84] A. E. Mohr, E. A. Riskin, and R. E. Ladner, “Unequal loss protection: Graceful degradation of image quality over packet erasure channels through forward error correction,” *IEEE journal on selected areas in communications*, vol. 18, no. 6, pp. 819– 828, 2000.

[85] R. Puri and K. Ramchandran, "Multiple description source coding through forward error correction codes. Inproc," in *Asilomar Conference on Signals, Systems, and Computers, Asilomar, CA*, 1999.

[86] A. Albanese, J. Blomer, J. Edmonds, M. Luby, and M. Sudan, "Priority encoding transmission," *IEEE transactions on information theory*, vol. 42, no. 6, pp. 1737– 1744, 1996.

[87] V. Bhaskaran and K. Konstantinides, "Image and video compression standards: algorithms and architectures," 1997.

[88] P. Lambert, W. De Neve, Y. Dhondt, and R. Van de Walle, "Flexible macroblock ordering in h. 264/avc," *Journal of Visual Communication and Image Representation*, vol. 17, no. 2, pp. 358–375, 2006.

[89] J. Wu, C. Yuen, and J. Chen, "Leveraging the delay-friendliness of tcp with fec coding in real-time video communication," *IEEE Transactions on Communications*, vol. 63, no. 10, pp. 3584–3599, 2015.

[90] C.-K. Kim, H.-r. Lee, T.-j. Jung, B.-G. Kim, and K.-d. Seo, "An efficient delay- constrained arq scheme for mmt packet-based real-time video streaming over ip networks," *Journal of Real-Time Image Processing*, vol. 12, pp. 257–271, 2016.

[91] Y. Wang and Q.-F. Zhu, "Error control and concealment for video communication: A review," *Proceedings of the IEEE*, vol. 86, no. 5, pp. 974–997, 1998.

[92] Q. Gong, "A weakly secure multiple description coding scheme in lossy multipath channels for fine-grained svc streaming," *CCF Transactions on Networking*, vol. 3, no. 1, pp. 66–80, 2020.

[93] J. Huang, Z. Zhang, H. Wang, and H. Liu, "Video transmission over cognitive radio networks," in *2011 IEEE GLOBECOM Workshops (GC Wkshps)*, pp. 6–11, 2011.

[94] W. Castellanos, P. Guzmán, P. Arce, and J. C. Guerri, "Mechanisms for improving the scalable video streaming in mobile ad hoc networks," in *Proc. Of the 12th ACM Symp. On Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Netw.*, pp. 33–40, 2015.

[95] D. Bhardwaj, K. Kant, and D. S. Chauhan, "Qos-aware routing protocol using adaptive retransmission of distorted descriptions in mdc for manets.," *Int. J. Ad Hoc Ubiquitous Comput.*, vol. 28, no. 1, pp. 55–67, 2018.

[96] M. Majid, M. Owais, and S. M. Anwar, "Visual saliency based redundancy allocation in hevc compatible multiple description video coding," *Multimedia Tools and Applications*, vol. 77, no. 16, pp. 20955–20977, 2018.

[97] F. Boumehrez, R. Brai, N. Doghmane, and K. Mansouri, “Quality of experience enhancement of high efficiency video coding video streaming in wireless packet networks using multiple description coding,” *Journal of Electronic Imaging*, vol. 27, no. 1, p. 013028, 2018.

[98] R. B. Chenna, C. Singhal, and S. De, “Mdtc video transmission using channel aware multipath routing in wireless mesh networks,” in *Proceedings of the 19th International Conference on Distributed Computing and Networking*, pp. 1–9, 2018.

[99] J. Zong, L. Meng, Y. Tan, J. Zhang, Y. Ren, and H. Zhang, “Adaptive reconstruction based multiple description coding with randomly offset quantizations,” *Multimedia Tools and Applications*, vol. 77, no. 20, pp. 26293–26313, 2018.

[100] H. Kusetogullari and A. Yavariabdi, “Evolutionary multiobjective multiple description wavelet based image coding in the presence of mixed noise in images,” *Applied Soft Computing*, vol. 73, pp. 1039–1052, 2018.

[101] S. G. Lv and Y. Q. Cao, “An algorithm of video network transmission based on unbalanced multiple description coding,” *International Journal of Embedded Systems*, vol. 10, no. 5, pp. 437–444, 2018.

