

COLLABORATIVE CACHING FOR D2D CONTENT SHARING IN 5G

by

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Declaration of Authorship

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Dedication

To

My mother and my father for their love and support

My grandmother for her love and prayers

My family

My friends

Abstract

Due to a huge number of mobile devices expected to be connected to 5G wireless networks and their expected demand for high data-rate multimedia services, the core network and backhaul links are expected to carry enormous amount of traffic. Caching the most popular files at the network edge and in user's devices to support user proximity services in 5G will help to offload traffic in the core network and to increase the cache hit probability. Device-to-Device (D2D) communication in 5G can be utilized to share the cached files between any pair of devices with a minimal involvement from the base station. However, there are many challenges that are needed to be addressed including interference management, mode selection, device discovery, contents placement, popularity index calculation, and the non-cooperative situations in D2D. This thesis attempts to solve most of the above-mentioned problems via collaborative content caching and sharing using D2D communication in 5G networks. The primary objective of the research is to maximize the overall system offloading gain and the cache hit probability in downloading the popular file contents. The proposed system model exploits the social-networking concept, assuming the cell structure in a condensed populated area, such as a university campus or an auditorium. We combine the process of content caching and D2D communication in the WiFi range. In particular, joint resource allocation, mode selection, cache placement and replacement for multiple D2D devices are addressed. Data traffic offloading in three modes of operation, self-offloading, D2D offloading, and Base Station-to-Device (B2D) offloading and mode selection algorithm are implemented. Furthermore, we vary the network parameters and the cache model parameters to assess their impacts on the system performance. The performance of the proposed cache scheme is evaluated through extensive simulations and compared with the popular cache scheme and the baseline performance of the random cache scheme, and it is found that the proposed scheme outperforms the two schemes by 9.4% and 20%, respectively, with respect to cache hit probability. The effects of users' mobility and disconnection on system performance are also investigated.

Keywords: *5G; Cooperative Caching techniques; Device-to-Device communication; Popularity index.*

Table of Contents

Abstract	6
List of Figures	9
List of Tables	11
List of Abbreviations	12
Chapter 1. Introduction	14
1.1. Overview	14
1.2. Objectives.....	16
1.3. Research Contribution.....	16
1.4. Thesis Outline	17
Chapter 2. Background and Literature Review	18
2.1. Basics of 5G Networks: Definition, Architecture, Challenges and Potential Enablers	18
2.1.1. Main features of 5G networks.	19
2.1.2. Some technologies emerged with 5G	19
2.2. D2D communication in 5G Networks	23
2.2.1. Peer device discovery and communication.	24
2.2.2. Interference management.	25
2.2.3. D2D communication over WiFi Direct.	26
2.2.4. High mobility devices communication in D2D.	27
2.2.5. D2D communication in HetNet.	28
2.3. Caching Techniques in 5G Networks	28
2.3.1. Caching in a Multi-Tier HetNet	30
2.3.2. Content popularity model.	30
2.3.3. Content cache placement.	31
2.3.4. Content cache replacement.	32
2.3.5. Incentive-based caching in D2D networks.	32
Chapter 3. System Model	33
3.1. Network Model.....	33
3.2. Cache Model.....	35
3.2.1. Self-offloading mode.	35
3.2.2. D2D mode.	35
3.2.3. B2D mode.	35
3.3. Transmission Model.....	36
3.3.1. Channel model	36

