VIDEO STREAMING OVER D2D NETWORKS

by

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Dedication

To

My parents for their love, encouragement and support

My grandfather for being my first teacher

My grandmother for her prayers

My family

My friends

Abstract

Device-to-Device (D2D) communication has been presented as an innovation that can improve the cellular network performance by exploiting the proximity-based service between closely-located devices. Enabling D2D communication increases the energy efficiency, improves the capacity of the network and reduces the communication delay. Despite the above-mentioned advantages, D2D communication presents some challenges, for example, the need for proper interference management, power control, mode selection and device discovery. Nowadays, the increasing demand for video streaming has led to rapid growth in data traffic that is unable to be handled by traditional networks. Consequently, many works in the literature suggested employing D2D communication for video transmission to offload the cellular network and enhance the quality of video streaming. Moreover, the emergence of video-based applications has stimulated the need for high-performance D2D communication. This thesis focuses on video streaming over D2D communications underlaying a Long Term Evolution (LTE) network where Scalable Video Coding (SVC) is assumed. In particular, joint resource allocation, mode selection and power control for multiple D2D pairs are addressed. The objective is to maximize the throughput of D2D pairs while considering the minimum data rate requirements by both the Cellular Users (CUs) as well as the D2D pairs and maintain video quality and continuity. Resources are allocated to each CU and D2D pair in three modes of operation; cellular, dedicated and reuse and a mode selection algorithm is implemented. Furthermore, a packet-layer video assessment model is applied to predict the impact of network conditions on video quality. Finally, the effect of mobility on mode selection is examined. The performance of the proposed scheme is evaluated through extensive simulations and compared to the scenarios where only one mode of transmission is used for all D2D pairs. Simulation results show that mode selection improves the throughput of D2D pairs while providing better video quality. We assess the effect of user mobility on system performance and observe quality degradation for high mobility scenario.

Keywords: ***D2D communication, video streaming, mode selection, overlay, underlay, scalable video coding, temporal scalability, SNR scalability, PSNR.***

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List of Abbreviations

3GPP	3rd Generation Partnership Project
AP	Access Point
AWGN	Additive White Gaussian Noise
BL	Base Layer
BS	Base Station
CH	Cluster Head
CQI	Channel Quality Indicator
CSI	Channel State Information
CSVD	Cached and Segmented Video Download
CUs	Cellular Users
D2D	Device-to-Device
DASH	Dynamic Adaptive Streaming over HTTP
DL	Downlink
ELs	Enhancement Layers
ES	Exhaustive Search
FD	Full-Duplex
FDD	Frequency Division Duplex
FEC	Forward Error Correction
GOP	Group of Pictures
HetNets	Heterogeneous Networks
IDNC	Instantly Decodable Network Coding
IOT	Internet of Things
LTE	Long Term Evolution
MAC	Medium Access Control
MCS	Modulation and Coding
MDC	Multiple Description Coding
mmWave	Millimeter Wave
MOS	Mean Opinion Score

MSE	Mean Square Error
MTs	Mobile Terminals
MWIS	Max Weighted Independent Set
NC	Network Coding
OFDM	Orthogonal Frequency Division Multiplexing
OP	Outage Probability
PEUEs	Picocell Edge Users
PF	Proportional Fair
PRBs	Physical Resource Blocks
PSNR	Peak Signal to Noise Ratio
QoE	Quality of Experience
QoS	Quality of Service
RB	Resource Block
RR	Round Robin
RW	Random Walk
SINR	Signal to Interference plus Noise Ratio
SLNR	Signal-to-Leakage-plus-Noise Ratio
SMs	Storage Members
SNR	Signal to Noise Ratio
SVC	Scalable Video Coding
TB	Transport Block
TBS	Transport Block Size
TTI	Transmit Time Interval
UEs	User Equipments
UL	Uplink

List of Symbols

$a_{r,k}^{(m)}$	Decision variable indicates the assignment of RB r to pair k in mode m
$b_k^{f,l}$	The number of bits in enhancement layer l belongs to frame f
BW	Resource block bandwidth in LTE
$BL_{k,i}^{f_b}$	The TB number i for transmitting the base layer of a frame f
β_{th}	Buffer threshold
β_k	Buffer occupancy of the kth user
C	Number of cellular users
D	Number of D2D pairs
dt	Decodable threshold
$d(n)$	Quality degradation on the nth frame
$d_e(n)$	Quality degradation on the nth frame due to error propagation
$d_p(n)$	Quality degradation on the nth frame due to packet loss
d	Distance
f	Frequency
f_p	Frame playback rate
$h_{i,j}$	Channel gain between two communicating nodes $i, j \in \{dt, dr, bs, c\}$
I_{MCS}	Modulation and coding index
I_{TBS}	Transport block size index
N_j	Number of resources allocated to the user j, $j \in \{D2D, CU\}$
N_o	Additive white Gaussian noise power spectral density
n_k	Number of resources to be allocated to the kth user
$n_R(n)$	The number of valid blocks for decoding the nth frame
$n_T(n)$	Total number of blocks related to the nth frame
P_{eNB}	Maximum power of the eNB
P_{UE}	Maximum power of the UE

P_{bs}	Transmission power of the eNB
P_c	Transmission power of the cellular user
P_{dt}	Transmission power of the D2D transmitter
$Q_c(n)$	Quality after encoding of the *n*th frame
$Q(n)$	Final quality of the *n*th frame
$q_k^{f,l}$	Quality of the *l*th layer belongs to the frame f
$\bar{r}_k$	Average throughput of the *k*th user
R_k^{Req}	Required rate by user k
R_j^i	Achievable rate in mode i by user j, $j \in \{D2D, CU\}$ and $i \in \{D, C, R\}$
$\bar{R}_c$	Average throughput of CU when there is no interference in reuse mode
$R_{CU,D2D}$	Total throughput of D2D pair and CU sharing the same resources
$R(n)$	The number of bits for encoding the *n*th frame
SNR_j^i	Signal-to-noise ratio, $j \in \{D2D, CU\}$ and $i \in \{D, C, R\}$
$v(dt)$	Overhead obtained due to adoption of a certain level of tolerance
$x_k^{(m)}$	Decision variable indicates which of the three modes will be selected
α	The percentage of resources assigned to D2D communications
φ_k	Scheduling metric of the *k*th user
ψ_k	Proportional fair metric of the *k*th user
$\phi_{c,d}$	The SLNR between a CU and a D2D pair
$\vartheta_{c,d}$	The exhaustive search metric between a CU and a D2D pair

Chapter 1. Introduction

The past few decades have experienced exponential growth in both the number of subscribers and traffic demands. Voice calls and low data rate services dominated cellular traffic in the past. However, today the spread of portable gadgets and massive usage of mobile applications have prompted exponential growth in wireless traffic [1]. This rapid increase in data traffic will continue to be encountered over the coming years. Traffic growth has led to congestion on the available 2G/3G networks. Satisfying traffic demand represents a challenge to network operators. Hence, conventional solutions have been proposed to improve the capacity of networks such as increasing spectrum, reducing the cell coverage (femtocells) and using multiple antennas. However, the proposed approaches are either cost much to deploy new infrastructure or reached their limits (spectrum) [2]. Another solution to meet the continuous demand for data traffic is to evolve network technologies and as a consequence, the 3rd Generation Partnership Project (3GPP) developed a new technology Long Term Evolution (LTE) network. To further enhance the performance of a traditional cellular network, the 3GPP investigated the idea of enabling Device-to-Device (D2D) in the wireless network. D2D refers to direct communication between two User Equipments (UEs) without passing through the eNB. D2D communication is a novel approach that has been receiving much attention during the last few years as a promising solution to offload the Base Station (BS) and relieve network congestion [3–5].

The benefits of incorporating D2D communication into a conventional network include offloading wireless traffic, enhancing spectral and energy efficiencies, decreasing communication delay and boosting the system throughput [6]. Besides, D2D communication is considered as a technique to extend cellular network coverage and improve the performance of edge users who usually encounter poor services [7]. Despite the advantages of integrating D2D communication into cellular network, several technical and practical issues require further investigation such as interference management, mode selection, device discovery, resource allocation, security and mobility management [7].

1.1. D2D Classification

Generally, based on how spectrum sharing between the D2D link and the traditional cellular UEs is managed, D2D communication can be classified into two modes of operation, namely, inband and outband D2D as shown in Figure 1.1. Inband D2D communication occurs over the cellular spectrum, while outband D2D utilizes the unlicensed frequency bands. Inband D2D is further categorized into underlay and overlay D2D communication [6]. In underlay communication, D2D pairs share the same resources with active UEs, whereas in overlay D2D, a portion of cellular resources is dedicated to D2D communication. Clearly, underlay D2D improves the spectral efficiency, however, it could introduce interference to UEs [6]. A significant amount of literature studied inband D2D communication and the majority of research efforts focused on the issue of mitigating the interference between D2D links and the UEs [8, 9]. On the other hand, overlay D2D obviously mitigates interference [10], however, its major drawback inefficient utilization of resources. As a consequence, part of the existing literature proposed to move the D2D operations to the unlicensed band (outband) to completely eliminate the interference and enhance the spectral efficiency [11–13]. Wi-Fi Direct technology can be considered as some sort of outband D2D communication. Outband D2D communication, in turn, is divided into two subcategories, controlled and autonomous. Controlled D2D is proposed to improve the reliability of outband communication by using the BS as a central control device. Managing the communication between two different bands is an essential issue of outband D2D [7].

1.2. Overview of LTE Network

LTE is a network technology that has been developed to provide high data rate, low latency and support flexible bandwidth [14]. LTE employs Orthogonal Frequency Division Multiplexing (OFDM) that allocates multiple resource blocks of 180 kHz (12 sub-carriers each of 15 kHz) each to each user [15]. Various bandwidths have been defined for LTE from 5 MHz to 20 MHz. The eNodeB is the part that is responsible for resource allocation based on network configuration, network load and user requirements [16]. LTE Downlink (DL) adopts OFDMA and the resources are specified in

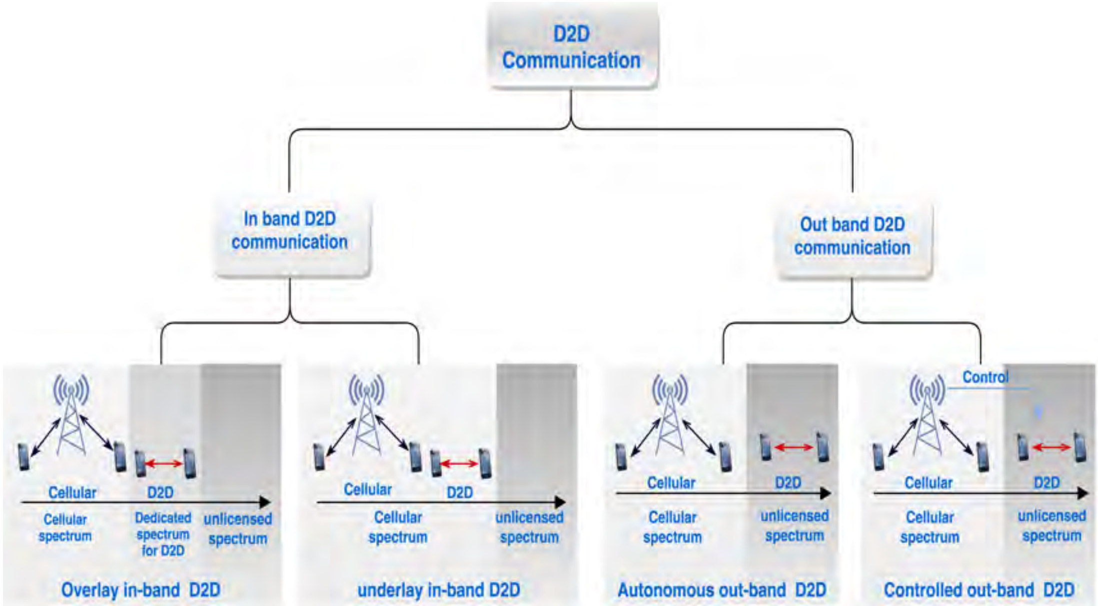

Figure 1.1: Classification of D2D communications.

both time and frequency domain [16]. The resource element is defined as the smallest resource unit with a duration of 66.667 microseconds which represents one symbol. Resources are assigned to a user in term of Resource Block (RB). One resource block groups seven consecutive symbols and occupies one time slot with a duration of 0.5 ms. Every two time slots form a sub-frame with a duration of 1 ms and 10 sub-frames represent one frame with a period of 10 ms. The eNodeB performs scheduling every 1 ms Transmit Time Interval (TTI) [15]. Figure 1.2 depicts LTE physical resource grid and DL resource allocation.

Scheduler is a part of LTE eNodeB that is responsible for allocating RBs to Cellular Users (CUs). Every TTI, the scheduler assigns time-frequency RBs to CUs in Uplink (UL) and DL [17]. Different scheduling techniques are proposed in the literature, for example, Round Robin, Proportional Fair and Best Channel Quality Indicator.

1. Round Robin (RR): is a scheduling algorithm that guarantees fairness among CUs because resources are assigned in an equal portion in circular order without taking into consideration the instantaneous channel conditions. Therefore, RR provides poor throughput system performance. However, RR has been used in many systems due to easy implementation [18].

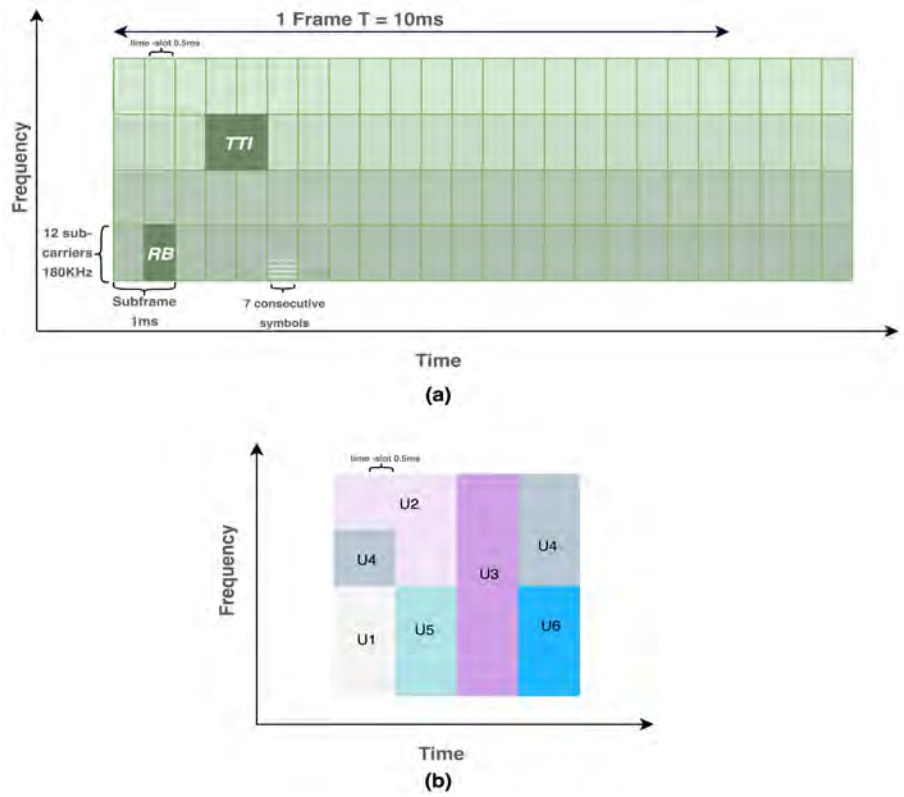

Figure 1.2: (a) LTE resource grid. (b) LTE downlink scheduling.

2. Proportional Fair (PF): is the most frequently used scheduler. PF is compromised-based scheduling to maintain a tradeoff between throughput and fairness. The objective is to maximize the overall system throughput while providing each user the minimum service [18].

3. Best Channel Quality Indicator (CQI): in best CQI scheduling, RBs are allocated to CUs with high CQI. CQI is the information sent by a user to the eNodeB and it indicates the channel quality. High CQI implies good channel conditions [18].

1.3. Overview of Video Streaming

Video is a sequence of images (frames) displayed one after another. Three types of frames (pictures) are used in video compression [19]:

- Intra-Coded picture (I frame): encoded independently without the reference to another frame.
- Predicted picture (P frame): encoded relative to the content of the preceding frame either P or I.

- Bi-directional predicted picture (B frame): encoded with the reference to previous and future frame either I or P.

Group of Pictures (GOP) is a collection of successive frames occur in repeating sequence starting with an I-frame followed by a number of P and B frames.

The challenge of video transmission over a cellular network with variable channel conditions and limited bandwidth motivated the idea of layered video coding. Scalable Video Coding (SVC) is a standard technique for video compression that allows encoding a video stream into multiple layers. SVC allows devices to adjust stream quality to adapt to network conditions by varying the bit rate [20]. Considering users' requirements for video streaming, multiple users may require different Quality of Experience (QoE) due to different channel conditions and allocated bandwidth. This can be achieved by using SVC, where a video sequence is encoded into a Base Layer (BL) and multiple Enhancement Layers (ELs). The base layer contains the information required to decode the video sequence at an acceptable quality level, while the enhancement layers are used to further enhance the video quality [21]. SVC supports three types of scalability, temporal, spatial and SNR/quality scalability. The concept of temporal scalability can be provided using hierarchical B-frames as shown in Figure 1.3. Different spatial frame resolutions are provided in spatial scalability. In SNR scalability, the spatial resolution remains the same and quality is enhanced. Quality scalability with enhancement layer drift concept is illustrated in Figure 1.4 [21,22].

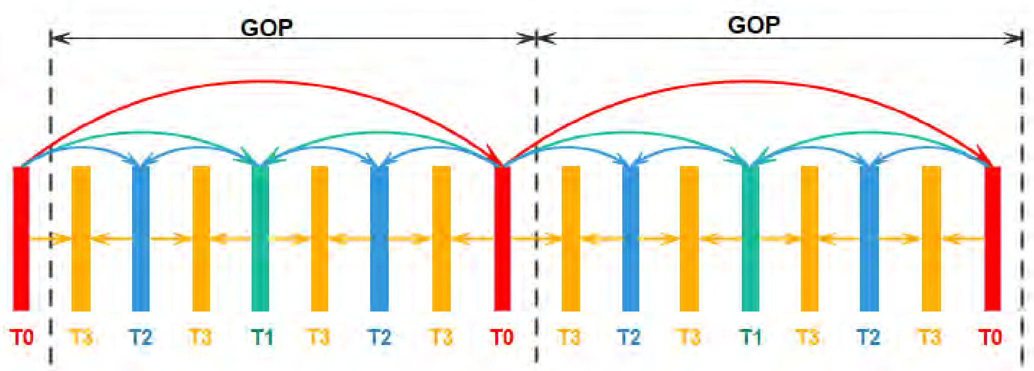

Figure 1.3: Temporal scalability.

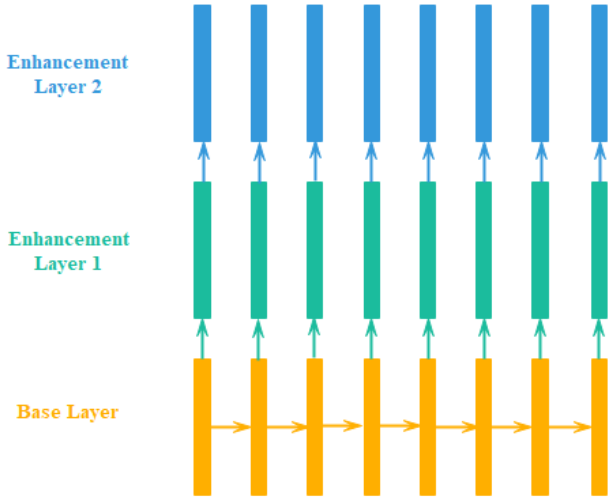

Figure 1.4: SNR scalability.

1.4. Video Streaming over D2D Communication

A few years ago, most of the mobile data traffic was due to low-rate data services and web-browsing applications. Recently, video-based applications (e.g., Netflix, YouTube, online gaming and social apps) have driven the explosive growth in data traffic [2]. According to the recent Global Internet Phenomena Report released by the networking company Sandvine in 2018, a video service like Netflix is actually responsible for 15% of the total downstream volume of traffic across the entire Internet [23]. Video service is a demanding application in term of deadline and bandwidth. Therefore, recent studies focused on improving the QoE of video streaming by employing D2D communication. QoE is generally linked to two main factors, namely, video quality and continuity of streaming, both of which are greatly influenced by channel conditions and the employed resource allocation technique.