[102] J. Chen, H. Zeng, C. Cai, *et al.*, “Spatial-frequency hevc multiple description video coding with adaptive perceptual redundancy allocation,” 2018.

[103] K. Khelil, T. Bouadjila, and F. Berrezzek, “Optimal filtering of wavelet-based multiple description image coding using correlating transforms,” in *2018 International Conference on Signal, Image, Vision and their Applications (SIVA)*, pp. 1–4, IEEE, 2018.

[104] D. T. Duong, “Wyner-ziv scheme based multiple description coding for robust video transmission over path diversity networks,” in *2019 International Conference on Advanced Technologies for Communications (ATC)*, pp. 137–141, IEEE, 2019.

[105] S. Majumder, S. Verma, and B. Acharya, “Iterative decoding of ldpc-rs-coded multiple description image,” in *Innovations in Soft Computing and Information Technology*, pp. 197–207, Springer, 2019.

[106] N. Wang, S. Ge, B. Li, and L. Peng, “Multiple description image compression based on multiwavelets,” *International Journal of Wavelets, Multiresolution and Information Processing*, vol. 17, no. 01, p. 1850063, 2019.

[107] S. Zhu, Z. He, X. Meng, G. Liu, and B. Zeng, “Multiple description image coding based on compression-guided optimization,” in *2019 Picture Coding Symposium (PCS)*, pp. 1–5, IEEE, 2019.

[108] M. Shabanyan and E. Akhtarkavan, "A way to reduce effects of packet loss in video streaming using multiple description coding," *Journal of Computer & Robotics*, vol. 13, no. 1, pp. 55–62, 2020.

[109] D. T. Duong, "New h. 266/vvc based multiple description coding for robust video transmission over error-prone networks," in *2020 International Conference on Advanced Technologies for Communications (ATC)*, pp. 155–159, IEEE, 2020.

[110] A. Arshaghi, N. Razmjooy, V. Estrela, P. Burdziakowski, D. Nascimento, A. Deshpande, and P. Patavardhan, "Image transmission in uav mimo uwb-ostbc system over Rayleigh channel using multiple description coding (mdc)," 2020.

[111] D. Narayan, M. Naravani, and S. Shinde, "Cross-layer optimization for video transmission using mdc in wireless mesh networks," *Procedia Computer Science*, vol. 171, pp. 282–291, 2020.

[112] S. Karthick, A. Rajakumari, and N. Rugthaicharoencheep, "An integrated cross layer design to enhance the quality of service of video streaming in mobile adhoc networks," *ICTACT J. Commun. Technol*, vol. 11, no. 1, pp. 2159–2162, 2020.

[113] L. Zhao, H. Bai, A. Wang, and Y. Zhao, "Deep optimized multiple description image coding via scalar quantization learning," *arXiv preprint arXiv:2001.03851*, 2020.

[114] S. Zhu, Z. He, X. Meng, J. Zhou, Y. Guo, and B. Zeng, "A new polyphase down- sampling-based multiple description image coding," *IEEE Transactions on Image Processing*, vol. 29, pp. 5596–5611, 2020.

[115] L. Meng, H. Li, J. Zhang, Y. Tan, Y. Ren, and H. Zhang, "Convolutional auto- encoder based multiple description coding network," *KSII Transactions on Internet and Information Systems (TIIS)*, vol. 14, no. 4, pp. 1689–1703, 2020.

[116] Y. Zhang and B. Gu, "Error-resilient coding by convolutional neural networks for underwater video transmission," *Journal of the Franklin Institute*, vol. 358, no. 17, pp. 9307–9324, 2021.

[117] M. Zeeshan and M. Majid, "Hevc compatible perceptual multiple description video coding for reliable video transmission over packet networks," *Telecommunication Systems*, vol. 76, no. 1, pp. 63–83, 2021.

[118] M. Kazemi, "End-to-end distortion modeling and channel adaptive optimization of mixed layer multiple description coding scheme," *Computational Intelligence in Electrical Engineering*, vol. 12, no. 4, pp. 31–42, 2021.

[119] L. Zhao, J. Zhang, H. Bai, A. Wang, and Y. Zhao, “Lmdc: Learning a multiple description codec for deep learning-based image compression,” *Multimedia Tools and Applications*, vol. 81, no. 10, pp. 13889–13910, 2022.