3.3.2.	SINR calculation and receiver sensitivity.	38
3.3.3.	Arrival of requests.	38
3.3.4.	Transmission rate.	39
Chapter 4.	Methodology	40
4.1.	D2D pair selection	40
4.2.	Cache Assisted D2D Communication.....	41
4.3.	Cache Placement and Replacement Strategies.....	42
4.4.	Random Cache Algorithm (RCA).....	42
4.5.	Popular Cache Algorithm with LFU Replacement (PCA).....	42
4.6.	Popular Cache with LFU plus Instantaneous Popularity Index (PCLIA) Algorithm	44
4.7.	Content Popularity Distribution	45
4.8.	Disconnection Rate	45
4.8.1.	Low disconnection rate.	46
4.8.2.	Average disconnection rate.	46
4.8.3.	High disconnection rate.	46
4.9.	Mobility Model	46
Chapter 5.	Results and Analysis	47
5.1.	Simulation Setup and Main Parameters	47
5.2.	Simulation Results	49
5.2.1.	Impact of varying network parameters	51
5.2.2.	Impact of varying the Zipf parameter in popular caching schemes	53
5.2.3.	Performance of the proposed caching algorithms in terms of the cache hit probability	50
5.2.4.	Impact of considering D2D alone in the calculation of the cache hit probability	50
5.2.5.	Impact of varying the disconnection rate in the PCLIA algorithm	58
5.3.	Mobility Model	58
Chapter 6.	Conclusion and Future Work	60
6.1.	Conclusion	60
6.2.	Future Work	61
References	62
Appendix A:	Source Code	70
Vita	100

List of Figures

Figure 2.1: A general architecture of 5G cellular network	20
Figure 2.2: Solutions to achieve low latency in 5G networks	19
Figure 2.3: Technologies Emerged in 5G networks.....	20
Figure 2.4: D2D communication utilizing licensed and unlicensed spectrum, with no assistance from the network and with network assistance	24
Figure 2.5: Classification of D2D communication	24
Figure 2.6: D2D communication in a Two-tier HetNet, consisting of MBS, SBS, and D2D links.	20
Figure 2.7: Different types of request off-loading 5G networks	30
Figure 2.8: Zipf Probability Distribution Function	31
Figure 3.1: The proposed 5G networks architecture	34
Figure 3.2: WiFi Channel frequency distribution with 12 channels and a bandwidth of 22 MHz each	37
Figure 4.1: The proposed MSDT algorithm	41
Figure 4.2: Distance Calculation between two D2D devices UE_1 and UE_2	41
Figure 4.3: The proposed Cache assisted in D2D network algorithm	43
Figure 4.4: The proposed Cache Placement and Replacement strategies	44
Figure 5.1: A sample cell structure with one MBS at the centre and the users are distributed using PPPs with density $\lambda = 5 \times 10^{-5} / m^2$	48
Figure 5.2: The hit probability versus the user density λ in (users / m^2) with different sending time threshold t (ms)....	51
Figure 5.3: The hit probability versus the D2D distance (m) with different Zipf parameter η	52
Figure 5.4: The cache decision under different values of the zipf parameter η	53
Figure 5.5: The cache hit probability versus different values of the Zipf parameter η with different cache storage capacity	53
Figure 5.6: Performance evaluation of the three caching algorithms under different values of the cache storage capacity	54
Figure 5.7: Performance evaluation of the three caching algorithms under different values of the D2D cooperation distance (m).....	55

Figure 5.8: Performance evaluation of the three caching algorithms under different values of the user density λ (users / m^2).....	56
Figure 5.9: Hit probability using D2D traffic offloading for the three caching algorithms under different values of the user density λ (users/ m^2).....	57
Figure 5.10: The impact of user's disconnection as implemented by the PCLIA algorithm under different values of the user density λ (users / m^2).....	58
Figure 5.11: Node movement in RWM model	59
Figure 5.12: The impact of mobility on the offloading probability	59

List of Tables

Table 2.1: Comparison of the different types of Base Stations..	22
Table 2.2: Comparison of different D2D communication technologies.....	27
Table 5.1: System Main Parameters..	48
Table 5.2: Distance in km between 10 D2D devices as implemented by MSDT algorithm.....	49
Table 5.3: SINR calculations in dB between 10 D2D devices as implemented by MSDT algorithm.....	50