In this study, we jointly address mode selection and resource allocation for multiple D2D pairs to improve video streaming over D2D networks. The main idea is to allocate resources and select mode of transmission for multiple D2D pairs to maximize the throughput while considering QoE requirements.

1.5. Objective

In this thesis, we combine D2D communication underlay LTE network with SVC to improve users' experience. Particularly, the objective is to jointly perform resource allocation, power control and mode selection to maximize the throughput of D2D pairs while maintaining continuous video playback with an acceptable quality level. Three modes of operation are considered; cellular, dedicated and reuse. Resource allocation and scheduling are performed in each mode taking into consideration the minimum rate required by CUs and D2D pairs, buffer occupancies as well as quality requirements. In reuse mode, the compatible D2D pair to each CU and power control are implemented to minimize the interference to CUs. Mode selection algorithm selects the mode that maximizes the throughput. The proposed scheme also determines the number of ELs to be transmitted based on buffer occupancy and frame deadline. Furthermore, the impact of network conditions and packet loss on video quality is estimated by using the packet-layer assessment model that uses the information of packet headers as input for quality estimation. Finally, the effect of mobility on quality of video stream and mode selection is examined.

1.6. Research Methodology

The following steps are followed to achieve the research objective:

- Design a joint resource allocation and mode selection approach that allocates resources and schedules both CUs and D2D pairs in cellular, dedicated and reuse modes, then performs mode selection to maximize the throughput.
- Investigate the transmission power to maximize the throughput taking into consideration mutual interference between D2D pairs and CUs in case of reuse mode.
- Modify the proposed approach to support video streaming over D2D network to satisfy users' requirements.
- Decide the number of layers to be fetched for each frame taking into account the playback deadline.
- Simulate the proposed mode selection approach for SVC over the D2D network using MATLAB software.

- Study the effect of mobile D2D pairs by adopting the Random Walk mobility model.
- Analyze results of experimentation for different schedulers and mode selection approaches to find the technique that provides better performance. Finally, the proposed mode selection approach is compared to the scenario when one mode of operation is assigned to all D2D pairs.

1.7. Thesis Outline

The rest of the thesis is organized as follows: Chapter 2 provides an overview of the available literature on mode selection and video streaming over D2D communication. Chapter 3 describes the system model and explains resource allocation, power control and mode selection mechanisms for video streaming over D2D communication underlay LTE network. The proposed approach is evaluated through computer simulation using MATLAB, simulation results and discussion are presented in Chapter 4. Chapter 5 contains the report conclusion and the future work.

Chapter 2. Literature Review

2.1. Mode Selection in D2D Communication

Integrating D2D into a cellular network introduces some challenges such as interference management, mode selection, mobility management and devices discovery that need further investigation. Generally, a D2D transmitter and receiver can communicate using three different modes; cellular, dedicated and reuse. In the cellular mode, a D2D pair communicates through an eNB using uplink and downlink channels as if it is a conventional cellular user. A D2D link could also be established over a portion of the cellular spectrum, which is dedicated to D2D communication in overlay D2D, whereas in underlay communication, D2D pairs reuse the cellular resources. Mode selection thus refers to the problem of deciding on which of the above three modes could be used to establish a connection.

Mode selection has got considerable research interest and usually it is jointly studied with power control, resource allocation or channel assignment [24]. For example, in [25], a mode selection approach is presented where the mode that maximizes the rate is selected as a mode of operation taking into consideration channel conditions and possible interference to CUs. Power control with joint resource allocation and mode selection is proposed in [26] with the goal of minimizing the D2D transmission power. If the required power of D2D transmission is above a predefined threshold, a cellular mode is selected. Also, power control with mode selection algorithm is proposed in [27]. The mode (cellular or D2D) that achieves higher power efficiency is chosen for transmission. The power efficiency is defined as a function of power consumption and transmission throughput. The objective of joint power control and mode selection mechanism introduced in [28] is to maximize the system throughput subject to minimum Signal to Interference plus Noise Ratio (SINR) of cellular and D2D users. In [29], mode selection and resource allocation are investigated. The dedicated mode is chosen as a mode of transmission when the D2D transmitter and receiver are close to each other and there are available resources. If there are no sufficient resources and the interference level is acceptable D2D pair reuses cellular spectrum. Otherwise, D2D pair communicates through the eNodeB. Finally, a distance-based mode selection algorithm with the aim of reducing the interference to CUs is introduced in [30]. Only cellular and reuse mode are considered, the main idea is to split the cell coverage into inner and outer regions. Users close to the BS (inner) operate in a cellular mode, while users in the outer region reuse the cellular spectrum.

2.2. Video Streaming over D2D Communication

D2D-based video transmission still encounters several challenges that are currently being investigated such as an extra energy overhead for D2D transmitters, complex network architecture and how to accommodate different video playback qualities for each user [31]. In the following sections, the available papers in video streaming over D2D networks that discuss different practical issues are presented.

2.2.1. Interference management. Introducing D2D communication imposes various challenges including mode selection, interference management as well as device discovery and security. An important issue that needs to be addressed in D2D communication underlaid cellular networks is the mutual interference between cellular and D2D users to maintain an appropriate level of Quality of Service (QoS). Clearly, integrating D2D communication into cellular networks introduces two kinds of interference, namely, co-tier and cross-tier interference. Co-tier interference is considered as interference between D2D pairs when multiple pairs share the same resources. While cross-tier interference occurs between D2D and cellular users when D2D pairs reuse the same resources allocated to cellular users. These two types of interference can occur between users within the cell; intra-cell interference, or between users from adjacent cells; inter-cell interference [7]. Figure 2.1 depicts different types of interference in D2D-underlaid wireless networks. Several interference management mechanisms have thus been discussed in the literature. These mechanisms target allocating radio resources (power and bandwidth) to cellular and D2D users in an efficient way so as to decrease the level of interference. This, in turn, maximizes the system throughput as well as preserves power [7]. Usually, resource allocation is jointly discussed with mode

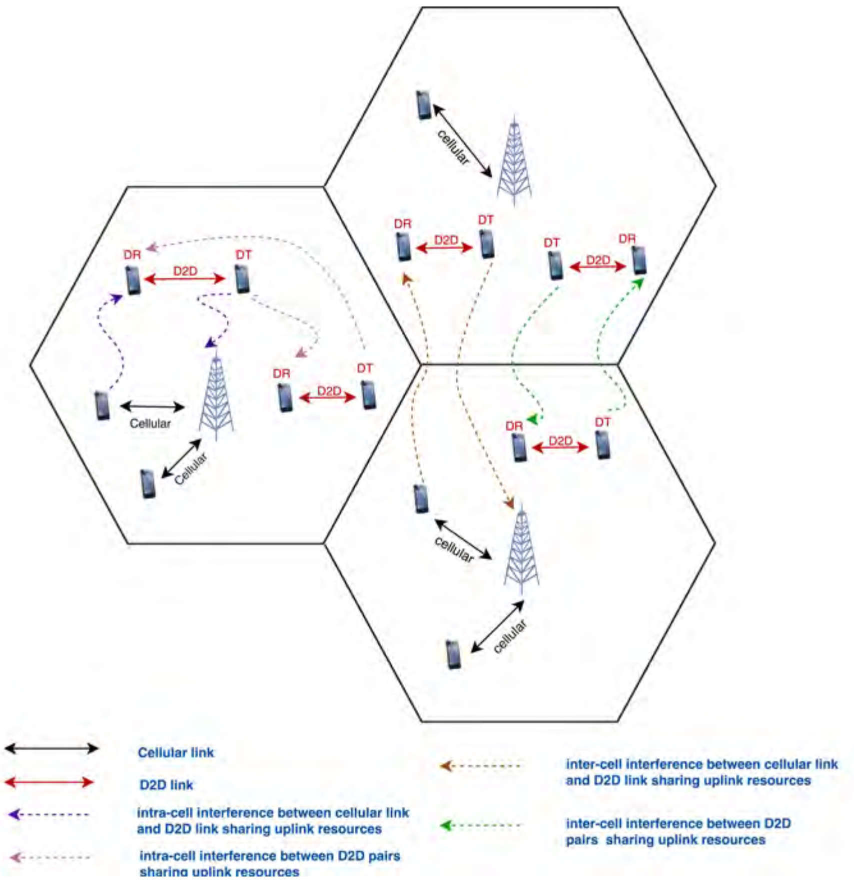

Figure 2.1: Types of interference in D2D-underlaid cellular network.

selection. In this subsection, we focus on works that addressed the effect of interference on the video streaming process on D2D links and ways to mitigate this.

To mitigate intra-cell interference between D2D pairs, some researchers allowed only one D2D transmission to be active per cluster in each time slot [32–34]. Furthermore, to avoid interference to UEs, they adopted outband D2D communication in the form of Wi-Fi Direct. Others ignored the existence of inter-cell interference completely between cellular and D2D links. For example, Golrezaei *et al.* assumed that the inter-cell interference is small and can be neglected [32], [35]. Also, in [36] the transmission power is assumed to be adjusted so that the cluster coverage is bounded by a radius r and the inter-cell interference is ignored.

Acknowledging the existence of inter-cell interference, many works have proposed the use of power control to limit its level. For example, the authors in [37] proposed a new algorithm to simultaneously send video using cellular and D2D links. When the transmitter and receiver are closely located, D2D transmission is enabled and the BS assigns a reuse uplink frequency for the D2D link while keeping the cellular transmission. A power control algorithm is then employed to limit the interference between the cellular and D2D links to a specific threshold. Similarly, interference from D2D pairs to CUs is mitigated by a D2D transmitter power control algorithm in [38] where simulation results also showed that enabling Full-Duplex (FD) transmission for the D2D terminals improves the achievable throughput and video quality via decreasing the download time. Also, an interference-limited area approach is proposed in [39] and applied to limit the interference from cellular users.

A different approach for handling interference has been proposed in [40] where the main idea is to control the interference level between the D2D and cellular users based on the importance of the video frames being transmitted. Specifically, based on whether the data belongs to an I-, P- or B-frames. The authors considered a network model consisting of an LTE UE that is uploading a video file to the network and a D2D user who is simultaneously transmitting data traffic to its neighbor. The D2D transmitter adjusts the probability of transmission depending on the type of frame being uploaded by the UE assuming that any damage in the I-frame affects the whole GOP. The authors formulated an optimization problem using the Markov process to maximize the throughput of the D2D link constrained to achieving a minimum Peak Signal to Noise Ratio (PSNR) for the video being uploaded to the network by the LTE UE.

Finally, a city monitoring application is presented in [41] where video streams from surveillance cameras are first processed for object detection purposes by real-time resources then uploaded to the network. The objective is to control the interference at the BS from D2D links that reuse the uplink spectrum. Based on the frame type and D2D transmission probability, a D2D transmitter decides whether to transmit data and interfere with the uplink video transmission or not. When an I-frame is being transmitted, the D2D transmitter chooses not to communicate with its neighbor and the interference at the eNodeB is reduced. Otherwise, if B or P frames are transmitted, the D2D link is established and interference will be introduced to the BS.

Resource allocation in video transmission over D2D links are tightly coupled to interference management and they both could actually be jointly tackled. Wu *et al.* investigated this issue in [42] and [43]. In [42], an algorithm is designed with the goal of minimizing the video Mean Square Error (MSE) for simultaneous k D2D pairs. The BS allocates sub-carriers and transmission power to each D2D pair based on the channel state and video rate distortion. A joint sub-carriers assignment and transmission power allocation algorithm with the goal of maximizing the overall video quality is proposed in [43] where k D2D pairs and N sub-carriers are assumed. Initially, randomly chosen N D2D pairs are assigned to N sub-carriers. Then using iterations, the remaining D2D pairs are assigned to sub-carriers while considering co-channel interference to the pre-assigned D2D pairs so that the overall video MSE decreases. Considering FD communications, power allocation for relay-assisted D2D communication is discussed in [44]. The objective is to maximize the D2D users' data rate while satisfying rate requirements for cellular users as well. In [45], a technique to offload cellular networks and reduce the number of resources needed for video streaming by using different interfaces such as Wi-Fi Direct and LTE Direct was proposed. By comparing different paths, the best interface is selected and when the video is transmitted using Wi-Fi Direct, the number of used LTE RBs is minimized. Furthermore, scheduling and admission control algorithms for a sequence of video chunks are formulated in [46]. Each chunk is encoded at various quality levels and the objective is to select the quality mode, source coding rate and the channel coding rate for each chunk for all the users. The quality of the chunk and the source coding rates selection is performed during the admission control phase, while the channel coding rates assigned by each helper are selected during the transmission scheduling phase.

2.2.2. Mode selection. A joint mode selection and video coding algorithm for video streaming is discussed in [24] to maximize the video quality in consideration of maximum energy consumption. After selecting the coding scheme for each frame (I, P or B), it is forwarded using one of the transmission modes; cellular transmission (direct BS, BS-relay) or D2D transmission (underlay-overlay). Also, power control is jointly considered with mode selection for variable bit rate (VBR) video streaming in [47] aiming at maximizing the overall data rate while considering buffer utilization (buffer underflow and overflow events). Transmission power in each of the three possible modes; cellular, dedicated and reuse, is determined then the optimal mode that achieves the best data rate is selected. Simulation results showed that the proposed strategy performs better than using one mode for the transmission. Mode selection is also studied in [48] and the mode is chosen based on the channel state CQI. However, only cellular and dedicated modes are considered to avoid interference to cellular users in the reuse mode. In a similar way, using outband D2D, the transmission mode is chosen to maximize the throughput under the packet delay constraint in [49]. Based on channel quality, the packet is transmitted directly from BS or through a relay via a D2D link.

2.2.3. Effect of D2D communication on video quality. Video-based applications have become the dominant traffic in wireless networks and in this type of applications, minimum requirements on the QoE of the end user need to be met. To improve the QoE, the work in [50] introduced a QoE-aware resource allocation algorithm for adaptive D2D video streaming. In adaptive video transmission, there is a tradeoff between video quality and the number of stall events. Transmitting video with high data rate results in high quality but this may lead to stall events under bad radio conditions. The proposed approach aims to maximize the quality of video taking into account the number of stall events. It performs better than QoE-oblivious resource allocation. Also, a QoE-aware power allocation algorithm for video transmission is presented in [51] to improve the user experience. The approach was to formulate an optimization problem that maximizes the video quality for all D2D users subject to a minimum data rate needed by each user, a maximum transmission power and a specific level of interference that can be tolerated. Similar to [52] and [53], Dynamic Adaptive Streaming over HTTP (DASH) is adopted for video streaming in [54]. Using the Max Weighted Independent Set (MWIS) and FlashLinQ link methods, scheduling and streaming algorithms are designed to maximize the quality of video transmission. First, scheduling is performed to decide which D2D pairs will transmit at each time slot by considering the interference threshold. Each video file is then split into chunks and each chunk is encoded at different quality levels so that in the next transmission step, each scheduled transmitter determines the quality level of each chunk. For a high-quality video with low-latency constraints, the authors in [55] proposed a joint source selection and power control mechanism with the aim of selecting the best source device. The power of the selected device is then adjusted to enhance video quality. Also, in [56], a location-based mechanism that exploits location information of the transmitter and receiver to choose the optimal route that maximizes the QoE of video streaming is proposed. Experimental results demonstrate that the proposed scheme significantly improves the QoE.

Even though most of the available work in the literature employ SVC as a video coding technique, experimental results conducted in [57] to compare different coding techniques reveal that Multiple Description Coding (MDC) is the best encoding scheme for real-time D2D video streaming from the point of view of QoE. The problem of real-time streaming when multiple devices are interested in receiving the same live video has been studied in [58]. In this work, the live video stream is divided into blocks, which are further split into smaller chunks. Each device was allowed to receive chunks via cellular and D2D interfaces, simultaneously. The authors proposed an algorithm to minimize the transmission through the cellular interface to save cost while considering the QoE, which was defined in terms of the average number of received blocks.

One of the new enabling technologies for next-generation cellular systems is utilizing the Millimeter Wave (mmWave) band. Due to the abundantly available bandwidth at mmWave frequencies, it is expected that this technology will have a very positive impact on video transmission. By exploiting mmWave, D2D multi-hop transmission is introduced in [59] to maximize the quality of video transmission by selecting the optimal route. A similar problem is addressed in [60] while taking the effect of interference and fading into account.

On another related front, the use of heterogeneous networks (HetNets) is expected to dominate in the near future. HetNets promise advantages such as offloading the cellular network, improving the data rates and expanding the coverage areas. This is achieved through the use of smaller cells including pico- and femtocells. However, the main issue in using this technology is that the Picocell Edge Users (PEUEs) suffer from low video quality due to interference from the much stronger microcell eNB. The work in [61] aims at improving the video quality of PEUEs by using two transmission paths; a direct path from the picocell eNB and a relay-assisted path from the picocell eNB to a selected relay then to PEUEs via D2D links. The second path is used only to recover frame losses if required as the relay sends the lost packets to the user until the frame is recovered. Comparing the proposed mechanism to the conventional scheme when there is only one transmission path from the picocell eNB to PEUEs and frame freeze is used as a frame recovery technique, the results show that the proposed approach enhances the video quality due to frames recovery using the extra added path.

2.2.4. Video caching for D2D communications. It has been observed that the significant increase in global data traffic is partly a result of duplicate downloads of popular video files [62]. Therefore, the majority of existing works on video transmission over D2D links propose the idea of caching popular video files in smartphones and sharing them with other users via D2D communication. D2D video caching thus exploits the large memory of smartphones and benefits from the redundancy in requested video content [2], [32].

2.2.4.1. Cell-clustering based caching schemes. Caching popular video files in mobile devices and getting videos from the users in the vicinity instead of the BS has been extensively studied in the literature [2], [32–36]. The idea of video caching is usually associated with the concept of clustering where groups of users are clustered together based on some criteria. Using caching schemes, video files can thus be received via different paths as illustrated in Figure 2.2. When a user requests a specific video file from the network and the BS finds that it has been cached by one of the requester's neighbors where the distance between them is less than a specific collaboration distance r, the file is transmitted using a direct D2D link. This transmission mode is labeled as direct D2D transmission as shown in Figure 2.2. When a user within the same cluster caches the file but the distance between the pair is larger than r, a relay is selected to transmit data between the pair. Alternatively, if the file is not available within the cluster, the BS gets the file from another cluster and forwards it to the requester, this is denoted as inter-cluster cooperation. Finally, if the requester caches the file, this is called self-requested transmission.

Golrezaei *et al.* [2], [32], [33] proposed splitting the cell into smaller square clusters. Every time the BS receives a video streaming request, it first checks the availability of the video file in the clusters. If the video content is cached by one of the

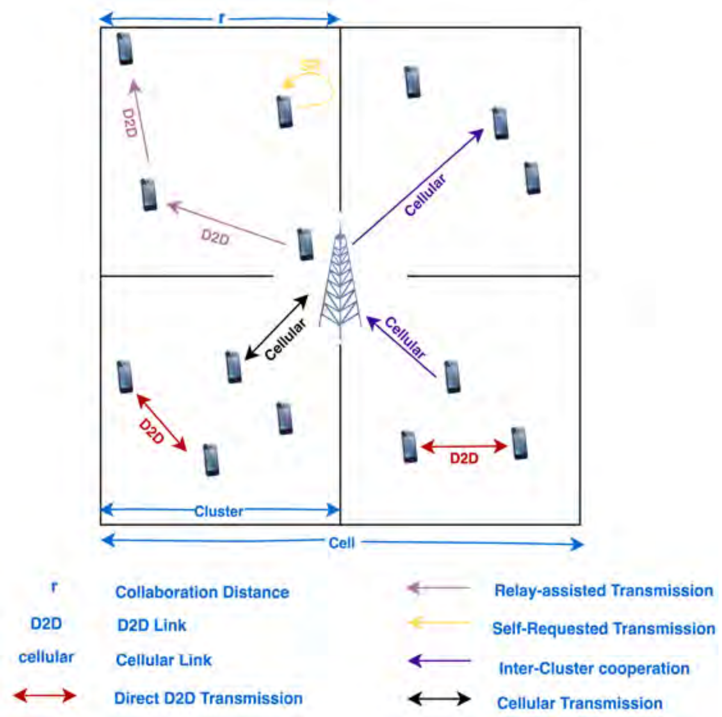

Figure 2.2: Various paths for video dissemination in D2D caching system.