[120] T. H. Le, M. Antonini, M. Lambert, and K. Alioua, “Multiple description video coding for real-time applications using hevc,” in *2023 IEEE International Conference on Image Processing (ICIP)*, pp. 2580–2584, IEEE, 2023.

[121] X. Hu, W. Ye, J. Tang, E. Ramadan, and Z.-L. Zhang, “Robust multiple description neural video codec with masked transformer for dynamic and noisy networks,” *arXiv preprint arXiv:2412.07922*, 2024.

[122] A. Chen, S. Mao, Z. Li, M. Xu, H. Zhang, D. Niyato, and Z. Han, “Multiple de- scription coding for point cloud,” in *ICC 2024-IEEE International Conference on Communications*, pp. 3408–3413, IEEE, 2024.

[123] H. Li, “Multiple description source coding for cognitive radio systems,” in *2010 Proc. Of the Fifth Int. Conf. on Cognitive Radio Oriented Wireless Networks and Communications*, pp. 1–5, 2010.

[124] A. Chaoub and E. Ibn-Elhaj, “Multiple description coding for cognitive radio networks under secondary collision errors,” in *2012 16th IEEE Mediterranean Electrotechnical Conf.*, pp. 27–30, 2012.

[125] S.-y. LI, W.-j. XU, G. Yan, N. Kai, and J.-r. LIN, “Resource allocation for multiple description coding multicast in ofdm-based cognitive radio networks,” *The Journal of China Universities of Posts and Telecommunications*, vol. 19, no. 5, pp. 51–57, 2012.

[126] S. Zhang, W. Xu, S. Li, and J. Lin, “Resource allocation for multiple description coding multicast in ofdm-based cognitive radio systems with non-full buffer traffic,” in *2013 IEEE Wireless Commun. and Netw. Conf. (WCNC)*, pp. 199–204, 2013.

[127] A. Chaoub, E. Ibn-Elhaj, and J. El-Abbadi, “Multiple description coding based distributed communications over cognitive radio networks,” in *ICT 2013*, pp. 1–5, IEEE, 2013.

[128] T. T. T. Quynh, N. K. Hoang, N. Van Ly, N. L. Trung, N. Q. Tuan, E. Bastug,S. Azarian, V. N. Q. Bao, T. X. Nam, M. Debbah, *et al.*, “Network coding with multimedia transmission and cognitive networking: An implementation based on software-defined radio,” *REV Journal on Electronics and Communications*, vol. 10, no. 3-4, 2021.

[129] H. A. Karim, H. Mohamad, N. Ramli, and A. Sali, “Multiple description video coding for underlay cognitive radio network,” in *Int. Conf. on Cognitive Radio Oriented Wireless Netw.*, pp. 643–652, 2015.

[130] Z. Zhang, Q. Zhang, J. Miao, F. R. Yu, F. Fu, J. Du, and T. Wu, “Energy-efficient se- cure video streaming in uav-enabled wireless networks: A safe-dqn approach,” *IEEE Transactions on Green Communications and Networking*, vol. 5, no. 4, pp. 1892– 1905, 2021.

[131] A. C. Bovik, *Handbook of image and video processing*. Academic press, 2010.

[132] T. Brandao and M. P. Queluz, “No-reference psnr estimation algorithm for h. 264 encoded video sequences,” in *2008 16th European Signal Processing Conference*, pp. 1–5, IEEE, 2008.

[133] Y. Liao and J. D. Gibson, “Refined error concealment for multiple state video coding over ad hoc networks,” in *2008 42nd Asilomar Conf. on Signals, Systems and Comput.*, pp. 2243–2247, 2008.

[134] Q. Huynh-Thu and M. Ghanbari, “Scope of validity of psnr in image/video quality assessment,” *Electronics letters*, vol. 44, no. 13, pp. 800–801, 2008.

[135] Y. Zhao, R. Adve, and T. J. Lim, “Outage probability at arbitrary snr with cooperative diversity,” *IEEE communications letters*, vol. 9, no. 8, pp. 700–702, 2005.

[136] Y. Liao and J. D. Gibson, “Routing-aware multiple description video coding over mobile ad-hoc networks,” *IEEE Transactions on Multimedia*, vol. 13, no. 1, pp. 132– 142, 2010.

[137] L. Sibomana, H.-J. Zepernick, H. Tran, and C. Kabiri, “A framework for packet delay analysis of point-to-multipoint underlay cognitive radio networks,” *IEEE Trans- actions on Mobile Computing*, vol. 16, no. 9, pp. 2408–2421, 2016.