List of Abbreviations

3GPP	The 3 rd Generation Partnership project
AOA	Angle of Arrival
AP	Access Point
AWGN	Additive White Gaussian Noise
B2D	Base Station to Device
BS	Base Station
CDN	Content Delivery Network
CP	Content Provider
CSI	Channel State Information
D2D	Device to Device
EPC	Evolved Packet Core
GPS	Global Positioning System
HetNet	Heterogeneous Networks
IoT	Internet of Things
ITU-R	International Telecommunication Union Radio communication
LTE	Long Term Revolution
LFU	Least Frequently Used
LRU	Least Recently Used
LRV	Lowest Relative Value
M2M	Machine-to-Machine Communication
MBS	Macro Base Station
MD2D	Multiple Device to Device

MEC	Mobile Edge Computing
mMIMO	massive Multiple Input Multiple Output
MNO	Mobile Network Operator
MSDT	Maximum SINR with Distance Threshold
MTC	Machine Type Communication
NFV	Network Function Virtualization
OFDMA	Orthogonal Frequency Division Multiple Access
P2P	Peer to Peer
ProSe	Proximity-based Service
QoE	Quality of Experience
QoS	Quality of Service
Rx	Receiver
RA	Resource Allocation
RAN	Radio Access Network
RWM	Random Walk Model
SAE	System Architecture Evolution
SBS	Small Base Station
SDN	Software Defined Network
SINR	Signal to Interference plus Noise Ratio
SP	Service Provider
Tx	Transmitter
UE	User Equipment

Chapter 1. Introduction

In this chapter, we provide a short introduction about the collaborative and proactive wireless caching, and device-to-device communication in the 5G wireless cellular networks, and the problems encountered in this field. We then present the problem investigated in this study as well as the expected thesis contribution.

1.1. Overview

The ever-proliferation of mobile devices in daily life use of people led to the huge growth in wireless traffic demand. However, this growth is impeded by the highly congested backhaul links. A legacy approach is to deal with such growth by densifying the network, for example a heterogeneous network (HetNets) which consists of all types of small cells such as the Macrocells, Microcells, Picocells and Femtocells, along with the provisioning of Machine to Machine (M2M) and Device-to-Device (D2D) communication which can be deployed to enhance the system capacity and ensure a high quality of experience (QoE). Such arrangement could lead to an increased cost of deploying a huge amount of needed base stations. Therefore, researchers have found the motivation to find new wireless communication technologies to cope up with the ever increasing demand of wireless services [1].

The publication of 5G services and the performance metrics was first done by the International Telecommunication Union Radio communication (ITU-R), along with the 3GPP specification of system usage that cannot be achieved with the 4G Evolved Packet System (EPS). The three features of ubiquitous connectivity, zero latency and high-speed connection in terms of gigabits/sec have characterized this evolution in 5G. In ubiquitous connectivity the user equipment will be connected ubiquitously without any disruption in the service. When it comes to zero latency, 5G will support services with extremely low latency in the order of 1 millisecond or less and this could be achieved by using a high speed connection and the use of caching techniques [3]-[4].

The advancement in wireless communication systems as in 5G networks are characterized by the increase in data rate to provide multimedia services and to accommodate the increasing demand in data connectivity. The continuously increase in data rate could be accommodated by increasing the bandwidth and by increasing the signal-to-interference-plus-noise ratio as well. On the other hand, the bandwidth could

be increased by frequency reuse, which could be achieved by using small cells and massive Multiple Input Multiple Output (mMIMO) systems; it can also be increased by using millimetre wave (mm-wave) technology [2].

The heterogeneous network architecture that will be deployed in 5G will allow for a multi-tier architecture, in the form of base station (BS), network nodes, and user equipment. User equipment will have a self-organizing characteristics such as self-load balancing, power adaptation and self-offloading when the requested files are already cached in the UE and hence the request will be satisfied immediately [5]-[7].

Caching at the network edge, has been introduced by many researches to tackle the problem of the rapid increase in the number of user equipment (UE) and in return the increase in the demand of higher data rates. It provides an efficient technique by bringing the contents closer to the end user, which could be categorized by moving contents from a central to distributed cache systems, where the contents are cached at the network edge devices such as the cache helpers and in the UEs.