UEs in the cluster where the requesting UE resides, the file is sent using D2D communication, otherwise, the BS serves the request. An important condition to have D2D transmission is ensuring that the collaboration distance between the D2D pair is smaller than a specific distance r, which is defined according to the transmission power. A cluster is called active if one D2D link is established within the cluster. Clearly, the cluster size needs to be optimized with the aim of maximizing the number of active clusters, which, in turn, helps in achieving throughput maximization. Furthermore, the authors formulated an expression for the scaling law of active D2D links with the number of UEs per cell in [2]. A new inter-cluster cooperation D2D caching architecture with the goal of minimizing the network delay is proposed in [34]. When the requested video content is not available within a specific cluster, inter-cluster cooperation is allowed. The BS gets the file from another cluster then sends it to the requester as shown in Figure 2.2. Simulation results revealed that the proposed algorithm decreases the network average delay by about 45% to 80%. In [36], the clustering idea is still adopted but with the cell divided into hexagonal instead of square clusters to improve the spectral efficiency. Moreover, relay-assisted transmission as denoted in Figure 2.2 is introduced when the separation between the members of the D2D pair is greater than r. Experimental results showed that the relay-assisted approach improves spectral efficiency with a small reduction in system throughput compared to non-relay approaches because relay transmission occupies two time slots. The authors in [35] provided an expression for the collaboration distance r as a function of caching content parameters. They also illustrated that throughput-scaling behavior depends on the popularity of the video file.

2.2.4.2. Centralized vs. distributed video caching. Generally, caching schemes can be divided into being either centralized or distributed. In the centralized approach, resource block and transmission power allocation, as well as the files to be cached by each device, are controlled by a central device (mainly, the BS or eNB) [33], [63]. Most of the studies in the literature have adopted centralized caching due to optimal file assignment by the eNB compared to the distributed version. In distributed caching, on the other hand, each device decides which file to cache, independently from the BS, which could lower the caching efficiency and leads to overlap and duplication of caching contents [34], [35], [64]. Having said that, a possible downside of centralized caching is the involved signaling overhead since it requires knowledge of Channel State Information (CSI) and the requests from users by the eNB [65]. The work in [32] studied the performance of centralized and distributed caching systems and analyzed the collaboration distance for both.

2.2.4.3. Caching in conjunction with video multicasting. Lots of works in the literature discussed combining video multicasting and caching in D2D communication. Multicasting allows serving multiple users concurrently by one transmitter. It has been reported in [66] that combining traditional video multicasting and D2D communication improved the overall data rate of the cell and, in particular, enhanced the performance of users placed at the edge of the cell. The basic idea of D2D multicast is dividing the users in the cell into a number of clusters based on their common interest in receiving a specific video file. Then, each Cluster Head (CH), who has previously received the required video from the BS, simultaneously transmits it to the multiple users in the cluster through D2D links. In [67], the authors proposed two caching models to determine the optimal number of video files M_o to be cached by the CHs. In the first approach, they optimized the value of M_o in order to maximize the hitting probability, while in the second model they tried to find the value of M_o that minimizes the energy consumption. The optimal number of video files to be cached was then compared between the two strategies. A D2D cooperative-assisted algorithm is introduced in [68] to achieve the required QoE of video for each UE where communication occurs in two steps; multicast and cooperative. Firstly, the BS multicasts the video content to a group of UEs via cellular links. Afterwards, in the cooperation stage, the users who successfully decoded all video layers (referred to as the responsible UEs) assist other UEs (the target UEs) to meet their QoE by transmitting the needed data using D2D communication. A similar idea was adopted in [69] to develop real-time video dissemination (e.g., for news or sports channels) to a group of UEs using two transmission phases. The authors presented an approach aiming at minimizing the mean video distortion using Instantly Decodable Network Coding (IDNC) and real-time video attributes. Two attributes of real-time video transmission were considered; namely, packets need to be decoded before a specific deadline and the different contribution of each packet to video quality. Firstly, the BS broadcasts video packets to all UEs, but due to the network conditions, some packets might be lost. Hence, in the next transmission phase, the devices cooperate using D2D communication to retrieve the missing packets. It is claimed that the proposed scheme enhances the quality of the received video. On another but related front, an approach to reduce the energy consumed by the BS and mobile devices in multicasting is presented in [70]. The energy-based cluster formulation mechanism consists of two stages; first, in the initialization phase all users communicate directly with the BS (one device per coalition) which represents a case without D2D communication. The following step is to find the user (cluster) that consumes the highest energy C_i per node. To reduce the energy consumption, the BS searches for the user C_j when it is merged with the highest energy consumption user, the total energy consumption reduces. This can be achieved by transmitting data to user C_j directly from the BS, then the user forwards data to the user with the high energy consumption C_i using D2D link. So that the total energy consumed by the formed cluster is lower than the energy consumed by cluster members individually communicating directly with the BS $E_{Ci \cup Cj} \leq E_{C_i} + E_{C_j}$. This process is repeated until no further enhancement (more energy saving) can be achieved. As before, the BS first broadcasts the video to the CH via cellular links, then the CH forwards the video to other devices through D2D links.

Although D2D communication is considered as a technique for offloading cellular networks, outband D2D (Wi-Fi direct) video multicasting in a dense area may result in congestion to the D2D links. This is due to simultaneous transmissions from multiple D2D pairs, which leads to degradation of transmission performance and increases the packet losses. In addition, the users could still be receiving data from the eNB via cellular links and forwarding it to other UEs using D2D communication. The existence of two types of connections may thus lead to cross-network interactions and eventual degradation in the performance of D2D transmission. To overcome these problems, powerful medium Medium Access Control (MAC) techniques are needed for efficient coordination of D2D transmissions. Using Network Coding (NC), the work in [71] presented an adaptive cooperative NC-based MAC (ACNC-MAC) approach for outband D2D communication.

How and which UEs are to be clustered together for video multicasting has also been extensively studied in the literature. A clustering technique with the aim of minimizing the total energy consumed by the BS and improving the video quality of the users situated at the edge of the cell was proposed in [70]. Also, Shen *et al.* [72], [73] proposed an energy efficient approach using the merge and split algorithm to form D2D coalitions to save the energy consumed at the BS. To control the total energy per coalition, the coalition head is chosen to reduce the energy consumption and a relaxation factor is introduced to determine the acceptable level of energy consumption per coalition. Alternatively, in [74], devices are separated into groups based on user interest. The two factors used to identify the CH are CQI and the battery level. Comparing [75] to [74], rather than transmitting the full video from the BS to the CH, the video is divided into segments and each CH receives a portion of the segments. Following that, each CH forwards the segments to its neighboring CHs. Finally, the complete video is transmitted to the devices within the cluster using Wi-Fi. Considering social behavior, [76] proposed mechanisms for cluster formation and CH selection using social characteristics of the users with the aim of increasing spectrum and energy efficiencies. Similar to [76], clusters are formed based on user preference, social attributes and location information [31]. First, the BS multicasts the video base layer to all users using minimum transmission rate, then the highest-rate link is selected for enhancement layers transmission. Clearly, some users with bad channel quality might be unable to decode all enhancement packets correctly, hence users multicast enhancement layers to each other to improve their QoE.

All the aforementioned papers targeted improving the performance of cellular networks using D2D communication. Another possible scenario where D2D communications can relieve the stress on a communication network is the case of Wi-Fi direct, which can be used to offload Wi-Fi Access Point (AP) in dense areas. In [77], for example, the authors considered an area with high-density traffic where multiple users are interested in downloading the same video file from a Wi-Fi AP. When all users try to download the file simultaneously, this increases the interference level and results in rate degradation. Hence, the authors suggested using D2D as a solution to offload the Wi-Fi AP. Clustering and scheduling algorithms are used to divide users into groups and organize files transmission where clustering is based on the position of users; users close to each other form a cluster. The user located at the center of the cluster is selected as a group owner, which receives the file of interest from the Wi-Fi AP and forwards it to the group members. In order to further reduce the interference between clusters, power control techniques are applied as well. Another example is in [78] where the authors suggest that a device can have two Wi-Fi links; a Wi-Fi direct link to a neighboring user and a Wi-Fi link to a hotspot. If the rate of the Wi-Fi direct link is higher, the video is transmitted using only the Wi-Fi direct link. If the throughput of the hotspot link is higher, the device can receive the video either from the hotspot only or from both links simultaneously.

2.2.4.4. Caching in conjunction with other schemes. Following up on the idea above and in order to improve the average and aggregate throughput of video streaming, Cached and Segmented Video Download (CSVD) has been presented in [79]. The BS splits the cell into small clusters and the UEs are assigned to each cluster based on their locations. Next, for each cluster, the BS selects the central users as Storage Members (SMs) to cache popular video files. Instead of caching the complete video content in one node, the BS subdivides the video into segments and stores them in multiple SMs so that the video can be simultaneously received from multiple nodes. When a user requests a video file, there are three transmission scenarios: if the file is available in the SMs, it is transmitted directly to a requester via a D2D link. If the requester is one of the SMs in one cluster, the BS sends the video through a cellular link and asks the SMs in the target cluster to save the file. Otherwise, the BS forwards the file to the user through a regular cellular transmission. The authors extended their work and introduced a new architecture to improve the QoE of video transmission in [52] and [53]. They combined the algorithm proposed in [79] with DASH and evaluated the performance of the new architecture. The metrics used to evaluate the QoS were video stalling, continuity index, initial delay and the bit rate. The proposed mechanism accomplishes significant improvements in QoE as captured by the above-mentioned metrics.

2.2.4.5. Energy consumption considerations. Many studies focused on the energy consumed by mobile devices and the BS to deliver a particular video file to a specific requester. Clearly, energy consumption is a critical issue especially for the UEs due to their limited batteries. In [80], an expression for the total energy consumed and the total hit probability (probability of being served by a D2D link) for video streaming over a D2D caching system is derived. The authors considered the energy consumed by the D2D transmitter and the BS when the file is not cached and the energy consumed to access video content in storage. Their target was to obtain a relationship between energy consumption and the content distribution mechanism. The energy consumed by a wireless device that accepts to participate in video distribution (referred to as the helper) is studied in [81]. The authors mainly considered SVC where Forward Error Correction (FEC) and MDC are applied. In MDC, the video stream is divided into substreams referred to as descriptions so the authors proposed an energy-aware rate and description allocation technique for video transmission in which the optimal number of descriptions to be assigned to each helper is optimized with the goal of maximizing the energy savings taking into account the channel gains, distances and interference to the BS. Considering the D2D CSI and the energy of the helpers, the rate of each video segment and the number of descriptions for each helper are determined. Comparing the proposed scheme to two non-optimal strategies, the results illustrate that the proposed approach conserves up to 300 joules and enhances the QoE. Later in [82], the same authors considered the effect of co-channel interference on cellular UEs for further system performance enhancement, in particular, the aim was to achieve high energy efficiency while considering the interference between D2D links and UEs. In [83], a caching strategy to maximize the cellular network offloading with an energy consumption constraint is investigated. Two parameters are optimized; the transmission power to minimize the energy consumption at helper devices and the caching distribution strategy to maximize the BS offloading. A user-centric caching technique is adopted where only users within a specific collaboration distance work as helpers. Also, the authors in [84] defined an optimization problem trying to satisfy energy and spectral efficiency requirements for video transmission using D2D communication. They formulated a problem with the goal of minimizing the energy consumption while meeting the rate requirements using transmission power adjustment, resource allocation and relay selection. Moreover, to avoid D2D links interruption during video dissemination due to battery outage at the helpers, a joint route scheduling and video traffic workloads algorithm based on a predefined energy budget for each device are presented in [85]. The proposed framework improves the performance of D2D-based cooperative video dissemination and results in a three-fold extension in its lifetime.

Along with energy considerations, the economic aspects of D2D communication are discussed in [86]. The goal is to offload cellular traffic into multi-hop D2D video distribution links since providers charge for cellular transmission and not for D2D links. A video dissemination algorithm with the objective of cellular traffic cost minimization taking into account the energy consumed by individual devices is formulated.

2.2.4.6. Incentive-based D2D schemes. Recently, an intuitive question has emerged; why should any user cache a video file, transmit it using D2D communication and drain its battery to provide high data rate for another user. Previously, researchers assumed that users are willing to collaborate and relay data to others using a direct D2D link. However, this is an impractical assumption. Practically, users will not help in distributing the video without getting benefits, so the providers have to pay incentives to encourage such behavior. To address the aforementioned issue, recent research directions investigate how users should be rewarded. For example, the work in [87] proposes motivating the users using a token-based strategy in which the requester purchases the service electronically from the helper and pays a token. A token acts like credit for the user so they can get relay service in the future. Likewise, an incentive mechanism to prompt users to participate in video distribution is introduced in [88]. Users are categorized into multicast and core users based on their social and mobility characteristics. Core users assist the BS in transmitting video to multicast users. A pricing-based scheme using Stackelberg game theory is proposed to reward core users. In that game, the BS is considered as a game leader that sets the initial price. After that, the followers (core users) show their strategies to the leader. A similar theory is employed in [55] for a pricing problem formulation. However, the UEs are set as leaders and the BS as a follower. Similarly, the authors in [1] proposed a contract algorithm by which the BS decides which user can be selected as a relay and determines the price to be paid for users who accept to work as sellers. They also proposed two algorithms to match between sellers and buyers with the objective of reducing the energy consumption at the BS. Incentive-based distributed cache in which users are rewarded for caching and helping in video distribution is presented in [64] where users can select to cache video files that increase their incentive. A major difference from the incentive-based mechanisms mentioned earlier is that the effect of interference is also considered where for each UE, the net utility is calculated as the rewards paid by the BS after subtracting the interference the D2D link introduces to the system.

2.2.4.7. Challenges. There are still some challenges in video caching D2D schemes that require further investigation. These include whether a user will still accept, in spite of the incentives, to participate in video distribution or not, reliability of the transmission, which basically depends on channel conditions, so efficient interference management and scheduling for D2D communication are required, the effect of mobility and finally, the need for regular updates of cache contents. These limitations may result in an increase in the Outage Probability (OP). As a result, some authors, as in [62] proposed a technique to reduce the OP via proposing multiple devices to a single device algorithm, where a reference user in dense areas requests a video file and receives it from multiple serving nodes at the same time thus effectively achieving diversity in reception. They derived an expression for the OP as a function of the UE memory size, the popularity of the requested videos as well as the SINR. The effect of different degrees of mobility on the performance of D2D caching has also been studied in [89].

2.2.5. D2D video streaming in public safety networks. D2D communications have generally been used in local services (e.g., social apps and local advertising), emergency communications and Internet-of-Things (IoT) improvement [90]. D2D is also considered as a technique that can significantly improve the performance of a cellular network when natural disasters such as earthquakes and hurricanes happen because the conventional network may be severely damaged [90]. For this reason, D2D communication has been exploited in public safety networks to transmit and receive real-time video, images and critical information to/from the disaster site [91]. Yaacoub *et al.* studied the performance of D2D communications in public safety networks in [92] where a coalitions formation algorithm is proposed to maximize the minimum throughput. The considered system consists of a BS and multiple users forming clusters where only one device CH communicates with the BS, receives video directly and then forwards the data to other Mobile Terminals (MTs). In the beginning, all MTs are connected to the BS, next, the MTs are sorted in ascending order using their achievable throughput so that the first device is the one with the worst channel conditions. Starting from the first MT, the D2D link that maximizes the rate is selected. If this MT is a CH, then the link to the BS is disconnected and the CH and group members are connected to the device that maximizes their rates using D2D links. In [91], a cooperative cluster formation approach with the target of minimizing the energy consumption of UEs using a merge algorithm is suggested. The proposed approach conserves the energy in both uplink and downlink directions. Furthermore, a relay selection algorithm is introduced in [93] to expand the coverage and improve the throughput of cellular users when the disaster location is far from the BS. The data is transmitted to the selected relay using D2D communication then a direct link is used to forward data to the BS. A relay is selected based on the relay-path throughput; a UE with the highest-path throughput is chosen as a relay. A resource allocation algorithm for D2D communication to improve the aggregate throughput of a public safety network is considered in [94]. Multiple D2D pairs are allowed to share the same resources when the interference level is below a specific threshold. Two scheduling algorithms are studied for that purpose; round robin and proportional fair.

Chapter 3. Methodology

In this chapter joint resource allocation, power control and mode selection approach for D2D-underlaid LTE network is presented. The proposed system model and assumptions are introduced first, then resource allocation and rate calculations in three modes of operation are discussed. Next, the mode selection mechanism is presented. Also, a power control algorithm to reduce the interference from D2D pairs to CUs in reuse mode is introduced. Following that, the effect of packet loss on video quality is discussed. Lastly, RW mobility model is implemented to represent the movement of UEs.

3.1. Throughput based Resource Allocation and Mode Selection Scheme

3.1.1. System model. We consider a single LTE cell with the eNB located at the center of the cell. A set of C CUs $\{1,2,3,...,C\}$ are randomly distributed. There are D D2D pairs enumerated by the set $\{1,2,3,...,D\}$. D2D pairs and CUs share a set of R orthogonal sub-channels $\{1,2,3,...,R\}$. Resource blocks are scheduled every TTI of 1 ms duration. Let dt and dr denote transmitter and receiver belong to the same D2D pair. Assume D2D communications underlay the existing network and share the downlink spectrum with CUs with Frequency Division Duplex (FDD). P_{UE} and P_{eNB} represent the maximum power of D2D transmitter and eNB respectively. Equal power allocation is adopted such that all RBs have the same transmission power, which is equal to the maximum power divided by the total number of RBs [95–97]. The channel gains $h_{i,j}$ between any two communicating nodes $i,j \in \{dt,dr,bs,c\}$ where bs denotes the base station and c denotes a CU, are assumed to be constant within each TTI.

Micro urban channel models introduced in [98, 99] are used in simulation. We consider distance-based path loss, shadow fading and Rayleigh fading. Shadow fading is modeled as a log-normal random variable. UE-to-UE follows the following path-loss $40\log_{10}(d[\text{km}]) + 49 + 30\log_{10}(f[\text{MHz}])$. Similarly, the path loss for eNB-UE link is defined as $36.7\log_{10}(d[\text{m}]) + 22.7 + 26\log_{10}(f[\text{GHz}])$.

Each D2D pair can operate in one of the three communication modes; cellular, dedicated and reuse based on the cellular network status as shown in Figure 3.1. In the

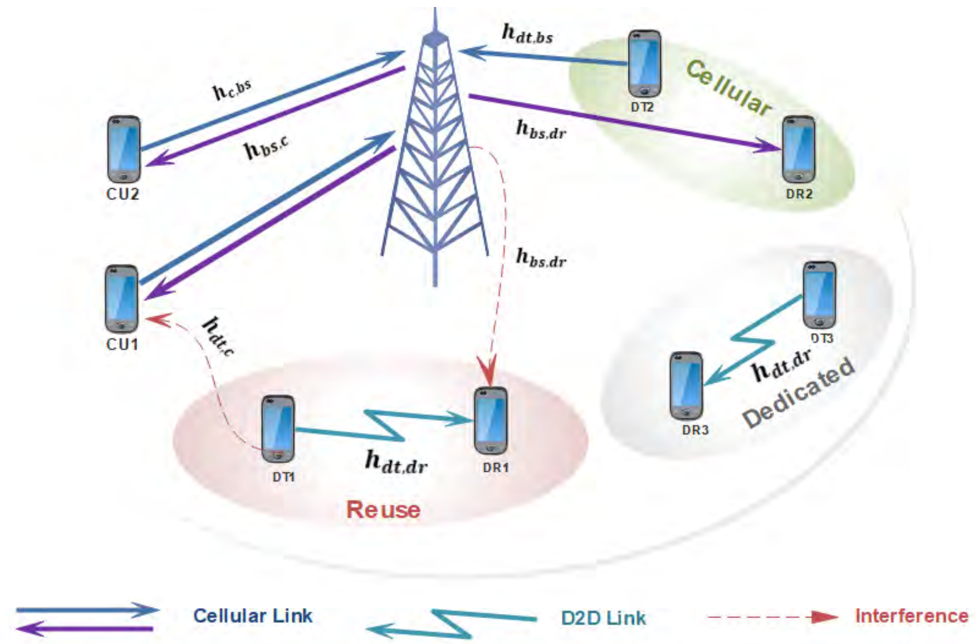

Figure 3.1: System model 1.

cellular mode, a D2D pair communicates as a conventional cellular user where uplink and downlink sub-channels are assigned to both the transmitter and receiver. If the dedicated mode is selected, dedicated resources will be assigned to each of the D2D links. Lastly, in the reuse mode, the D2D pairs share the downlink spectrum with the CUs and mutual interference is inevitable.

3.1.2. Resource allocation. Considering channel conditions, the minimum required rate by each user and the mutual interference between the D2D links and CUs, RBs could be allocated to each CU and D2D pair in three modes of operation as mentioned above. Two scheduling algorithms are considered in this work; round robin and proportional fair. The details of resource allocation and rate calculations in each mode are discussed in the following subsections.