APPENDICES

Appendix A

A1 Derivation of Outage Probability for SS-SR-SD path

Outage probability for SS-SR, $P_{out(S,R)}$

$$
\begin{aligned}
P_{out(S,R)} &= P_R\{\gamma_{SS}^{SR} < \xi\} \\
&= P_R\left\{\frac{P_S G_{SS}^{SR}}{N_0} < \xi\right\} \\
&= P_R\{G_{SS}^{SR} < \theta\} \\
&= \int_0^{\theta} \lambda_{SS}^{SR} e^{-\lambda_{SS}^{SR} x}\, dx \\
&= 1 - e^{-\lambda_{SS}^{SR}\theta}
\end{aligned}
$$

Outage probability for SR-SD, $P_{out(R,D)}$

$$
\begin{aligned}
P_{out(R,D)} &= P_R\{\gamma_{SR}^{SD} < \xi\} \\
&= P_R\left\{\frac{P_R G_{SR}^{SD}}{N_0} < \xi\right\} \\
&= P_R\{G_{SR}^{SD} < \beta\} \\
&= \int_0^{\beta} \lambda_{SR}^{SD} e^{-\lambda_{SR}^{SD} x}\, dx \\
&= 1 - e^{-\lambda_{SR}^{SD}\beta}
\end{aligned}
$$

Outage probability for relay path SS-SR-SD, P_{out1}

$$
\begin{aligned}
P_{out1} &= P_R\{\gamma_{SS}^{SR} < \xi\} \;\; or \;\; P_R\{\gamma_{SR}^{SD} < \xi\} \\
&= 1 - \left(1 - P_{out(S,R)}\right)\left(1 - P_{out(R,D)}\right) \\
&= 1 - \left(1 - \left(1 - e^{-\lambda_{SS}^{SR}\theta}\right)\right)\left(1 - \left(1 - e^{-\lambda_{SR}^{SD}\beta}\right)\right) \\
&= 1 - e^{-\lambda_{SS}^{SR}\theta} e^{-\lambda_{SR}^{SD}\beta}
\end{aligned}
$$

A.2 Derivation of Outage Probability for SS- SD path

Outage probability for SS-SD, $P_{out(S,D)}$

$$\begin{aligned} P_{out(S,D)} &= P_R\{\gamma_{SS}^{SD} < \xi\} \\ &= P_R\left\{\frac{P_S G_{SS}^{SD}}{N_0} < \xi\right\} \\ &= P_R\{G_{SS}^{SD} < \theta\} \\ &= \int_0^{\theta} \lambda_{SS}^{SD} e^{-\lambda_{SS}^{SD} x}\, dx \\ &= 1 - e^{-\lambda_{SS}^{SD}\theta} \end{aligned}$$

Appendix B

B.1 Derivation of Timeout Probability for SS-SR-SD path

Timeout probability for SS-SR, $P_{tout,u}^{(1a)}$

$$
\begin{aligned}
P_{tout,u}^{(1a)} &= P_r\{T_{1,u} \geq t_{thr}\} \\
&= P_r\left\{\frac{\delta}{ln(1+\gamma_1^u)} \geq t_{thr}\right\} \\
&= P_r\{\gamma_1^u \leq k_{SU}\} \\
&= P_r\left\{\frac{\bar{P}_S G_{SS}^{SR}}{P_P G_{PS}^{SR} + N_0} \leq k_{SU}\right\} \\
&= \int P_r\left\{G_{SS}^{SR} \leq \frac{k_{SU}(P_P y + N_0)}{\bar{P}_S}\right\}\frac{1}{\lambda_{PS}^{SR}} e^{-\frac{y}{\lambda_{PS}^{SR}}} dy \\
&= \int\left(1 - e^{-\frac{1}{\lambda_{SS}^{SR}}\left(\frac{k_{SU}(P_P y + N_0)}{\bar{P}_S}\right)}\right)\frac{1}{\lambda_{PS}^{SR}} e^{-\frac{y}{\lambda_{PS}^{SR}}} dy \\
&= 1 - \frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_S \lambda_{SS}^{SR} + P_P \lambda_{PS}^{SR} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_S \lambda_{SS}^{SR}}}
\end{aligned}
$$