The evolution of mobile cellular network architecture from BS-centric into content-centric in the future 5G network has led to the movement of the network functions, contents, and resources from the centre to the edge. This is achieved by utilizing the advanced cloud computing technologies, Software Defined Network (SDN), and the Network Virtualization Function (NFV) techniques. The network resource mainly includes caching and communication resources. Caching at the network edge provides an efficient technique to maximize the overall system offloading gain by bringing the contents closer to the end user, and by utilizing the enormous amount of the low cost storage resources, that is available at different locations in the network [8]- [10].

For the caching techniques to be effective, the cached content can be collaboratively shared between UEs using a novel technology known as device-to-device (D2D) communication. Two devices could only communicate if both are within a small area and within a coverage of the same BS. This communication could be assisted by the BS, which is responsible of keeping track of the user's location, and responsible for establishing the connection between the two devices. The fact that the

BS doesn't require to transmit a content that has already been transmitted will save a great amount of bandwidth [11].

In legacy cellular systems, user's requests are satisfied by fetching the contents from the Internet Content Delivery Network (CDN) using the congested backhaul links. However, the evolution of the base station and the low cost of the storage units, led to the revolutionary techniques in caching the popular content at the BS and the UEs, and by utilizing the D2D communication, which enables user devices to exploit content sharing according to the social relations among users. This leads to reduction in the latency to its minimum, which at the end, is one of the key challenges in the development of 5G cellular systems.

Despite the advantages of introducing caching and D2D communication into cellular network, several technical and practical issues require further investigation such as interference management, mode selection, device discovery, content placement, popularity index calculation and the non-cooperative D2D. Content placement, replacement, and content sharing between D2D in 5G wireless networks have been explored in this thesis.

1.2. Objectives

Driven by the exponential demand of multimedia services over wireless networks, and the limited backhaul link capacities, which cause a bottleneck to the network affordability of facilitating the delivery of such services, we will focus on the problem of optimally caching the most popular content in the UE. The proposed caching scheme is implemented to provide a close proximity to the end user, in such a way that satisfies the user's high QoE, and assure a higher offloading gain. Moreover, we consider the collaborative content sharing of multimedia contents on the allocated D2D communication channels in the 5G cellular network infrastructure. The objective of this work is to develop algorithms that would maintain the optimal placement of contents in the user equipment and collaboratively share the contents, in a way that users enjoy the content delivery without the need to avail the content from the congested core network, which in return will increase the overall system offloading gain.

1.3. Research Contribution

The expected contributions of this research work can be summarized as follows:

- Propose an optimal cache placement schemes that focus on caching the most popular contents at the base station and the user equipment, by determining the popularity index of the requested content, and making the content caching decision based on that popularity index. The caching decision is the key factor in determining the success of the proposed algorithm, which ensures a high offloading gain and a nearly zero latency criterion.
- Propose a collaborative content sharing among user's devices using D2D dedicated channels to communicate, in order to satisfy their requirements and serve their requests without the need to access the congested core network.
- Finally, most of the available literature considered either only caching or D2D communications. In this work, the combination of both techniques will be studied to enhance the overall system offloading gain. Moreover, the proposed system will take into account the effect of device mobility.

1.4. Thesis Outline

The rest of the thesis is organized as follows: Chapter 2 provides brief information about the advanced 5G cellular network and the recent techniques applied in content caching and sharing via D2D communication. Moreover, related works from literature are investigated and discussed. The system model with the associated network model, cache model, and transmission model are discussed in Chapter 3. The methods and algorithms employed are discussed in Chapter 4. Chapter 5 present the performance evaluation for the implemented cache-assisted D2D communication. Finally Chapter 6 conclude the thesis and outlines the future work.

Chapter 2. Background and Literature Review

In this chapter, we discuss the fundamentals of caching in 5G networks and the definitions of its architecture alongside the motivation of using this technology in the environment of device-to-device communication. We then present the techniques reported in literature for content caching and content delivery. Finally, we discuss the related work in this field of research.