1. Cellular mode: In this mode, the D2D transmitter and receiver communicate through the eNB using uplink and downlink sub-channels. Accordingly, the total number of CUs in this mode is effectively $K = C + D$. The first step is to assign RBs to the CUs using RR and PF scheduling. In RR scheduling, RBs are circularly assigned to CUs, whereas in PF the goal is to achieve a balance between fairness and throughput. The user with good channel conditions has a higher

priority thus RBs are allocated first to users with the highest proportional fair metric [100]. The number of RBs to be allocated to each user in PF scheduling can be estimated using the resource allocation algorithm proposed in [16]. The number of RBs, n, to be assigned to the kth user to achieve the required rate can thus be found as

$$n_k = \frac{\bar{r}_k}{\frac{1}{K}\sum_{j=1}^{K}\bar{r}_j} \times \frac{R_k^{\text{req}}}{\frac{1}{K}\sum_{j=1}^{K}R_j^{\text{req}}} \tag{1}$$

where $\bar{r}_k$ is defined as

$$\bar{r}_k = \frac{1}{R}\sum_{n=1}^{R}\text{SNR}_{k,n} \tag{2}$$

$\text{SNR}_{k,n}$ is signal-to-noise ratio of user k on RB n over a specific TTI, R is the total number of available RBs and R_k^{req} is the required throughput by user k.

The achievable rate of any user will depend on the nature of its communications link; whether D2D or CU. Thus, using Shannon's capacity formula and assuming a D2D link, the rate of D2D pair in cellular mode R_{D2D}^{C} can be calculated as

$$R_{D2D}^{C} = \min\left\{ B_{D2D}^{C}\log_2\left(1+\frac{P_{dt}|h_{dt,bs}|^2}{N_o B_{D2D}^{C}}\right), B_{D2D}^{C}\log_2\left(1+\frac{P_{bs}|h_{bs,dr}|^2}{N_o B_{D2D}^{C}}\right)\right\} \tag{3}$$

whereas for a regular CU, the rate is found to be

$$R_{CU}^{C} = \min\left\{ B_{CU}^{C}\log_2\left(1+\frac{P_c|h_{c,bs}|^2}{N_o B_{CU}^{C}}\right), B_{CU}^{C}\log_2\left(1+\frac{P_{bs}|h_{bs,c}|^2}{N_o B_{CU}^{C}}\right)\right\} \tag{4}$$

In (3) and (4), N_o is the Additive White Gaussian Noise (AWGN) power spectral density and B_{D2D}^{C} and B_{CU}^{C} are the bandwidths allocated to a D2D pair and a CU in the cellular mode, respectively. These can be found using

$$B_{D2D}^{C} = N_{D2D} \times BW \tag{5}$$

$$B_{CU}^{C} = N_{CU} \times BW \tag{6}$$

where N_{D2D} and N_{CU} are the number of RBs allocated to a D2D pair or a CU, respectively and BW represents the resource block bandwidth in LTE, which is 180 kHz. After calculating the rate using the estimated number of RBs, the next step is to schedule the users based on the following PF metric

$$\psi_k = \frac{R_k}{\bar{R}_k} \tag{7}$$

where R_k and $\bar{R}_k$ represent the instantaneous and average throughputs of the kth user, respectively. It is important to note here that in the cellular mode, two cases can be considered based on the number of available RBs. First, when the number of RBs is greater than the total number of resources required by the CUs, all users will be scheduled. However, when there are not enough RBs, part of the CUs with low PF metric will not be assigned RBs.

2. Dedicated mode: In this mode, two approaches are examined. First, we assume that part of the cellular spectrum is dedicated to D2D communication and any D2D pair communicates directly without passing through the eNB. The percentage of RBs dedicated to D2D communication is denoted by α where the value of α that maximizes the total system throughput will be chosen as will be shown in the simulations result section. D2D pairs are scheduled using RR and PF schedulers as before. Clearly, in PF scheduling, when the total number of RBs required by the D2D pairs is greater than $\alpha \times R$, some D2D pairs will not be scheduled. In the second approach, the cellular users are scheduled first, then the remaining resources are allocated to D2D communications. If all RBs are assigned to CUs, then no dedicated D2D links will be established. The throughput of a D2D pair or a CU in the downlink direction can thus be calculated as

$$R_{D2D}^{D} = B_{D2D}^{D} \log_2 \left(1 + \frac{P_{dt} |h_{dt,dr}|^2}{N_o B_{D2D}^{D}} \right) \tag{8}$$

$$R_{CU}^{D} = B_{CU}^{D} \log_2 \left(1 + \frac{P_{bs} |h_{bs,c}|^2}{N_o B_{CU}^{D}} \right) \tag{9}$$

where B^{D}_{D2D} and B^{D}_{CU} denote the bandwidth in dedicated mode for a D2D pair or a CU, respectively.

3. Reuse mode: In reuse mode, D2D pairs reuse the cellular spectrum to improve the spectral efficiency. However, they introduce interference to CUs. As will be shown later in the results section, PF scheduling provides better performance compared to RR scheduling in the cellular mode, therefore it is used for scheduling CUs in the reuse mode as well. Each D2D pair reuses the RBs of one CU. Hence, for each CU, the most "compatible" D2D pair needs to be selected. We assume that the number of CUs is greater than D2D pairs to ensure that all D2D pairs will be assigned to CUs. Various metrics to decide on the compatible D2D pair are proposed in [95] as detailed below:

   (a) Random: this metric randomly assigns D2D pairs to CUs.

   (b) Signal-to-Leakage-plus-Noise Ratio (SLNR): SLNR is a measure of how the D2D link leaks into CU communication. Specifically, it is the ratio between the desired signal and the leakage signal of a D2D link. The SLNR between a CU and a D2D pair is thus expressed by

$$\phi_{c,d} = \frac{P_{dt}|h_{dt,dr}|^2}{P_{dt}|h_{dt,c}|^2 + N_o B_R} \tag{10}$$

   where $P_{dt}|h_{dt,c}|^2$ represents the leakage signal and B_R is the bandwidth allocated to CU in the reuse mode.

   (c) Exhaustive Search (ES): following this metric, the CU shares its allocated RBs with a D2D pair that results in the highest exhaustive search metric, which is defined as

$$\vartheta_{c,d} = \frac{R_{CU,D2D}}{\bar{R}_c} \tag{11}$$

   where $\bar{R}_c$ is the average throughput of the CU when there is no interference and RBs are not shared with any D2D pair and $R_{CU,D2D} = R^{R}_{D2D} + R^{R}_{CU}$ with R^{R}_{D2D} and R^{R}_{CU} being the instantaneous throughputs of the D2D pair and CU sharing the same RBs, respectively. These can be calculated as

$$R_{D2D}^{R} = B_{D2D}^{R} \log_2 \left(1 + \frac{P_{dt}|h_{dt,dr}|^2}{P_{bs}|h_{bs,dr}|^2 + N_o B_{D2D}^{R}} \right) \tag{12}$$

$$R_{CU}^{R} = B_{CU}^{R} \log_2 \left(1 + \frac{P_{bs}|h_{bs,c}|^2}{P_{dt}|h_{dt,c}|^2 + N_o B_{CU}^{R}} \right) \tag{13}$$

3.1.3. Power control algorithm. In cellular and dedicated modes, since no interference is experienced between the CUs and D2D pairs in single cell scenario, the maximum output power of the eNB and D2D transmitter can be used to maximize the total system throughput. However, in the reuse mode, D2D pairs interfere with CUs links, which leads to degradation of the CUs throughput. Therefore, a power control algorithm is hereby developed to reduce the interference introduced to CUs with the goal of maximizing the total system throughput while guaranteeing the minimum rate required by the D2D pairs. At each TTI, the rates of each D2D pair and CU sharing the same RBs are calculated. If the achievable rate by a CU in the reuse mode is less than the required while the D2D pair is exceeding the target rate, the power of the D2D transmitter is reduced by a specific step Δ until either the CU reaches its minimum required rate or the D2D throughput declines to the minimum rate or the minimum transmit power needed to maintain the D2D connection is reached P_{min} of 0 dBm (0.001 w). When the rates of both the D2D pair and the CU exceed the minimum rates, the power of the D2D pair is decreased by the same power step Δ as long as the total rate after power reduction is greater than that before the power control step or again, the minimum D2D power is reached. It is worth noting that we choose not to implement power control at the eNB level since the interference from the eNB to the D2D receiver is small due to long distance between them. Therefore, applying power control by decreasing the power of eNB will not result in throughput enhancement. Details of the proposed power control mechanism are illustrated in Algorithm 1.

3.1.4. Mode selection. In this work, a mode selection approach with the objective of maximizing the throughput of D2D pairs while achieving the minimum rate required by CUs and D2D pairs is presented. Based on the rates achieved by each D2D

Algorithm 1 Power Control Algorithm

for each TTI, a CU with a required minimum rate $R_{CU}^{\min}$ and a D2D pair with a required minimum rate $R_{D2D}^{\min}$ sharing the same RBs **do**
    Initialize $P_{bs} = P_{eNB}$ and $P_{dt} = P_{UE}$;
    Calculate the D2D pair rate R_{D2D} using (12);
    Calculate the CU rate R_{CU} using (13);
    if $R_{D2D} > R_{D2D}^{\min}$ & $R_{CU} < R_{CU}^{\min}$ **then**
        repeat
            Update $P_D = P_D - \Delta$;
            Calculate the D2D pair new rate R'_{D2D} using (12);
            Calculate the CU new rate R'_{CU} using (13);
        until $R'_{D2D} = R_{D2D}^{\min} \,||\, R'_{CU} = R_{CU}^{\min} \,||\, P_D = P_{min}$
    else if $R_{D2D} > R_{D2D}^{\min}$ & $R_{CU} > R_{CU}^{\min}$ **then**
        repeat
            Update $P_D = P_D - \Delta$;
            Calculate the D2D pair new rate R'_{D2D} using (12);
            Calculate the CU new rate R'_{CU} using (13);
        until $R'_{CU} + R'_{D2D} > R_{CU} + R_{D2D} \,||\, R'_{D2D} = R_{D2D}^{\min} \,||\, P_D = P_{min}$
    end if
end for

pair in each mode, the eNB selects the mode of operation with the highest throughput. In cellular and dedicated modes, two scheduling techniques are implemented RR and PF, the rates of D2D pairs considered in mode selection are the rates achieved by the scheduler that maximizes the average throughput. In reuse mode, different metrics for selecting the compatible D2D pair and CU are compared. The metric that maximizes the average rate of D2D pairs is used to decide which of the three modes could be used for communication.

$$R_d = \max\{R_{D2D}^{C}, R_{D2D}^{D}, R_{D2D}^{R}\} \tag{14}$$

Two mode selection approaches are implemented, first when part of the cellular spectrum is dedicated to D2D communication and another approach when CUs are scheduled first then the remaining resources are assigned to D2D pairs in dedicated mode. To evaluate the mode selection, two approaches are compared to the scenarios when only one mode of operation is assigned to all D2D pairs.

3.2. QoE-aware Resource Allocation and Mode Selection for Video Streaming

3.2.1. System model. The proposed approach for mode selection presented in the previous section 3.1 cannot be directly applied to video streaming applications and further aspects should be considered such as video characteristics and user experience. Therefore, the system model proposed in section 3.1.1 is modified to support video streaming over D2D. We maintain the same network architecture as shown in Figure 3.2. We assume that the eNB is connected to a video server that delivers to the eNB a scalable-encoded video sequence using the H.264/SVC standard. Each frame is encoded into one base layer and L ELs. No-skip based streaming is adopted, if a base layer cannot be received by its deadlines, it will not be skipped and a stall event occurs. Assuming the video sequence is cached by each dt and the user is willing to collaborate, each dr can receive the video content either directly from the eNB or from its neighbor through a D2D link. The server is responsible for providing the video sequence encoded into multiple layers and extracting the encoding information, for example, frame rate, time duration, coding rate, layer quality and so on. Resource allocation, scheduling and mode selection are performed at the eNB. At the receiver side, we assume that the occupation of buffer and channel status information (CQI and CSI) are reported to the eNB.

Each D2D pair can operate in one of the three communication modes as mentioned earlier. In cellular mode, dr receives the video through the eNB. In dedicated and reuse, dr gets the video from dt in proximity either by sharing orthogonal resources with CU (reuse) or using dedicated resources (dedicated).

3.2.2. Resource allocation and power control. We consider SVC streaming scenario, where multiple UEs are trying to receive video sequence over D2D-underlaid cellular network in a single cell. In addition to channel conditions and required rate by each user, here, the resource allocation technique also considers QoE requirements; continuity and video quality. Based on the results obtained from a throughput based mode selection approach, the scheduler that maximizes the throughput is used in cellular and dedicated modes which is found to be PF scheduler as will be shown in the next

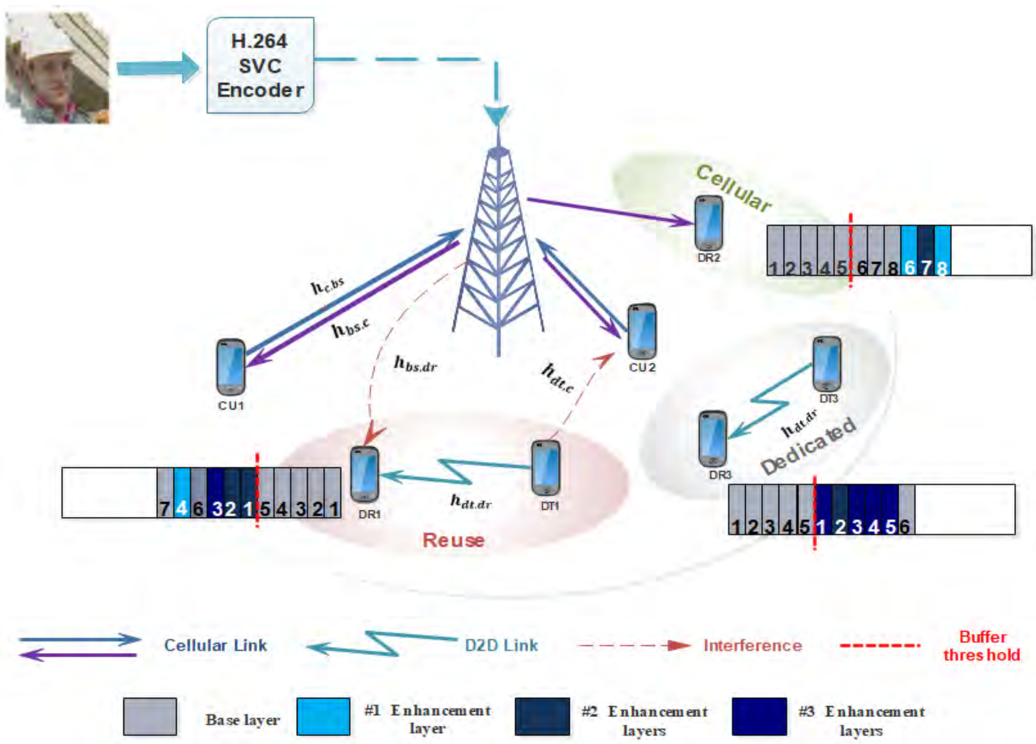

Figure 3.2: System model 2.

chapter. In reuse mode, ES metric is used to select a compatible D2D pair to each CU. After getting the number of resources to be allocated to each user, the value of SNR is calculated to be used in rate calculation in the following section. Finally, power control is performed for the D2D pairs operating in reuse mode.

The SNR in each mode of operation is calculated as follows:

- Cellular Mode

$$\mathrm{SNR}^{C}_{D2D} = \frac{P_{bs}|h_{bs,dr}|^2}{N_o B^{C}_{D2D}} \tag{15}$$

- Dedicated Mode

$$\mathrm{SNR}^{D}_{D2D} = \frac{P_{dt}|h_{dt,dr}|^2}{N_o B^{D}_{D2D}} \tag{16}$$

- Reuse Mode

$$\mathrm{SINR}^{R}_{D2D} = \frac{P_{dt}|h_{dt,dr}|^2}{P_{bs}|h_{bs,dr}|^2 + N_o B^{R}_{D2D}} \tag{17}$$

3.2.3. Rate calculation. For LTE network, the rate calculation may follow two approaches, one based on Shannon's capacity theorem and the second scheme based on LTE Transport Block (TB) structure.

1. Shannon's capacity can be used to predict the maximum theoretical rate of information transmitted through a channel using:

$$R_j^i = B_j^i \log_2(1 + \mathrm{SNR}_j^i) \tag{18}$$

where B is the bandwidth, $j \in \{D2D, CU\}$ and $i \in \{D, C\}$.

2. Based on LTE standard specifications, the rate can be calculated as follows:

   - 1 Time-slot (1 RB) occupies 0.5 ms.
   - There are 7 modulation symbols per 1 time-slot.
   - 1 Modulation symbol is used to transfer x bits, based on modulation scheme (QPSK, 16-QAM, or 64-QAM).

   According to LTE specifications:

   Maximum number of bits per TTI = number of subcarriers per RB * number of RBs per TTI * number of symbols per time slot * number of bits per symbol.

   Maximum number of bits per TTI = 12 * 2 * 7 * 6=1008 bits (assuming 64-QAM).

   The rate per TTI=1.008 Mbps.

   The maximum rate per sub-frame (TTI) is 1.008 Mbps, however, the overhead related to control signals should be considered. Therefore, based on LTE standard Release 13 each user is assigned a TB (in bits) over the system physical layer to transmit data. Each TB is transmitted over 1 TTI. The size of a TB, referred to as Transport Block Size (TBS), is decided upon the Modulation and Coding (MCS) assigned to the user and the number of Physical Resource Blocks (PRBs) allocated to the user by network scheduler as defined in the LTE Technical Specification in [101] Section 7.1.7.1, (Table A3). To find the rate, the eNB obtains the CQI from the feedback sent by the UE. The UE reports the CQI to the eNB by mapping the measured SNR to CQI [102], (Table A2). Periodic CQI reporting is adopted with a period of 2 ms. All RBs allocated to the same user should be assigned the same MCS index I_{MCS}. The size of TB to be assigned to the user is obtained based on mapping relation between I_{MCS}, TBS index I_{TBS} and the number of resources n_k allocated by network scheduler as defined in the LTE Technical Specification. In summary, in each mode of operation, the rate is found by

$$R^i_{k,t} = f(I_{MCS_{k,t}}, n_{k,t}) \tag{19}$$

where $i \in \{D,C,R\}$ and $f(I_{MCS_{k,t}}, n_{k,t})$ is a mapping relation between TRB index and number of resource blocks assigned to the user.

3.2.4. Mode selection. Based on the rate achieved by each D2D pair in each mode, the eNB selects the mode of operation that maximizes the throughput (14).

3.2.5. Problem formulation. The objective is to maximize the throughput of D2D pairs while guaranteeing minimum rate requirements of both CUs and D2D pairs by joint resource allocation, power control and mode selection. Denote $x^{(1)}, x^{(2)}, x^{(3)}$ are k dimensional vectors of cellular, dedicated and reuse modes, respectively, such that $x^{(3)}_k = 1$ if the kth D2D pair operates in reuse mode. $\mathbf{P} = \{P^{(1)}, P^{(2)}, P^{(3)}\}$ is a power matrix and indicates the transmission power in each mode for each user. $a^{(2)}_{r,k} = 1$ indicates the RB r is assigned to D2D pair k in dedicated mode and $a^{(2)}_{r,k} = 0$ otherwise. For cellular mode, UL and DL resources are considered $a^{(1_u)}_{r,k}$, $a^{(1_d)}_{r,k}$.