Timeout probability for SR-SD, $P_{tout,u}^{(1b)}$

$$
\begin{aligned}
P_{tout,u}^{(1b)} &= P_r\{T_{2,u} \geq t_{thr}\} \\
&= P_r\left\{\frac{\delta}{ln(1+\gamma_2^u)} \geq t_{thr}\right\} \\
&= P_r\{\gamma_2^u \leq k_{SU}\} \\
&= P_r\left\{\frac{\bar{P}_R G_{SR}^{SD}}{P_P G_{PS}^{SD} + N_0} \leq k_{SU}\right\} \\
&= \int P_r\left\{G_{SR}^{SD} \leq \frac{k_{SU}(P_P z + N_0)}{\bar{P}_R}\right\}\frac{1}{\lambda_{PS}^{SD}} e^{-\frac{z}{\lambda_{PS}^{SD}}} dz \\
&= \int\left(1 - e^{-\frac{1}{\lambda_{SR}^{SD}}\left(\frac{k_{SU}(P_P z + N_0)}{\bar{P}_R}\right)}\right)\frac{1}{\lambda_{PS}^{SD}} e^{-\frac{z}{\lambda_{PS}^{SD}}} dz \\
&= 1 - \frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_R \lambda_{SR}^{SD} + P_P \lambda_{PS}^{SD} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_R \lambda_{SR}^{SD}}}
\end{aligned}
$$

Timeout probability for SS-SR-SD, $P_{tout,u}^{(1)}$

$$P_{tout,u}^{(1)} = P_r\{T_{1,u} \geq t_{thr}\} \; or \; P_r\{T_{2,u} \geq t_{thr}\}$$

$$= 1 - \left(\frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_S \lambda_{SS}^{SR} + P_P \lambda_{PS}^{SR} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_S \lambda_{SS}^{SR}}}\right)\left(\frac{\bar{P}_S \lambda_{SS}^{SR}}{\bar{P}_R \lambda_{SR}^{SD} + P_P \lambda_{PS}^{SD} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_R \lambda_{SR}^{SD}}}\right)$$

B.1 Derivation of Timeout Probability for SS-SD path

Timeout probability for SS-SD, $P_{tout,u}^{(2)}$

$$P_{tout,u}^{(2)} = P_r\{T_{3,u} \geq t_{thr}\}$$

$$= P_r\left\{\frac{\delta}{ln(1+\gamma_3^u)} \geq t_{thr}\right\}$$

$$= P_r\{\gamma_3^u \leq k_{SU}\}$$

$$= P_r\left\{\frac{\bar{P}_S G_{SS}^{SD}}{P_P G_{PS}^{SD} + N_0} \leq k_{SU}\right\}$$

$$= \int P_r\left\{G_{SS}^{SD} \leq \frac{k_{SU}(P_P y + N_0)}{\bar{P}_S}\right\} \frac{1}{\lambda_{PS}^{SD}} e^{-\frac{y}{\lambda_{PS}^{SD}}} dy$$

$$= \int\left(1 - e^{-\frac{1}{\lambda_{SS}^{SD}}\left(\frac{k_{SU}(P_P y + N_0)}{\bar{P}_S}\right)}\right) \frac{1}{\lambda_{PS}^{SD}} e^{-\frac{y}{\lambda_{PS}^{SD}}} dy$$

$$= 1 - \frac{\bar{P}_S \lambda_{SS}^{SD}}{\bar{P}_S \lambda_{SS}^{SD} + P_P \lambda_{PS}^{SD} k_{SU}} e^{-\frac{k_{SU} N_0}{\bar{P}_S \lambda_{SS}^{SD}}}$$

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LIST OF PUBLICATIONS

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*, vol. 10, pp. 11750-11762, 2022, *doi: 10.1109/ACCESS.2022.3146396*.

N. K. Ibrahim, A. Sali, H. A. Karim and A. F. Ramli, "Multiple description coding (MDC) for video transmission in cognitive radio network systems," *2017 IEEE 13th Malaysia International Conference on Communications (MICC), Johor Bahru, Malaysia*, 2017, pp. 147-151, *doi: 10.1109/MICC.2017.8311749*.

Nor Khairiah Ibrahim, Aduwati Sali, Fazirulhisyam Hashim and Aizat Faiz Ramli, "Timeout and video performance using multiple description coding for video transmission over underlay cognitive radio networks,". (*Submitted to IEEE Access)*