2.1. Basics of 5G Networks: Definition, Architecture, Challenges and Potential Enablers

In the 5th generation networks, there will be a shift towards the network efficiency with the focus on densifying the network using Heterogeneous Network (HetNet) architecture. A HetNet comprises of a group of small cells that supports spatial frequency reuse, in the licensed or unlicensed band (e.g., WiFi, IEEE 802.11 wireless networks) along with the use of macrocells in the use of licensed band (e.g., LTE). A new frequency spectrum known as mm-wave will also be implemented to enable the ultra-high data-rate services [13]. Figure 2.1 depicts the architecture of 5G including the core network, the massive Multiple Input Multiple Output systems (mMIMO), and the D2D communication.

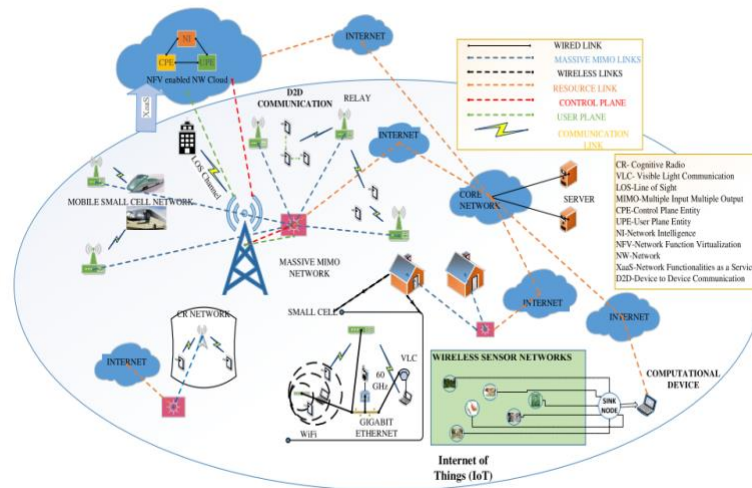


Figure 2.1: A general architecture of 5G wireless network [15]

The basic idea behind the development of 5G cellular system is to develop a system with the following characteristics [15]:

- Data volume per unit area will increase by 1000 times with respect to 4G.

- The number of connected device will increase by 10 to 100 times with respect to 4G.
- The user data rate will increase by 10 to 100 times with respect to 4G.
- The latency will be reduced by 5 times as compared to 4G.

2.1.1. Main Features of 5G Networks.

2.1.1.1. Ubiquitous Connectivity. The concept of “smart living” that the people has adopted led them to require a constant and ubiquitous mobile connectivity to the network to upload their activities and to download multimedia contents. When the number of devices connected to the Internet cross the limits of a thousand of millions in the coming decade, the network offloading on unlicensed bands will play a critical role in network load balancing, providing a higher bit rate services and a reduction in the overhead used in the control signalling. The 5G networks will provide seamless compatibility with dense HetNet to satisfy the high demand of multimedia services, so that end users will experience a high QoE [11]-[12].

2.1.1.2. Near Zero Latency. The main goal behind the development of the 5th generation networks is to provide devices with low-latency connectivity; hence, the target is to achieve a latency as low as 1ms in the air interface and 10ms in the D2D communication. Content caching will also play an important role in achieving near-zero latency. The proposed solutions to achieve the near zero latency are shown in Figure 2.2.

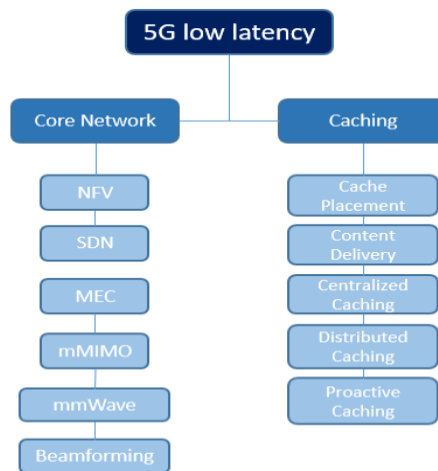


Figure 2.2: Solutions to achieve low latency in 5G networks.