The problem can be formulated as

$$\begin{aligned}
\max_{\mathbf{x},\mathbf{a},\mathbf{P}} \quad & \min\left\{ \sum_{k=1}^{K} x^{(1)}_k \sum_{r=1}^{R} a^{(1_u)}_{r,k} B \log_2\left(1 + \frac{P^{(1)}_k |h_{dt,bs}|^2}{\sigma^2_N}\right), \right.\\
& \left. \sum_{k=1}^{K} x^{(1)}_k \sum_{r=1}^{R} a^{(1_d)}_{r,k} B \log_2\left(1 + \frac{P^{(1)}_{bs} |h_{bs,dr}|^2}{\sigma^2_N}\right) \right\}\\
& + \sum_{k=1}^{K} x^{(2)}_k \sum_{r=1}^{R} a^{(2)}_{r,k} B \log_2\left(1 + \frac{P^{(2)}_k |h_{dt,dr}|^2}{\sigma^2_N}\right)\\
& + \sum_{k=1}^{K} x^{(3)}_k \sum_{r=1}^{R} a^{(3)}_{r,k} B \log_2\left(1 + \frac{P^{(3)}_k |h_{dt,dr}|^2}{P^{(3)}_{bs} |h_{bs,dr}|^2 + \sigma^2_N}\right)
\end{aligned} \tag{20a}$$

s.t.

$$x^{(1)}_k, x^{(2)}_k, x^{(3)}_k \in \{0,1\},\ \forall k, \tag{20b}$$

$$a_{r,k}^{(1_u)}, a_{r,k}^{(1_d)}, a_{r,k}^{(2)}, a_{r,k}^{(3)} \in \{0,1\}, \forall k, \tag{20c}$$

$$\sum_{m=1}^{3} x_k^{(m)} = 1, \tag{20d}$$

$$\sum_{k=1}^{K} a_{r,k}^{(m)} = 1, \forall m \in \{1,2,3\}, \tag{20e}$$

$$\sum_{m=1}^{3} x_k^{(m)} R_k \geq R_k^{\min}, \forall k \in \{1,2,\ldots,K\}, \tag{20f}$$

$$R_c \geq R_c^{\min}, \forall c \in \{1,2,\ldots,C\}, \tag{20g}$$

$$\beta_k \geq \beta_{th}, \forall k \in \{1,2,\ldots,K\}, \tag{20h}$$

Constraint (20d) denotes that any D2D pair can select at most one of the three modes of operation. Constraint (20e) implies that any resource block can only be allocated to one D2D pair. Constraints (20f) and (20g) indicate the minimum rate requirements of CUs and D2D pairs should be guaranteed. Finally, buffer occupancy of the D2D pair should not go below the buffer threshold as illustrated by constraint (20h). In the next subsection, we provide an alternative heuristic algorithm to find a solution for this problem (20a).

3.2.6. Proposed algorithm. The details of the proposed algorithm performed by the eNB to allocate resources to multiple D2D pairs as well as select the mode of operation is illustrated in Algorithm 2. Resources are allocated to D2D pairs taking into account channel conditions, required rate by a user, instantaneous buffer occupancy and frame quality to achieve a balance between quality and continuity. Each D2D pair sends feedback to the BS contains buffer occupancy, CQI and CSI. After finding the number of resources to be allocated to each UE in each mode, the eNB starts calculating the instantaneous rate of each D2D pair using (19). In the dedicated mode, the BS compares the instantaneous buffer occupancies of all D2D pairs to the buffer threshold to determine the urgency of transmitting the frame to each pair. D2D pairs are categorized into two groups based on buffer occupancy. D2D pairs with buffer underflow and others with buffer occupancies that are equal or above a predefined threshold. Starting with D2D pairs that are under-flowing, the BS schedules users with higher priority given to the pair with the lowest occupancy to avoid buffer starvation. If there are available RBs after scheduling under-flowing users, the BS schedules D2D pairs with $\beta_{k,t} > \beta_{th}$ and gives higher priority to D2D pairs with higher scheduling metric $\varphi_{k,t}$ which is defined in (21). This metric gives priority to the user with high quality and less number of required resources.

$$\varphi_{k,t} = \frac{q_k^{f,l}}{\frac{1}{D}\sum_{k=1}^{D} q_k^{f,l}} \Big/ \frac{n_{k,t}}{\frac{1}{D}\sum_{k=1}^{D} n_{k,t}} \tag{21}$$

where $q_k^{f,l}$ is the quality of layer l belongs to a frame f transmitted to the kth user.

In cellular mode, D2D pairs are scheduled as conventional CUs using PF metric. In reuse mode, the compatible D2D pair is selected for each CU using ES metric. Finally, for each pair, the mode with the maximum throughput is selected for transmission.

3.2.7. SVC layer selection. Given the achievable rate, frame deadline and buffer occupancy the number of layers to be fetched is determined. If the buffer occupancy of a user is below the threshold, a base layer is transmitted to maintain the continuity. For users with buffer occupancies above the threshold, to decide whether to transmit a base layer or transmit enhancement layers to improve the video quality, we first estimate the time by which enhancement layers will be received. Then we compare the estimated buffer occupancy at that time to the predefined threshold. Enhancement layers will be transmitted when the buffer occupancy after transmission exceeds the threshold. From Figure 3.3, buffer occupancy at time slot j is estimated by subtracting the number of frames will be played during the transmission of the enhancement layers from the current buffer occupancy as shown below

$$\beta_{k,j} = \beta_{k,i} - \left(\frac{\sum_{l=1}^{L} b_k^{f,l}}{\overline{r_k}} \right) \times f_p \tag{22}$$

where $\beta_{k,j}$ is the buffer occupancy of kth user at j time slot, $b_k^{f,l}$ is the number of bits in

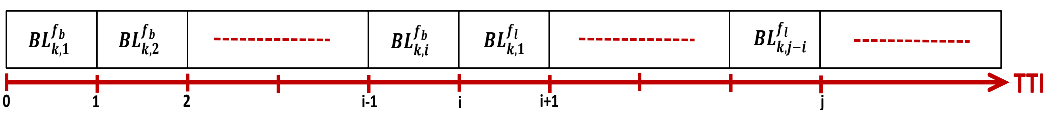

Figure 3.3: Transport block scheduling.

Algorithm 2 Resource Allocation and Scheduling Algorithm.

Input: NR, $q_k^{f,l}$, $f = \{1,2,...,F\}$, $l = \{0,1,2,...,L\}$, β_{th}, $\beta_{k,t}$, R_k^{req}, $\text{CQI}_{k,t}$, $K = \{1,2,3,...,K\}$;
Initialization: U=N=ϕ;
for each TTI t, $\forall k \in K$ **do**
    Dedicated Mode:
    $NR_D = \alpha \times NR$;
    Calculate $n_{k,t}$ using (1);
    Calculate $\varphi_{k,t}$ using (21);
    Find $R_{k,t}^D$ using (19);
    if $\beta_{k,t} < \beta_{th}$ **then**
        $U = U \cup u_k$;
    else
        $N = N \cup u_k$;
    end if
    Schedule U with min $\beta_{k,t}$;
    $NR_D = NR_D - \sum n_{k,t}$, for $u_k \in U$;
    if $NR_D > 0$ **then**
        Schedule N with max $\varphi_{k,t}$;
    end if
    Reuse Mode:
    Schedule CUs using PF metric (7);
    Select a compatible CU for K D2D pair using ES metric (11);
    Perform power control algorithm 1;
    Find $R_{k,t}^R$ using (19);
    Cellular Mode:
    $K = D + C$;
    $NR_C = (1 - \alpha) \times NR$;
    Calculate $n_{k,t}$ using (1);
    Find $R_{k,t}^C$ using (19);
    Schedule CUs using PF metric (7);
    Mode Selection:
    $R_{k,t}$=max($R_{k,t}^D$,$R_{k,t}^R$,$R_{k,t}^C$);
end for

enhancement layer l belongs to frame f and $\overline{r_k}$ is the average throughput of the kth user. f_p represents the playback rate. In Figure 3.3, $BL_{k,i}^{f_b}$ is the TB number i for transmitting the base layer of a frame f.

EL is transmitted when the estimated buffer occupancy after the transmission is above the threshold and when all lower layers it depends on have been fetched. The number of layers to be transmitted is found by satisfying the condition that the number of layers L of a frame f to be transmitted should be received before the frame display deadline by adding the current time slot i to the time required to transmit ELs as below

$$i + \frac{\sum_{l=1}^{L} b_k^{f,l}}{\bar{r}_k} < display\,time\,of\,a\,frame\,f \tag{23}$$

3.3. Effect of Packet Loss on Video Quality

3.3.1. Effect of tolerance on frame loss. Video is encoded as a sequence of three compressed frames I, P and B. For P or B frame to be considered decodable, all frames they depend on must be received and considered decodable. For example, partially received I or P frame propagates the error to all dependent frames and corrupts them. Decodable threshold criteria defined in [103] is employed to consider frame is decodable or not [103]. The frame is considered decodable if a fixed fraction dt is received and only when all frames it depends on are considered decodable. Thus, if dt equals 1, the decoder is intolerant to losses and one packet loss is enough to consider frame undecodable. Similarly, if $dt = 0.75$, decoder can tolerate up to 25% of losses. However, this tolerance is obtained at the expense of adding more data to the video stream (FEC redundancy). Given a certain value of dt, the overhead obtained due to the adoption of a certain level of tolerance $v(dt)$ is expressed by

$$v(dt) = \frac{1 - dt}{dt} \tag{24}$$

3.3.2. Effect of packet loss on frame quality. FEC is an effective technique to enhance the video quality by recovering the lost packets at the receiver. However, FEC cannot recover all packets if the number of lost packets exceeds the number of redundant packets. Hence, the effect of packet loss on the frame quality when the loss is larger than the tolerance level at the decoder needs to be considered. Packet loss seriously affects the quality of reconstructed video sequence transmitted over a lossy channel, and not only corrupts the frame with lost packets but also the error propagates to the subsequent frames until the next I frame due to video frame dependency. The visibility of distortion caused by packet loss is directly related to the video content, in particular, temporal and spatial complexity. The overall effect of packet loss on frame quality can be estimated using the packet-layer model proposed in [104]. The impact of packet loss is a combination of distortion due to packet loss and the distortion induced due to error propagation. The frame quality considering packet loss is defined as

$$Q(n) = \max(Q_c(n)) - d(n), 1) \tag{25}$$

where $Q(n)$ and $Q_c(n)$ represent the final and at the encoder side quality of the nth frame, respectively. $d(n)$ is the quality degradation on the nth frame and it is measured by

$$d(n) = d_e(n) + d_p(n) \tag{26}$$

$d_p(n)$ is the distortion on nth frame directly due to packet loss, whereas $d_e(n)$ is a quality degradation due to error propagation. Here, $d_p(n)$ is defined as

$$d_p(n) = \frac{n_T(n) - n_R(n)}{n_T(n)} . \left(\frac{\sigma(n)}{c_1}\right)^{c_2} .Q_c(n) \tag{27}$$

where c_1 and c_2 are model parameters [104], $n_T(n)$ is the total number of blocks related to the nth frame, the number of valid blocks for decoding the frame is denoted as $n_R(n)$ and $\sigma(n)$ is the estimated temporal complexity which is expressed as

$$\sigma(n) = |r_{P/I} - b.R(n)| \tag{28}$$

$$r_{P/I} = \frac{R_P}{R_I} \tag{29}$$

where $R(n)$ is the number of bits for encoding the nth frame in a GOP, R_P is the average number of bits for encoding P frames in the same GOP and R_I is the number of bits for encoding I frame. b is a model parameter obtained by training using four video sequences [104].

For error propagation, the authors in [104] assumed a linear function can be used to simulate the quality degradation of the current frame with respect to the reference frame when the distance between the current frame and the last frame suffered from packet loss less than 8 frames. On the other hand, the quality degradation is unchanged when the frame is far from the frame with lost packets.

The adopted model uses Mean Opinion Score (MOS) as video quality metric, whereas, the trace file provides the PSNR of encoded video sequence. Therefore, mapping from PSNR to MOS is performed [105].

$$Q = Q_{max} \left(1 - \frac{1}{1 + e^{p(PSNR-s)}} \right) \tag{30}$$

where Q_{max} is the max MOS, p and s are model parameters [105].

3.4. Mobility Model

In the previous sections, static nodes are considered. Here, we evaluate the effect of mobility on video quality and mode selection. Mobility models are used to represent the unpredictable movement of mobile nodes. Different mobility models are proposed in the literature and Random Walk (RW) model is selected to simulate the movement of mobile devices [106,107]. In RW, the node starts the movement by choosing speed and direction from predefined ranges [0, V_{max}] and [0, 2π]. The mobile node moves for a fixed time duration which is equal to 1 ms (1 TTI). After an interval of t, new speed and direction are chosen. Two metrics are used to show the effect of mobility, PSNR and contact probability. Contact probability is defined as the probability that the user is within the D2D range and data is received directly from the neighboring device using either reuse or dedicated mode [108].

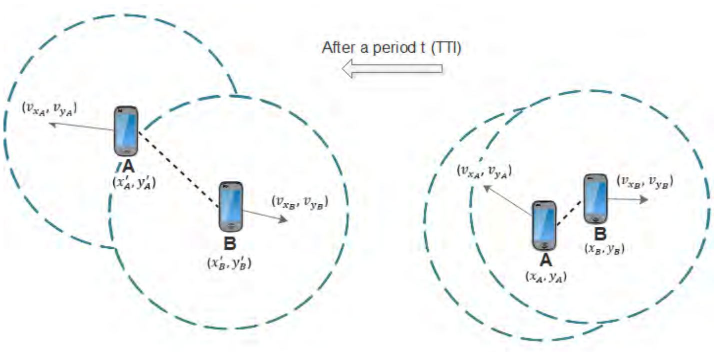

Figure 3.4: Mobility model.

Chapter 4. Simulation Results

In this chapter, we evaluate the performance of the mode selection approach presented in Chapter 3 through extensive simulations. We consider a single LTE cell with an eNB located at the center of the cell with a radius of 500 m and has 50 CUs. CUs are distributed randomly in the cell. Also, D2D pairs are placed randomly around the eNB, however, the D2D receivers are located within a disk around the transmitters with maximum radius r. Simulation results of the proposed approach are compared to the case when one mode of operation is assigned to all D2D pairs, either the cellular, dedicated or reuse.

4.1. Simulation Parameters

MATLAB has been used as a simulation environment and the numerical results are averaged over 1000 simulation runs. Besides the general system description, simulation parameters are set as shown in Table 4.1. Based on the LTE standard, we set the transmission power of the eNB and UEs to the maximum value 46 dBm (39.8 W) and 23 dBm (0.1995 W) respectively [101]. Micro urban channel models from [98,99] are used for the simulation. E-UTRA Band 7 is selected for UL and DL [101]. The maximum possible number of RBs for the LTE system is considered 100 RBs (20 MHz).

Moving to video streaming parameters, two video sequences have been used from trace file library; city and crew [109]. Video sequences are encoded into one BL and three ELs with playback rate of 15 frames per second. SNR scalability is adopted and the structure of a GOP is IBBBPBBBPBBBPBBB, with hierarchical dependency between the frames of each layer as shown in Figures 1.3 and 1.4. We set buffer threshold β_{th} to 4 frames. The decodable threshold dt is set to 0.75, thus 25% BLER can be tolerated. As a consequence, 33% overhead is added to the video stream. The authors in [104] obtained model parameters for packet-layer model (27) through training using four video sequences, $b = 0.25$, $c_1 = 0.182$ and $c_2 = 0.842$. Model parameter p for mapping model was set in [105] to 0.34 and the value of s depends on the video sequence (city $s = 26.32$, crew $s = 29.63$).

Table 4.1: Simulation parameters.

Parameter	Value
Cell radius	500 m
Distance between D2D Tx and Rx	30 m, 15 m
Uplink frequency	2.56 GHz
Downlink frequency	2.68 GHz
Number of cellular users	50
Number of D2D pairs	25
Maximum transmission power of eNB	46 dBm
Maximum transmission power of D2D Tx	23 dBm
Number of downlink RBs	100 (20 MHz)
Shadow fading std of D2D link	12 dB
Shadow fading std of cellular link	4 dB
Cellular pathloss model	$36.7 \log_{10}(d[\text{m}]) + 22.7 + 26 \log_{10}(f[\text{GHz}])$
D2D pathloss model	$40 \log_{10}(d[\text{km}]) + 49 + 30 \log_{10}(f[\text{MHz}])$

4.2. Throughput based Mode Selection Scheme

First, before applying video streaming, the proposed model is evaluated to find the metric and scheduling algorithm that maximize the throughput of D2D pairs in each mode. In cellular mode, the CDF of the average throughput in cellular mode when all D2D pairs communicate through the eNB as CUs is shown in Figure 4.1. Two scheduling schemes are implemented and it can be clearly seen that PF scheduling outperforms RR scheduling in both UL and DL, therefore, it is selected as a scheduling technique. Reasons for sharp CDF behavior in UL and DL include graph scaling and the small standard deviation (around 0.0002 Mbps) which implies that the achievable rates per TTI are close to the mean. Due to small power in UL (transmission power of UE) and based on equation (1), less number of resources are allocated to users in UL which reduces the difference in the average throughput between PF and RR in UL compared to DL direction.

Similarly, the performance of two schedulers are compared in dedicated mode and as expected PF provides better performance than RR scheduling as depicted in Figure 4.2. For the dedicated mode, as mentioned earlier, two approaches are implemented. In the first approach, a percentage α of RBs is allocated to the D2D pairs (PF-1). The total network throughput versus the percentage of RBs for a different number of CUs is illustrated in Figure 4.3. As shown in the figure, as the number of CUs increases, the value of α that maximizes the total throughput decreases. Increasing the number of D2D pairs does not affect the value of α and the total throughput increases. Using simulation parameters the value of α that maximizes the system throughput is found to be 70%. The second approach (PF-2) provides lower performance when the CUs are scheduled first and the remaining resources dedicated to D2D communications as presented in Figure 4.4. Although the first approach maximizes the total system throughput and improves the performance of D2D pairs, allocating 70% of RBs to D2D communications leads to 0.45 blocking probability for CUs.

In reuse mode, three metrics are used to select the compatible D2D pair to CU, namely, random, SLNR and exhaustive search as shown in Figure 4.5 and exhaustive search metric provides better performance.

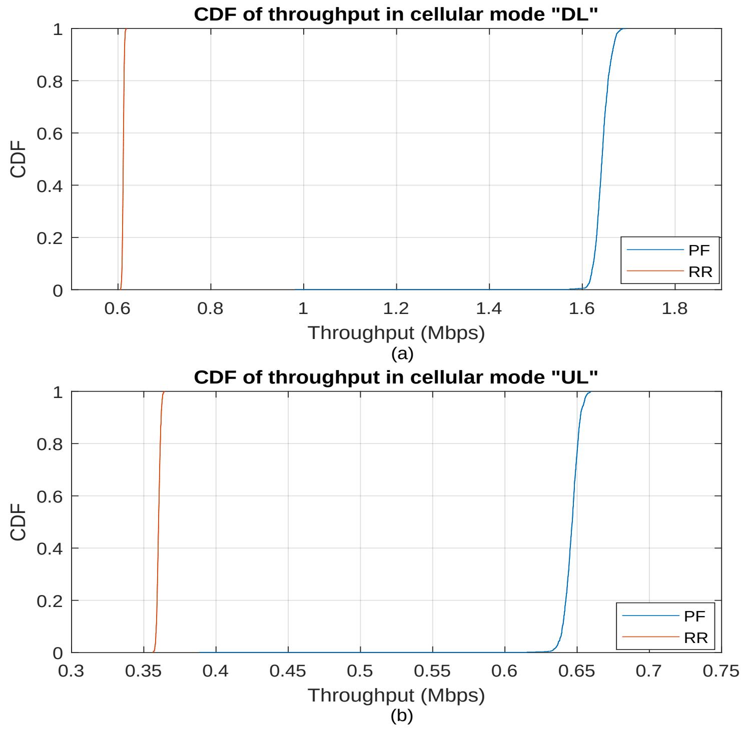

Figure 4.1: (a) CDF of the average throughput in cellular mode (DL). (b) CDF of the average throughput in cellular mode (UL).

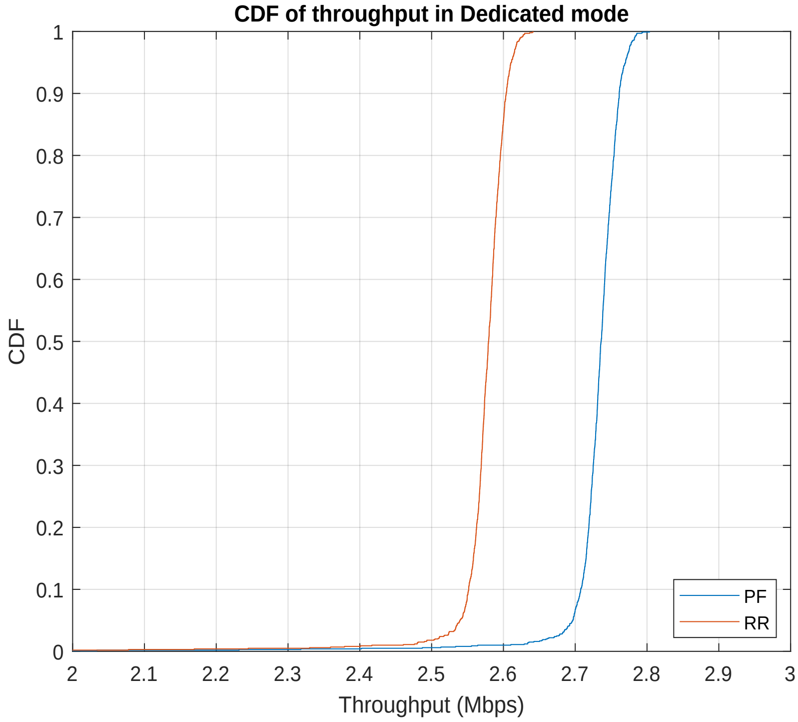

Figure 4.2: CDF of the average throughput in dedicated mode.

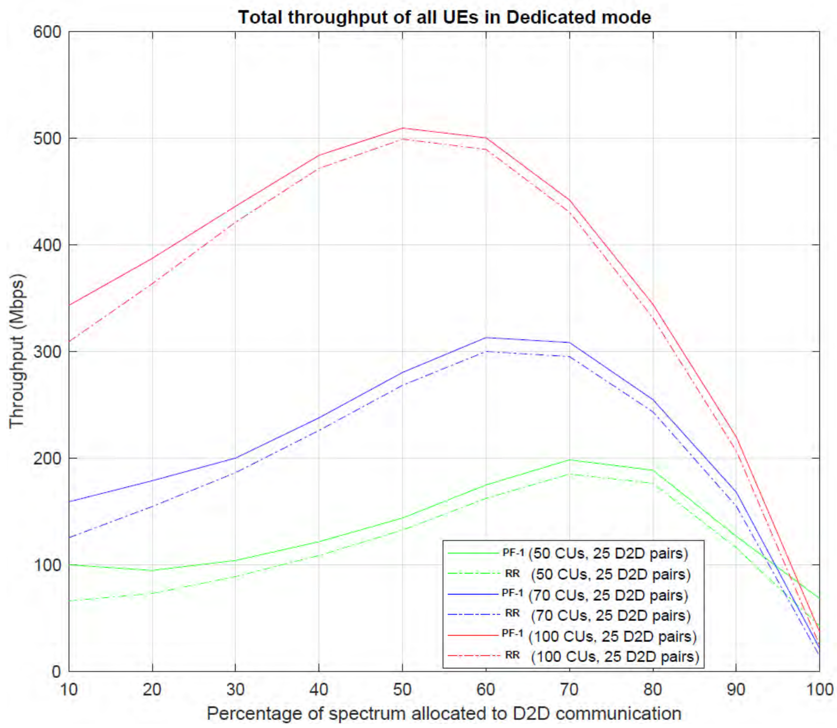

Figure 4.3: Total throughput in dedicated mode for different values of α and different numbers of CUs, D=25.

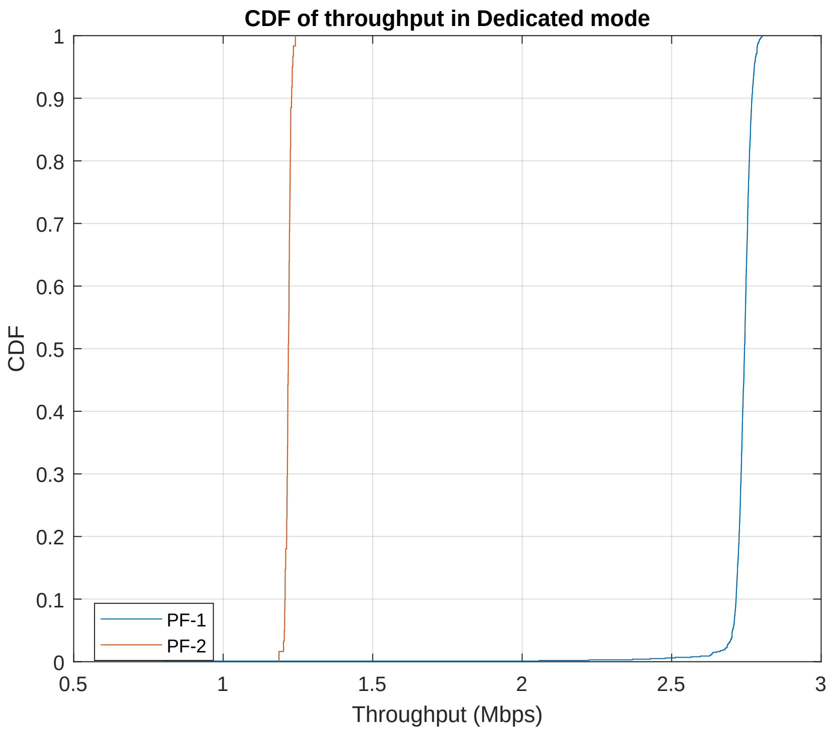

Figure 4.4: CDF of the average throughput in dedicated mode using two approaches.

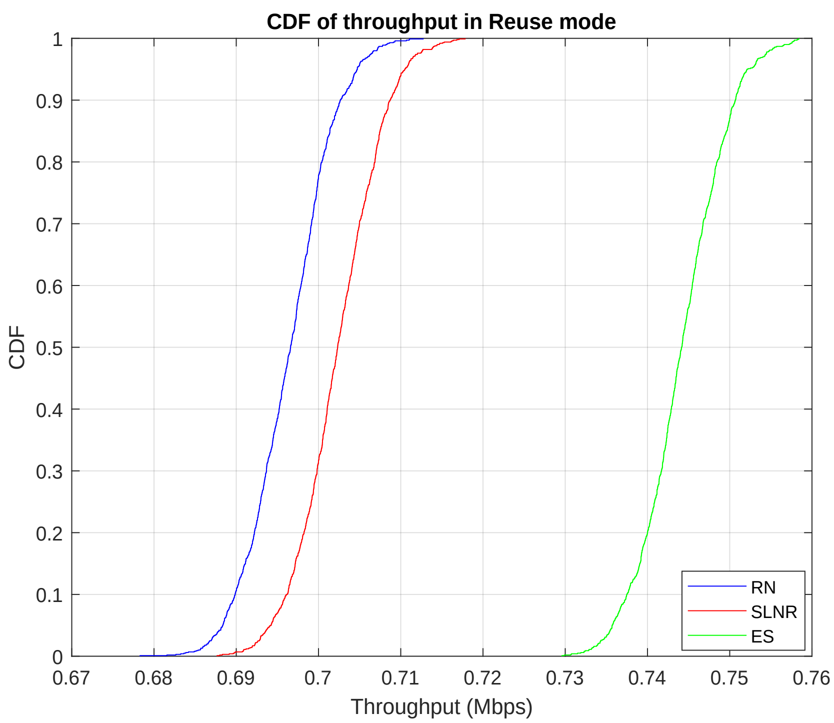

Figure 4.5: CDF of the average throughput in reuse mode.

The proposed mode selection approach is evaluated by comparing the approach to scenarios when mode of operation is assigned to all D2D pairs. Figure 4.6 compares mode selection approaches to three modes of operation, cellular, dedicated or reuse mode. In MS-1 70% of RBs are assigned to D2D communications whereas in MS-2 only remaining resources after CUs scheduling are dedicated to D2D. Mode selection with RBs dedicated to D2D pairs achieves the highest throughput.

The number of D2D pairs operating in each mode is depicted in Figure 4.7. The percentage of D2D pairs in each mode in two mode selection approaches is presented in Figure 4.8. 60% of D2D pairs operate in the dedicated mode when part of the spectrum is allocated to D2D communications. However, this percentage significantly declines to 34% for the second approach since only the remaining resources after CUs scheduling is assigned to D2D communications. As a result, the percentage of D2D pairs operating in cellular mode experiences a large increase from only 2% to 35%.

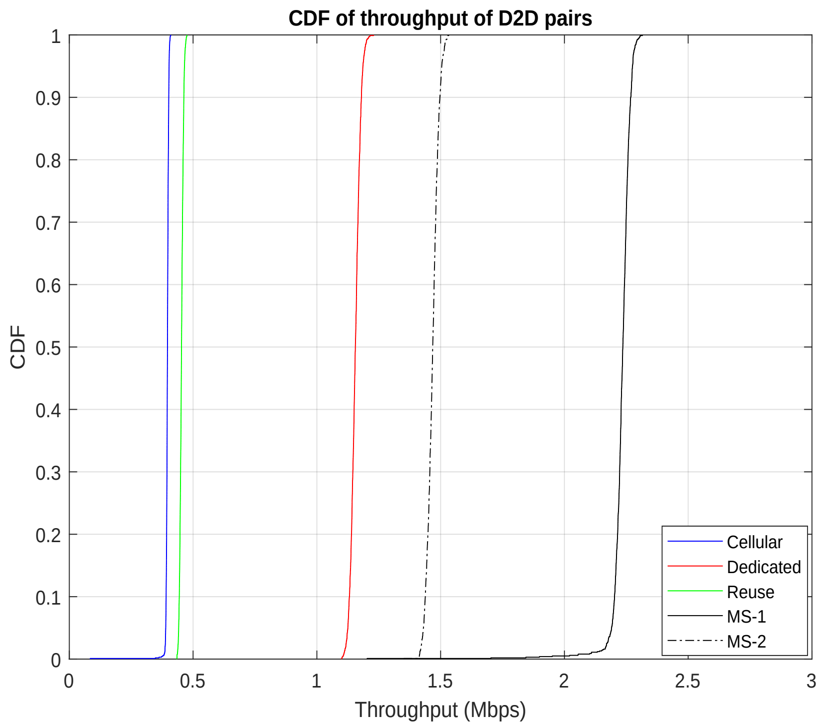

Figure 4.6: CDF of the average throughput comparing three modes of operation and two mode selection approaches.

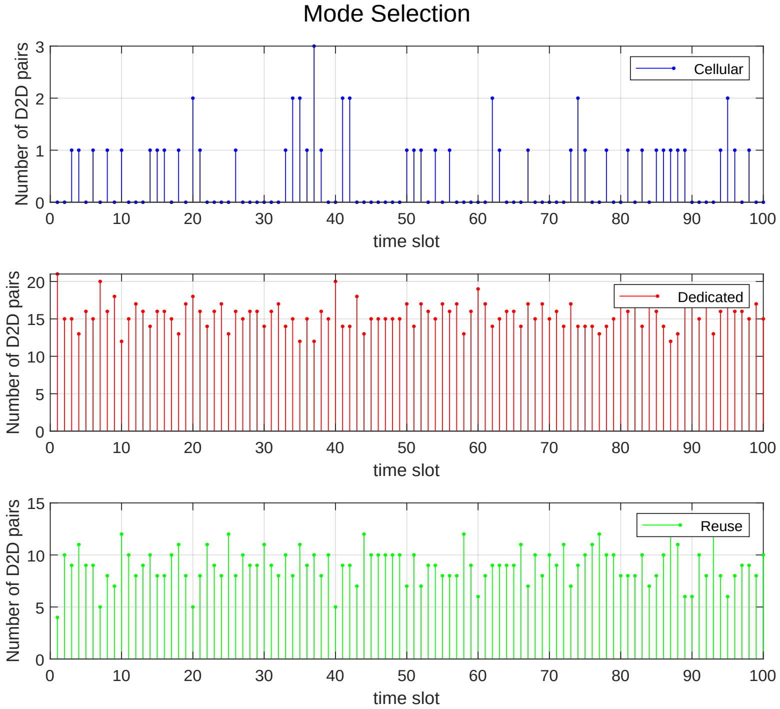

Figure 4.7: Number of D2D pairs operating in each mode.

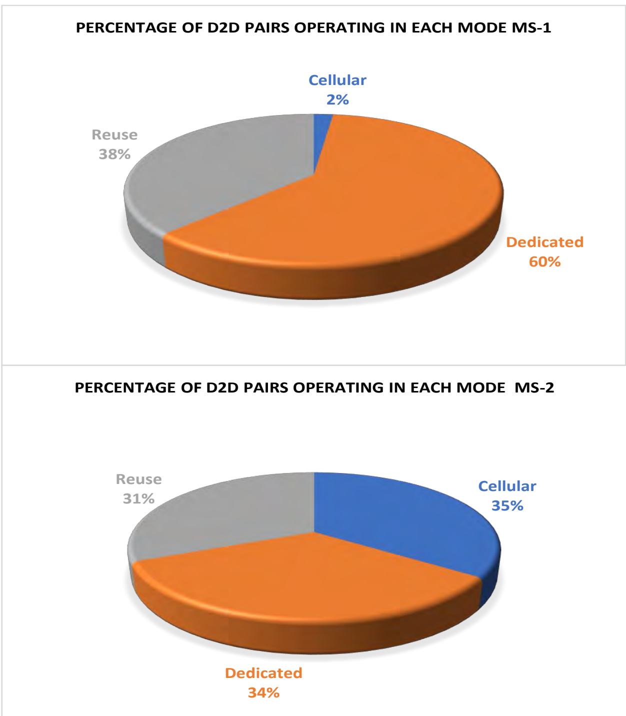

Figure 4.8: The percentage of D2D pairs operating in each mode.

- **The effect of changing the distance between D2D transmitter and receiver:**

The impact of changing the distance between the D2D Tx and Rx is next examined by varying the distance from 10 m to 70 m. PF provides better performance in the dedicated mode as shown in Figure 4.9 and the throughput achieved by ES is slightly better than random and SLNR metrics as presented in 4.10. In dedicated and reuse modes, there is a gradual decline in the system throughput as the distance between pair increases as shown in Figures 4.9 and 4.10.

Figure 4.11 represents the effect of increasing distance in three modes and mode selection. As expected, in cellular mode, changing the distance does not affect the overall throughput because all pairs communicate via the eNB. The throughput drops below 1 MHz in dedicated and reuse modes when the distance between transmitter and receiver is greater than 50 m and D2D pairs select to communicate through the BS (cellular mode).

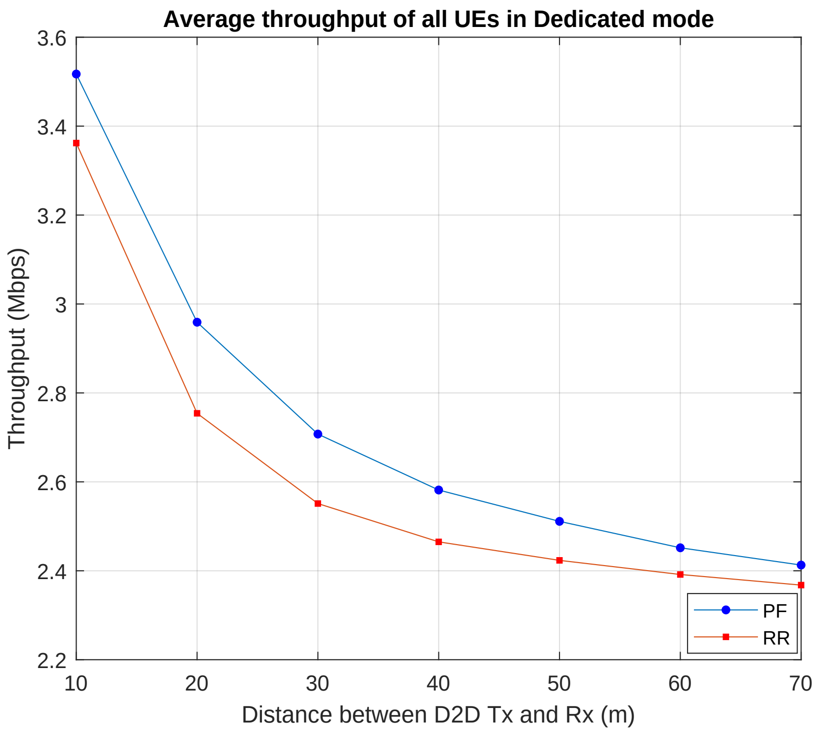

Figure 4.9: Average throughput of all UEs in dedicated mode for different distances between D2D Tx and Rx.

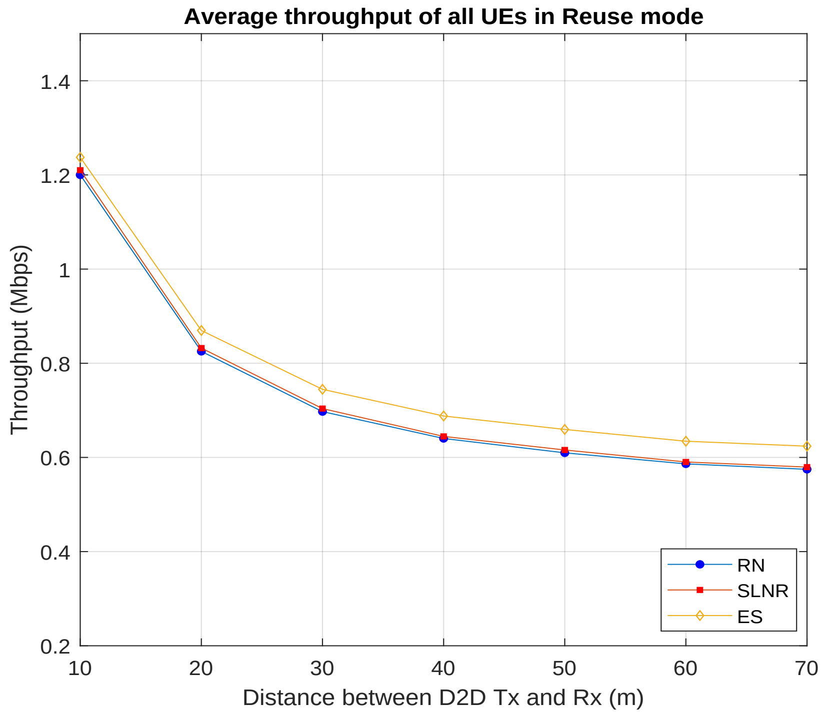

Figure 4.10: Average throughput of all UEs in reuse mode for different distances between D2D Tx and Rx.

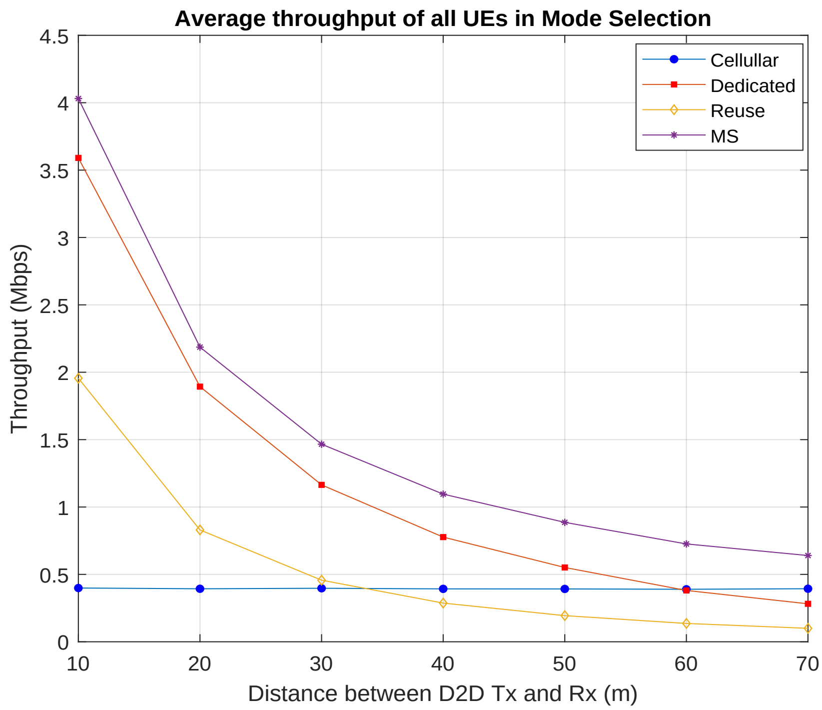

Figure 4.11: Average throughput of all UEs for different distances between D2D Tx and Rx comparing mode selection to the three modes of operation.

4.3. Power Control

Power control algorithm is implemented to reduce the interference from D2D pairs to CUs. Despite the reduction in the average throughput of D2D pairs after applying power control, the overall system throughput increases. Reducing the interference introduced by D2D pairs sharing the same resources increases the throughput of CUs, which in turn, enhances the total throughput as indicated by RN, SLNR and ES. RN-NPC, SLNR-NPC and ES-NPC refer to average throughput before applying power control.