2.1.1.3. High speed gigabit/sec Connection. 5G will support an end-user data rate of 100 Mbps in the spatial distribution communication network with a peak data rate of 10-20 Gbps [16].

2.1.2. Some technologies emerged with 5G

2.1.2.1. New Radio Frequency (NR). The continuous increase in higher data rate demands could be achieved by increasing the bandwidth and by increasing the signal-to-noise plus interference ratio. Hence, the increase in bandwidth could be achieved by frequency reuse, which could be accomplished by using MIMO systems and small cells. Another way to increase the bandwidth is the use of mm-wave, which is used in short-range services and deployed in small cells backhaul networks. The range of frequencies in mm-wave is 24, 28, 32, and 72-78 GHz [17]. In [18], researchers have studied mm-wave and they provided measurement results that show 28 and 38 GHz frequencies can be used to communicate in the cellular network. All the technologies that emerged in 5G are listed in Figure 2.3.

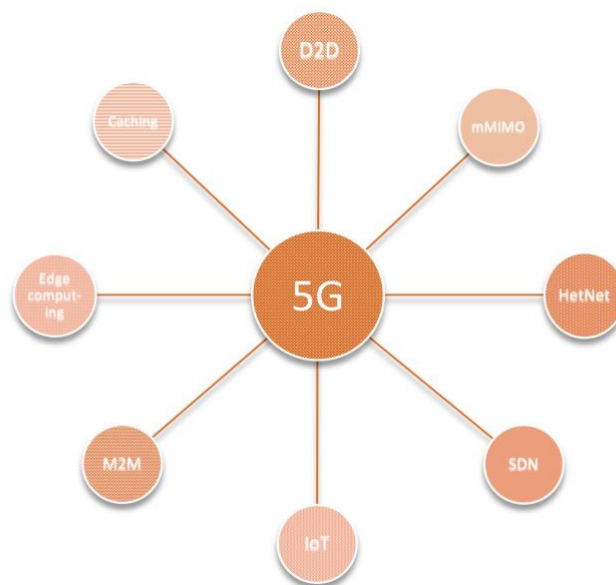


Figure 2.3: Technologies Emerged in 5G networks.

2.1.2.2. Massive MIMO antenna systems. It uses multiple hundreds or thousands of low power, inexpensive antennas to serve large number of system and user

equipment concurrently. The rapid increase in data rates could be achieved by using a BS equipped with multiple antennas to release more data streams and hence serve more UEs. In addition to the high increase in data rate, MIMO systems will ensure the selectivity in transmitting and receiving data streams; this in return will help in reducing the interference since the BS can redirect the transmission into the desired direction to cancel or minimize the interference effect. Furthermore, increasing the number of antennas that the BS have will ensure a high system throughput and more energy efficiency. Massive MIMO relies on beamforming to resist the destructive interference plus the fading that the transmitted and received signals face [19] -[20].

2.1.2.3. Machine-to-Machine Communication (M2M). Machine-to-Machine communication is also referred to as Machine Type Communication (MTC), and it can be defined as the communication between two devices without or with minimal user interaction. The main areas in which M2M is deployed are industry, healthcare, and intelligent transportation systems. The importance of M2M is its use in Internet of Things (IoT). M2M is mainly based on a network of sensors that exchange information about a certain task, hence the amount of transferred data is small i.e. few bytes per second for each device [21] -[22].

2.1.2.4. Beamforming. Beamforming is used in signals transmission and reception. Beamforming is used in smart antenna systems, which are called antenna arrays. These smart antennas use digital signal processing techniques to estimate the angle of arrival (AOA) of the signal and use it to adaptively change the weights of the antenna arrays to achieve the maximum signal gain ratio, while minimizing or nulling the effect of interference. In adaptive beamforming the antenna is steered in the desired direction to maximize the signal gain and minimize the effect of interfering signals that are received from the undesired directions [23]-[25].