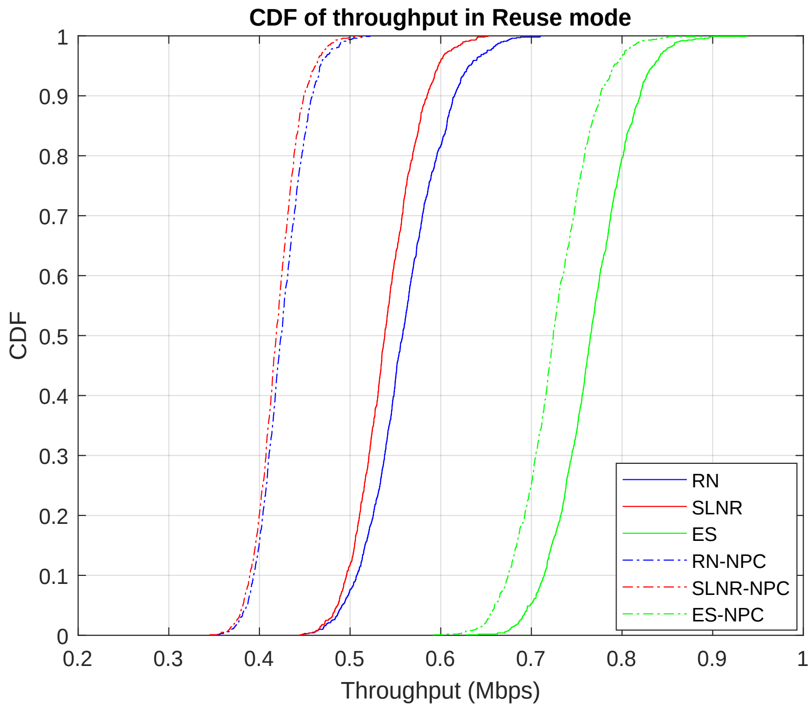

Figure 4.12: CDF of the average throughput of all UEs before and after applying power control.

4.4. Video Steaming

For video streaming scenario, trace file of the crew video sequence is used. The number of D2D pairs is set to 20 pairs and the maximum distance between transmitter and receiver to 15 m. Three metrics are evaluated throughput, PSNR and buffer occupancy. First Figure 4.13 depicts the average throughput of D2D pairs in three modes of transmission and mode selection. As can be seen, mode selection approach provides the highest throughput. Figure 4.14 compares the average PSNR of D2D pairs to the PSNR after encoding. The degradation in quality is due to the loss of ELs, either due to the loss of transport block or discard the layer when it misses the deadline. The values of the average PSNR using mode selection are higher compared to the other three modes, while cellular mode maintains average quality values that are close to the base layers quality as a result of low throughput. PSNR of one simulation run for three UEs is presented in Figure 4.15.

Mode selection provides high performance in term of continuity of the playback as the instantaneous buffer occupancy is much higher than the predefined threshold as presented in Figure 4.16. The values of Buffer occupancy in cellular and reuse modes are close to the predefined threshold. When the buffer occupancy is larger than the threshold this allows the transmission of more ELs, which in turn, improves the video quality. To verify the performance of the proposed approach, another video sequence (city) is tested. The average PSNR and throughput of D2D pairs using city video sequence are shown in Figures 4.17 and 4.18.

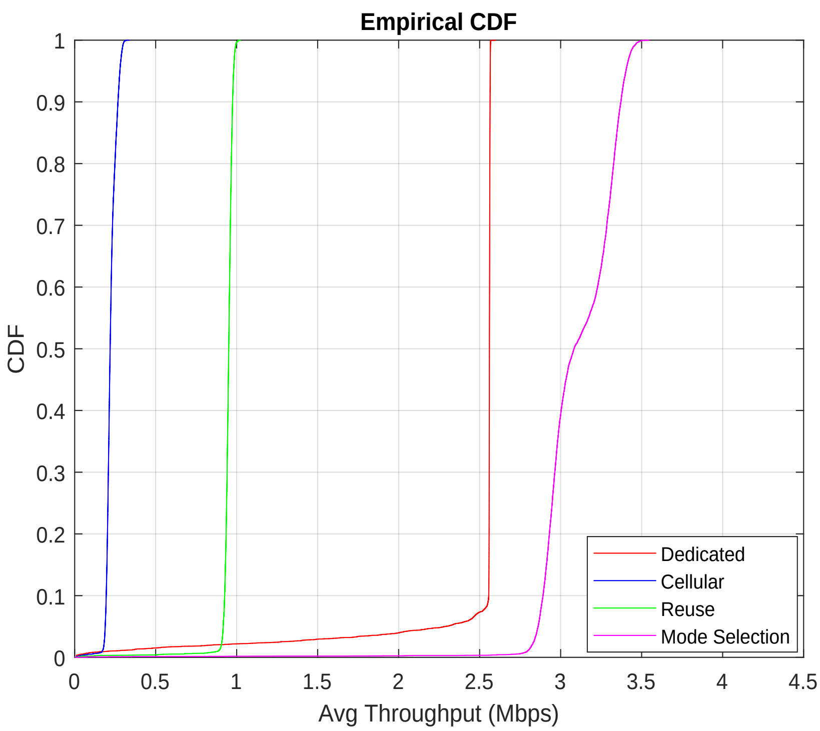

Figure 4.13: CDF of the average throughput of D2D pairs in mode selection and three modes of operation.

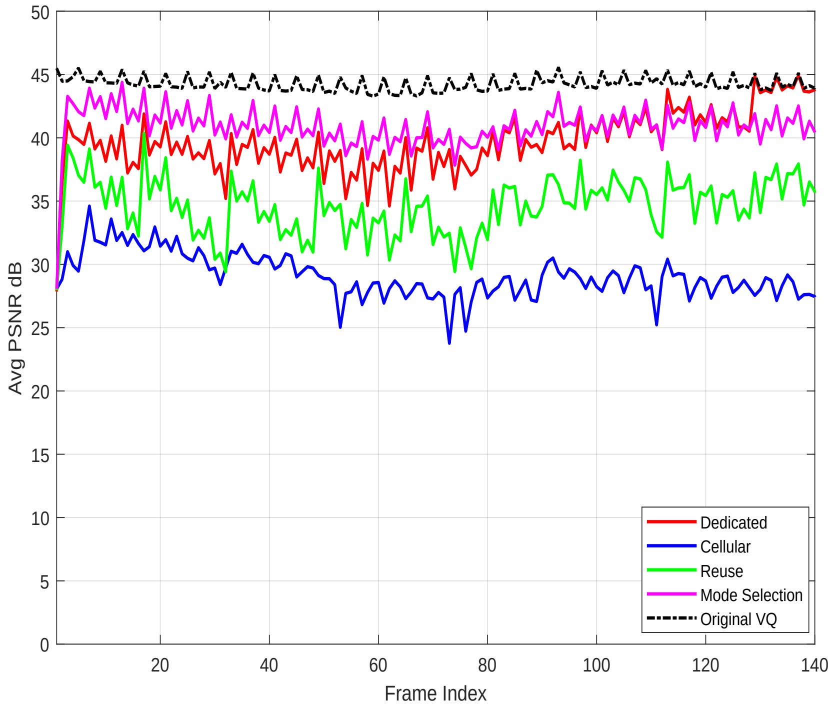

Figure 4.14: Average PSNR in mode selection and three modes of operation.

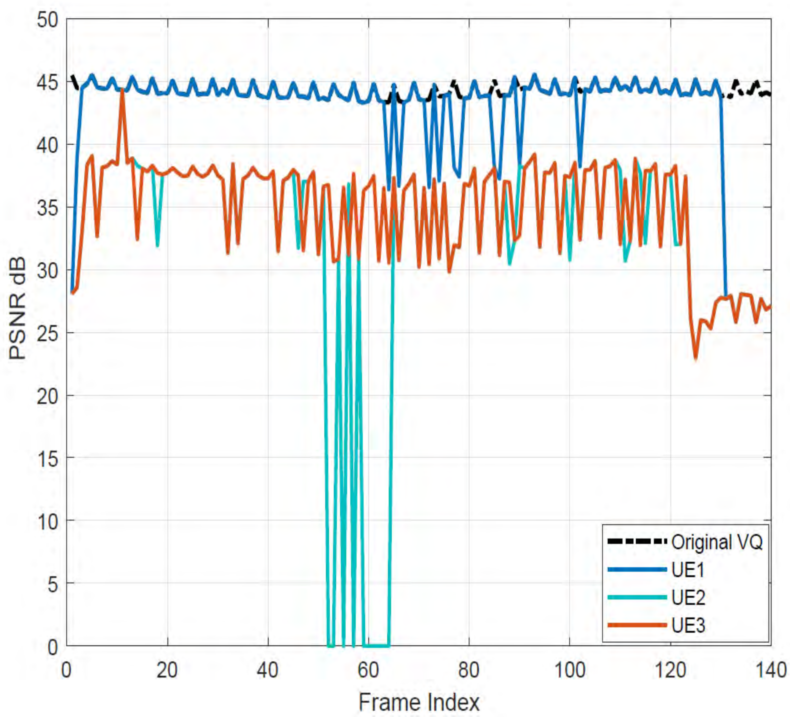

Figure 4.15: PSNR of video sequence as received by UEs.

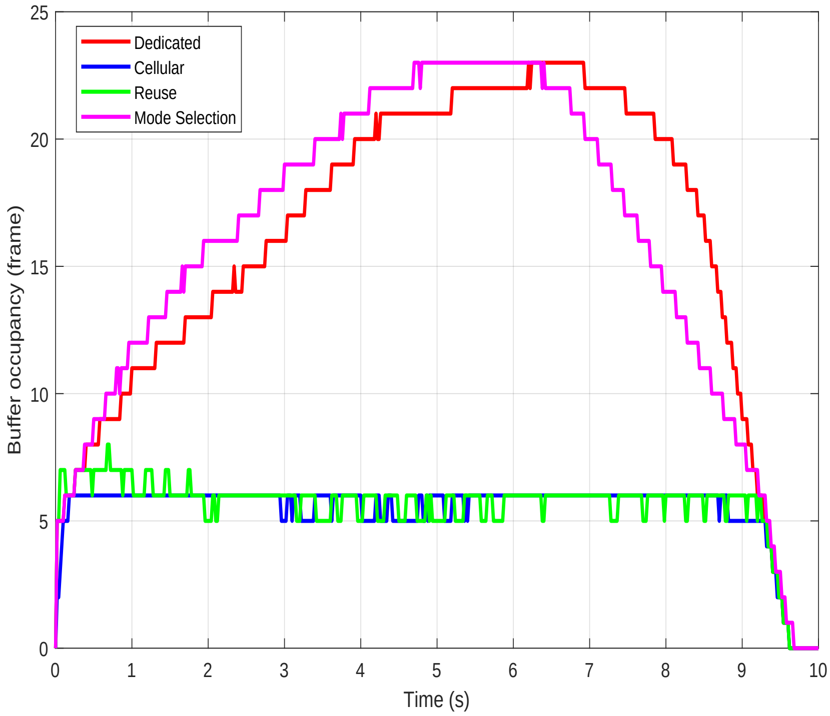

Figure 4.16: Average buffer occupancy in mode selection and three modes of operation.

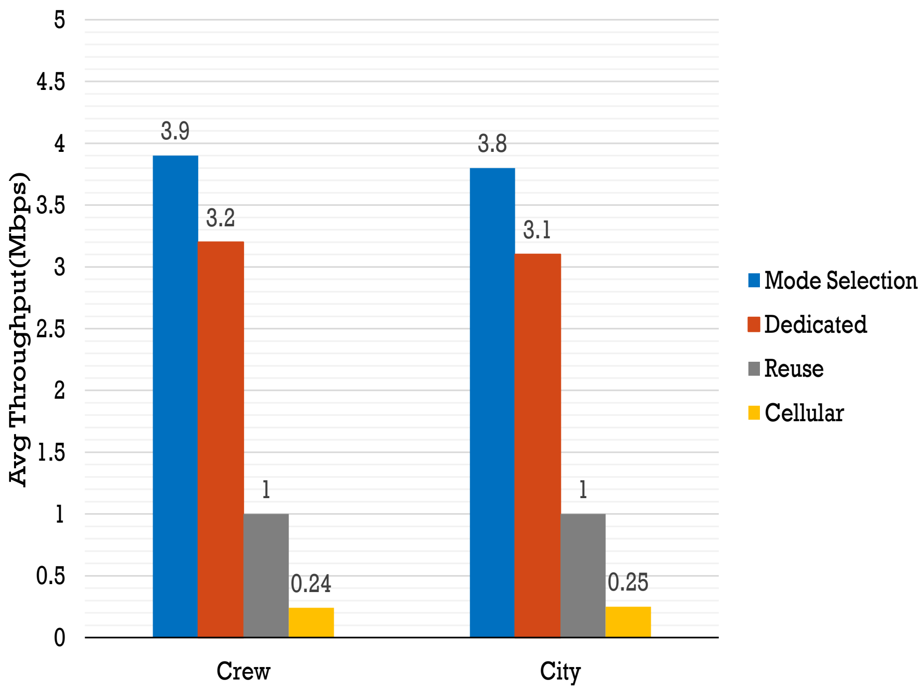

Figure 4.17: Average throughput for two video sequences.

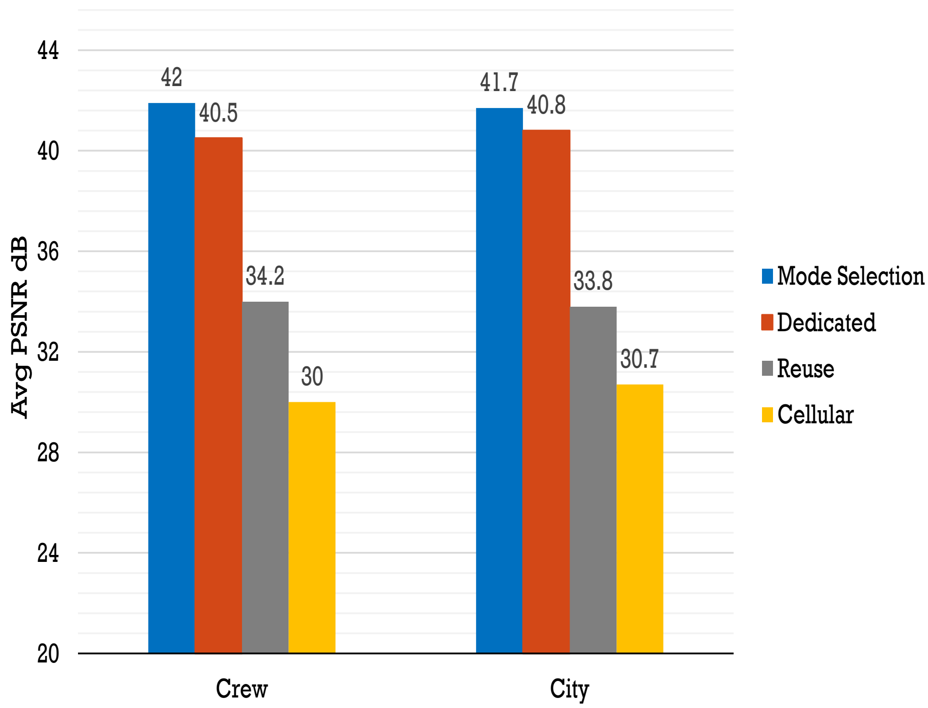

Figure 4.18: Average PSNR for two video sequences.

4.4.1. Effect of changing the number of D2D pairs. The effect of changing the number of D2D pairs is considered by changing the number of D2D pairs from 10 to 40. As the number of D2D pairs increases the average throughput decreases in all modes as illustrated by Figures 4.19. Accordingly, the average PSNR also decreases because when the throughput declines, less number of enhancement layers can be transmitted within the deadline based on equation (23).

When the number of D2D pairs equals to 10 pairs, the difference between the throughput achieved by dedicated mode and mode selection approach is about 0.2 Mbps. This is because for a few numbers of D2D pairs all users can be scheduled and enough resources will be assigned to each user to achieve the required rate.

4.4.2. Effect of changing the value of the buffer threshold. There is a steady decline in the video quality (PSNR) as the buffer threshold increases for dedicated mode and mode selection approach as shown in Figure 4.21. The reason for that is, as the buffer threshold increases more ELs will not satisfy the condition in (23) and miss the deadline which results in quality degradation. Therefore, for a small number of users,

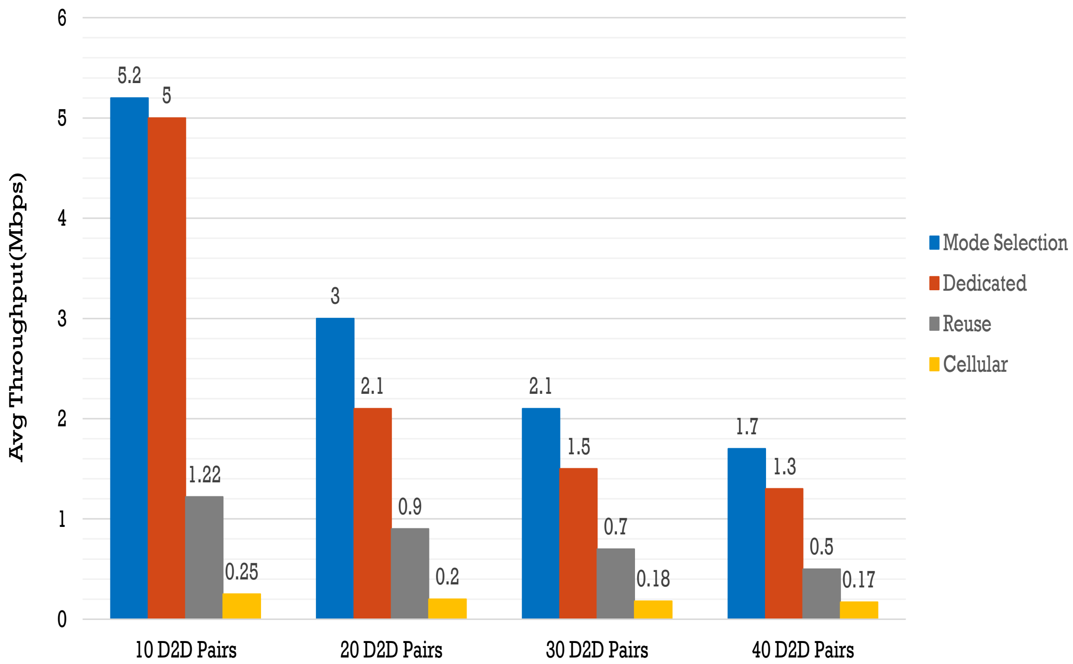

Figure 4.19: Average throughput for different number of D2D pairs.

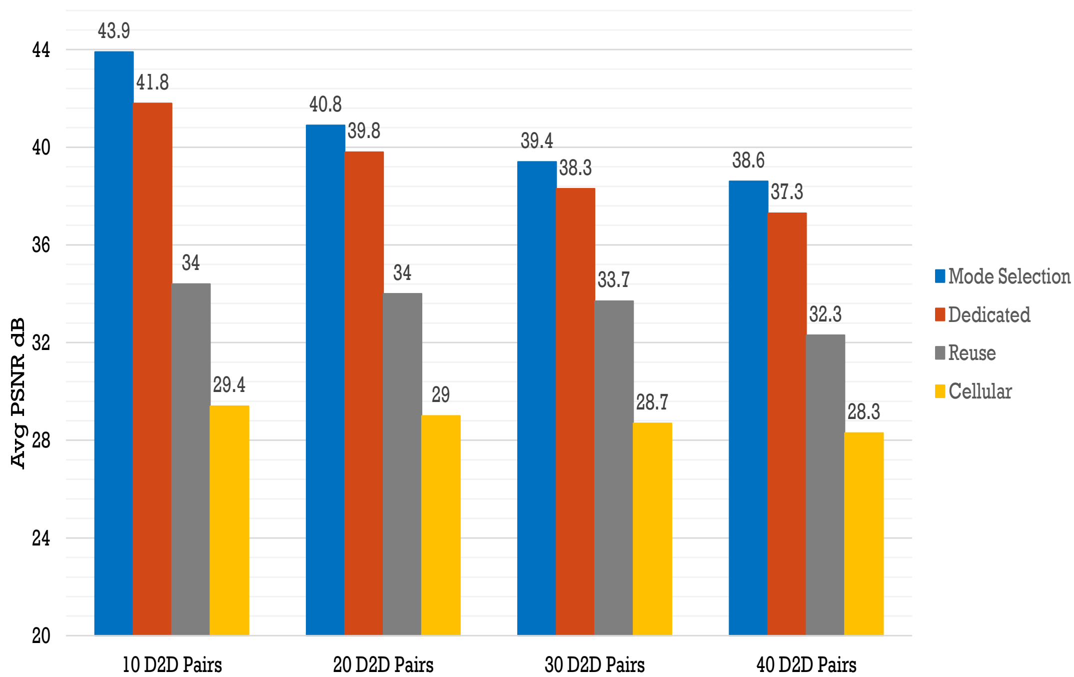

Figure 4.20: Average PSNR for different number of D2D pairs.

the buffer threshold can be set to a small value to get better quality. In contrast, in a dense area or when there is a limited number of resources, the buffer threshold should be set to a high value to avoid buffer starvation when no channels are assigned to the user. This can be illustrated in Figure 4.22 as the playback interruption occurred at $t = 5.1$ s due to no RBs are allocated to the user.

Average buffer occupancy when the value of βth equals 25 frames is presented in Figure 4.23. With a mode selection approach continuity is maintained.

4.4.3. Compare the performance of scheduling metrics .

In the proposed approach, both buffer occupancy and scheduling metric proposed in (21) are considered in user scheduling to maintain the video continuity with an acceptable quality level. In this section, we compare the performance of the proposed approach to the case when only buffer occupancy or scheduling metric is used. From Table 4.2 and Figure 4.24, although using only scheduling metric achieves average PSNR close to the proposed scheme, it provides the lowest performance in term of continuity. Considering only the length of the buffer in scheduling results in degradation on PSNR value.

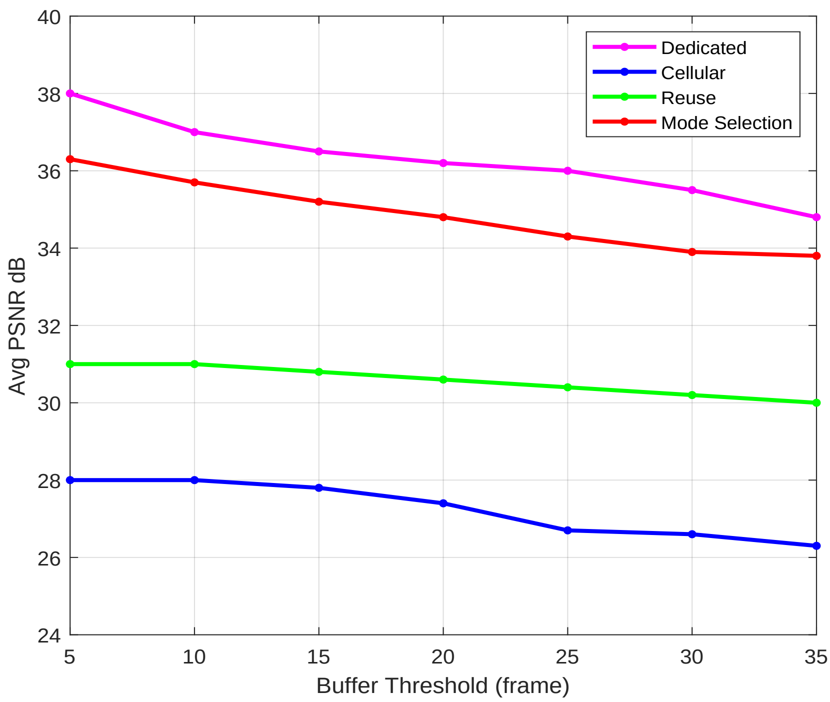

Figure 4.21: Average PSNR vs. buffer threshold.

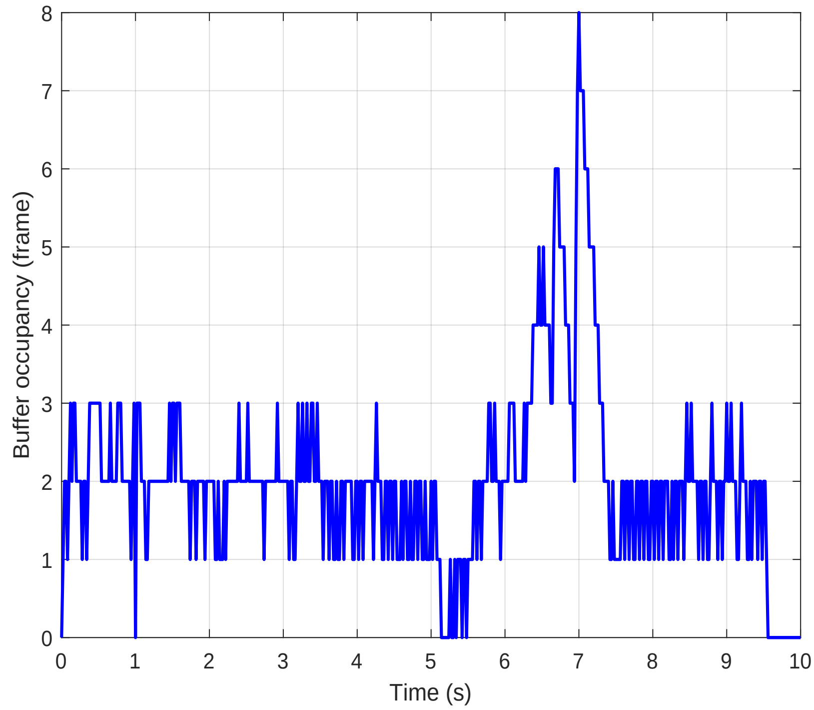

Figure 4.22: Buffer occupancy at UE when buffer threshold is set to 1 frame.

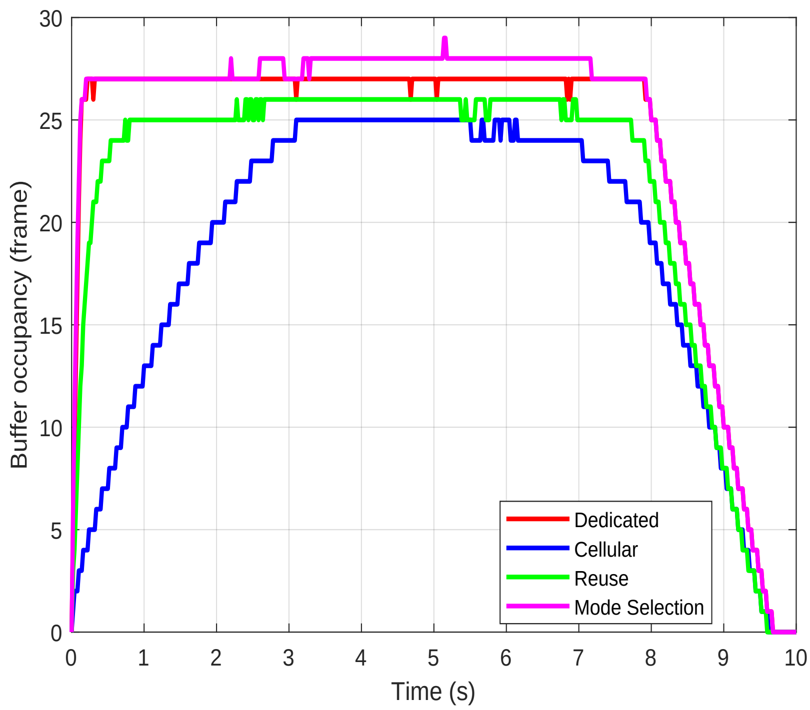

Figure 4.23: Average buffer occupancy for threshold value equals 25 frames.

Table 4.2: Average PSNR for different metrics.

D2D pairs	PSNR (dB)		
	Metric+occupancy	Metric only	occupancy only
10	44	44	43.5
20	40.8	40.7	40
30	39.4	39	38.5
40	38.6	38	37.5

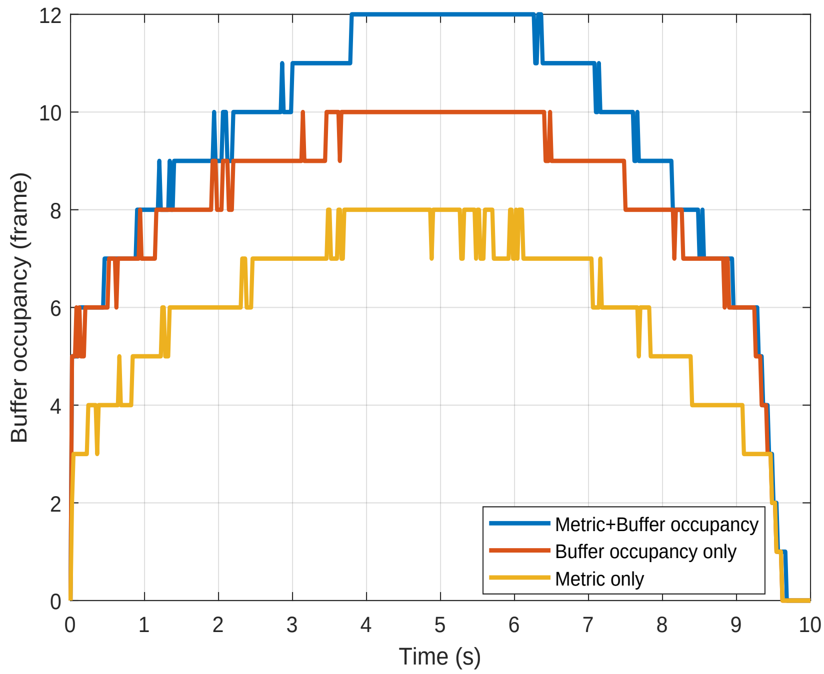

Figure 4.24: Average buffer occupancy for different scheduling metrics (40 D2D pairs).

4.5. Mobility Model

The impact of user mobility on the system performance is investigated and two metrics are considered, video quality (PSNR) and the contact probability. User movements using the RW model are captured in Figure 4.25. Two scenarios are implemented using the RW model, first movements of human where people moves according to a certain pedestrian pattern (0-40 km/h). Another case considered is the communications in V2V. Up to 40 km/h, the effect of mobility is not severe on both PSNR and contact probability. When the speed is above 40 km/h, the PSNR starts to drop gradually to reach about 33 dB at 130 km/h as shown in Figure 4.26. Similarly, the contact probability declines to 77% and some D2D pairs receive video directly from the eNB as illustrated by Figure 4.27. We can conclude that low mobility does not affect the system performance, while for the vehicular scenario, D2D communication and video quality demonstrate diminishing behavior. This is because proximity-based service loses its efficiency to provide D2D communications with a high capacity and the only alternative is to communicate through the cellular system.

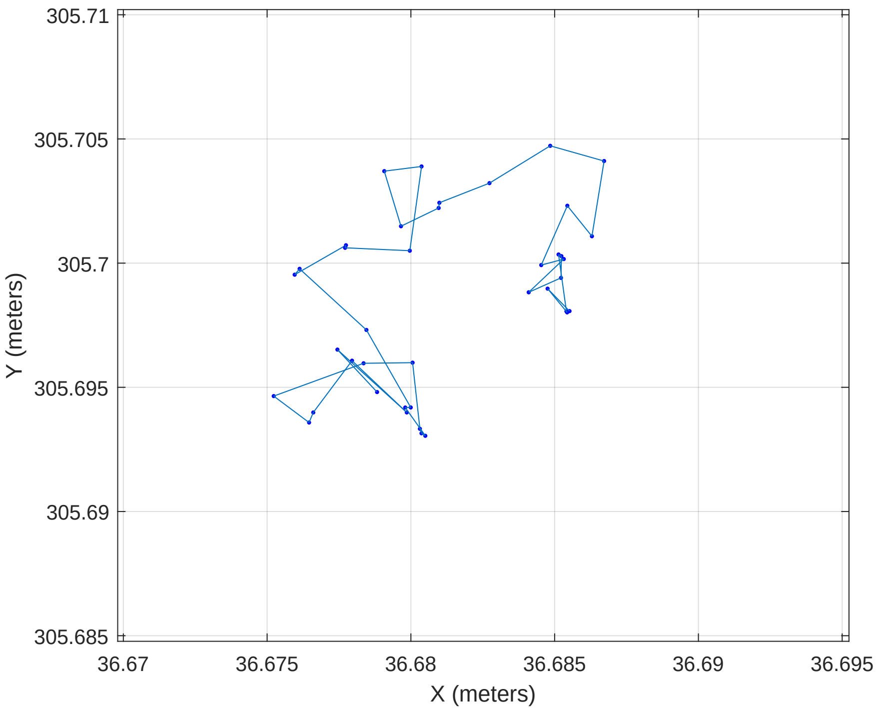

Figure 4.25: User movement trajectories for RW model.

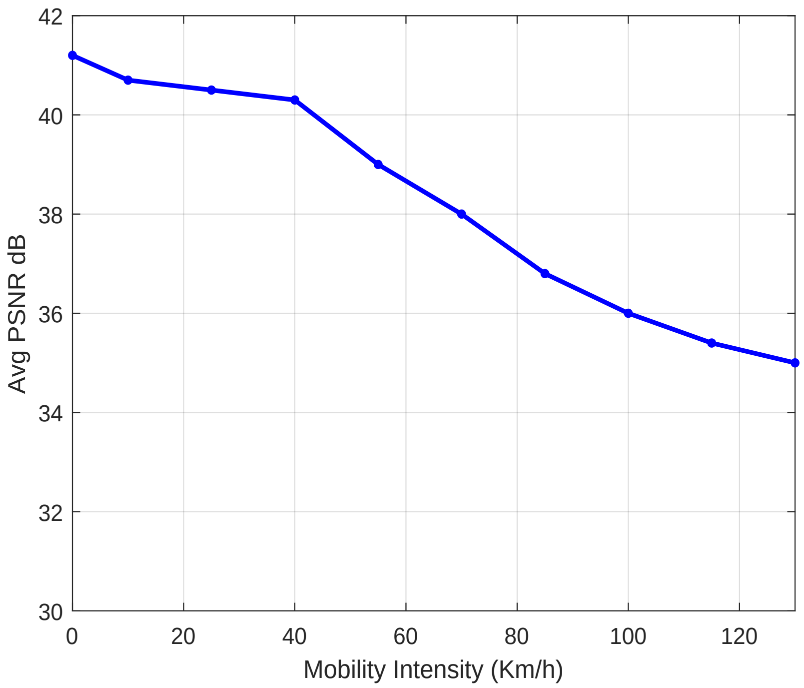

Figure 4.26: Average PSNR vs. mobility intensity.

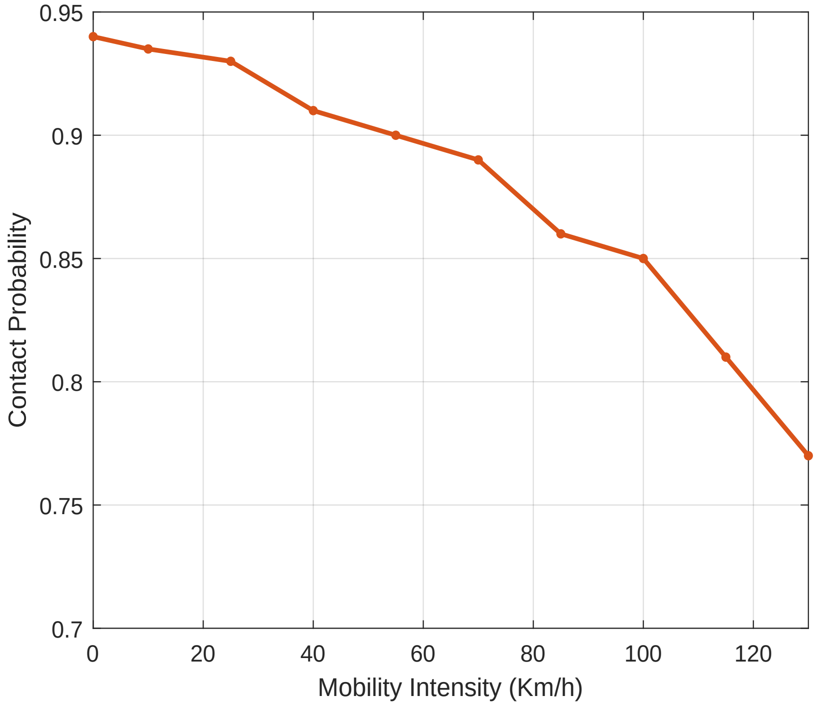

Figure 4.27: Contact probability vs. mobility intensity.

Chapter 5. Conclusion and Future Work

Device to Device (D2D) communication is presented as a key solution to enhance the performance of traditional cellular networks. Over the last decade, multimedia applications have constituted the main drive of the growing demands of cellular data traffic and D2D is proposed as a technique to offload wireless networks and can indeed be exploited to achieve high-quality video transmission.

The main focus of this thesis is to propose a scheme for video streaming over the D2D network. Resource allocation, mode selection and power control for multiple D2D pairs have been addressed. The objective is to maximize the throughput of D2D pairs while considering the rate required by Cellular User (CU) and D2D pair and quality of experience requirements represented by video quality and continuity. We further proposed a power control algorithm to manage mutual interference between D2D pairs to CUs in reuse mode after selecting a compatible D2D pair for each CU. Scalable Video Coding (SVC) is employed to provide the video with high quality to users with good channel conditions while maintaining the basic video quality for users experience bad conditions. The degradation in video quality due to unreliable transmission is estimated by using a packet-layer quality model assessment that uses information from the packet header to reduce the computational complexity in bit-stream models. Dynamic node instead of static network scenario is studied to examine the effect of mobility on mode selection and video quality.

Simulation results reveal that the proposed mode selection scheme provides better performance, in term of, average throughput, quality and maintain the video playback continuity compared to a single mode of operation. Furthermore, we found that for low mobility scenario, video quality and contact probability slightly decrease as the mobility intensity increases.

Although the mode selection approach outperformed other three modes of operation and provided the best performance, this study has some limitations need to be noted. First, periodic Channel State Information (CSI) and buffer occupancy reporting increases the signaling and overhead at the eNB. It would be easier if aperiodic CSI reporting is considered, however, this would not accurately represent the channel quality at every point. Secondly, users have different channel conditions, therefore, equal power allocation in cellular mode may not provide the best performance. Finally, D2D transmitter may not be allowed to cache all layers due to limited storage capacity.

This research can be extended in various ways and the above-mentioned limitations can be addressed in the future. First, the proposed system model can be further extended to a more complicated scenario, for example, the proposed algorithm can be implemented over the area of multiple LTE cells. In this case, the inter-cell interference should be studied and also the movement of the user equipment from one cell to another has to be implemented. In addition, complex quality scalability such as one layer control and two-layer control can be adopted which allows high efficient enhancement layer coding. Frame dependency and the impact of error propagation on enhancement layers have to be considered. Furthermore, transmission power of LTE eNB can be optimized to improve the performance in cellular. Another direction for the future work is to jointly consider caching and transmission of SVC streaming, where the number of layers of each video should be cached is determined. Considering SVC makes caching placement problem more complicated and the following issues should be addressed: which video files to be cached, number of layers to be cached by each user and how to transmit video content and satisfy the quality of service of users.

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Appendix A: Tables

In this section, tables that have been used in rate calculation in section 3.2.3 are provided. First Table A1 maps modulation order index I_{MCS} to the TBS index I_{TBS}. The UE reports the measured CQI to the BS by mapping the measured SNR according to Table A2. The transport block size is determined using the number of resources assigned to the user and TBS index I_{TBS} using Table A3, that shows part of the transport block size table provided by LTE specifications.

Table A1: Modulation and TBS index table.

I_{MCS}	Modulation	I_{TBS}
0	2	0
1	2	1
2	2	2
3	2	3
4	2	4
5	2	5
6	2	6
7	2	7
8	2	8
9	2	9
10	4	9
11	4	10
12	4	11
13	4	12
14	4	13
15	4	14
16	4	15
17	6	15
18	6	16
19	6	17
20	6	18
21	6	19
22	6	20
23	6	21
24	6	22
25	6	23
26	6	24
27	6	25
28	6	26

Table A2: SNR to CQI mapping and I_{MCS}.

CQI	SNR	Modulation	I_{MCS}
1	-6.7	QPSK	0
2	-4.7	QPSK	0
3	-2.3	QPSK	2
4	0.2	QPSK	5
5	2.4	QPSK	7
6	4.3	QPSK	9
7	5.9	16-QAM	12
8	8.1	16-QAM	14
9	10.3	16-QAM	16
10	11.7	64-QAM	20
11	14.1	64-QAM	23
12	16.3	64-QAM	25
13	18.7	64-QAM	27
14	21	64-QAM	28
15	22.7	64-QAM	28

Table A3: Transport block size table.

I_{TBS}	N_{PRB}									
	1	2	3	4	5	6	7	8	9	10
0	16	32	56	88	120	152	176	208	224	256
1	24	56	88	144	176	208	224	256	328	344
2	32	72	144	176	208	256	296	328	376	424
3	40	104	176	208	256	328	392	440	504	568
4	56	120	208	256	328	408	488	552	632	696
5	72	144	224	328	424	504	600	680	776	872
6	328	176	256	392	504	600	712	808	936	1032
7	104	224	328	472	584	712	840	968	1096	1224
8	120	256	392	536	680	808	968	1096	1256	1384
9	136	296	456	616	776	936	1096	1256	1416	1544
10	144	328	504	680	872	1032	1224	1384	1544	1736

Vita

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