2.1.2.5. Mobile Edge Computing (MEC). Users usually rely extensively on their devices to perform personal or business related operations. Therefore, MEC was developed which utilizes the cloud computing technologies to provide close proximity to the end user and perform the computing, storage, and networking operations at the network edge. This proximity will allow for a system to have a low latency and high data rates capabilities to access real-time contents that are supplied by the contents providers [26].

In the era of 5G, developers will overlay the existing Radio Access Network (RAN) networks with a distributed edge cloud computing, in a way that will help the Mobile Network Operators (MNO) plan their network and take loads from the core network and assign it to the network edge. This, in return, will reduce the core network and the backhaul link congestion [27].

2.1.2.6. Small Cells and Heterogeneous Networks. Deployment of small cells in the network will play a huge role in keeping up with the higher demand in data rates. This could be achieved by reducing the size of the cell, and hence the spatial frequency will be increased, while the power loss through channel propagation is reduced and the transmit power will also be reduced.

The simultaneous operation of different types of small cells from Macro, Micro, Pico, and Femto-cells will further enhance the system flexibility in the amount of power consumption, coverage area, and the number of users that could be served by the BS.

One of the key enhancements in the current standard of wireless networks that has been specified in the 3GPP standards (Rel.8-10) is the separation of the control plane and the user plane, such that the user can maintain connection with two different BSs; one to maintain the connectivity and mobility which is normally the Macro-cell, and the other one is to provide data transmission with higher data rate [28]-[29].

The network densification with different types of BS will form what is called HetNet, allowing a multiple tier of communication cellular networks. A two-tier HetNet could be formed by deploying a cell that consists of a Macro Base Station (MBS) and a number of Small Base Stations (SBSs) under the coverage of the MBS [30]. The different types of BS and their coverage areas are listed in table 2.1.

Table 2.1: Comparison of the different types of Base Stations.

Small cells/	macrocells	Microcells	picocells	femtocells
Power consumption	20w	1-5w	50mw-1w	>100mw
Coverage area	1-20km	500m-2km	>=200m	10-20m
Usage	Public hotspots	Neural Mobile services	Enterprises	Homes
Users	Many	>100	20-40	A few users

2.2. D2D Communication in 5G Networks

Device-to-Device communication is an emerging network paradigm for the purpose of enhancing the network performance and ensuring a higher probability of traffic offloading. D2D can be viewed as a multiple co-located devices wirelessly communicate to exchange contents and satisfy user's requests with a minimal or very controlled involvement of the MBS. The driving force for connecting devices via D2D links is to offload network traffic from the congested backhaul links to minimize the latency and the reduce the energy and cost, especially in supporting proximity services such as the social networking. The technologies that are used in D2D communication are designed to operate in short distances between the transmitter and the receiver of the content; hence it achieves high data rates while it consumes low energy.

Devices in D2D can communicate in licensed and un-licensed bands as shown in Figure 2.4. Communication in the licensed and un-licensed bands are named Inband and Outband D2D communication respectively; based on how the spectrum is shared between the D2D link and the Base Station to Device (B2D) communication as shown in Figure 2.5. Inband is highly controllable over cellular networks; it is further divided into underlay and overlay. In underlay both D2D and cellular communication share the same radio resources; in contrast, in overlay D2D communications are given dedicated cellular resources. The key drive for using Outband D2D communication is to eliminate the interference between D2D and cellular connections. The usage of unlicensed band will require the existence of an extra interface and adopt wireless technologies such as WiFi Direct, ZigBee, and Bluetooth. Outband D2D communication can be further subdivided into controlled and autonomous. In controlled Outband communication, the communication interface is controlled by the cellular system; while in the autonomous Outband communication, the communication interface is controlled by the user. The main advantage in Outband D2D over Inband D2D is that users can have simultaneous cellular and D2D transmission. While in Inband D2D a user can have either D2D or cellular transmission at the same time. In addition, Outband D2D can have lower transmission distances, and hence, the higher data rates [31]-[33].

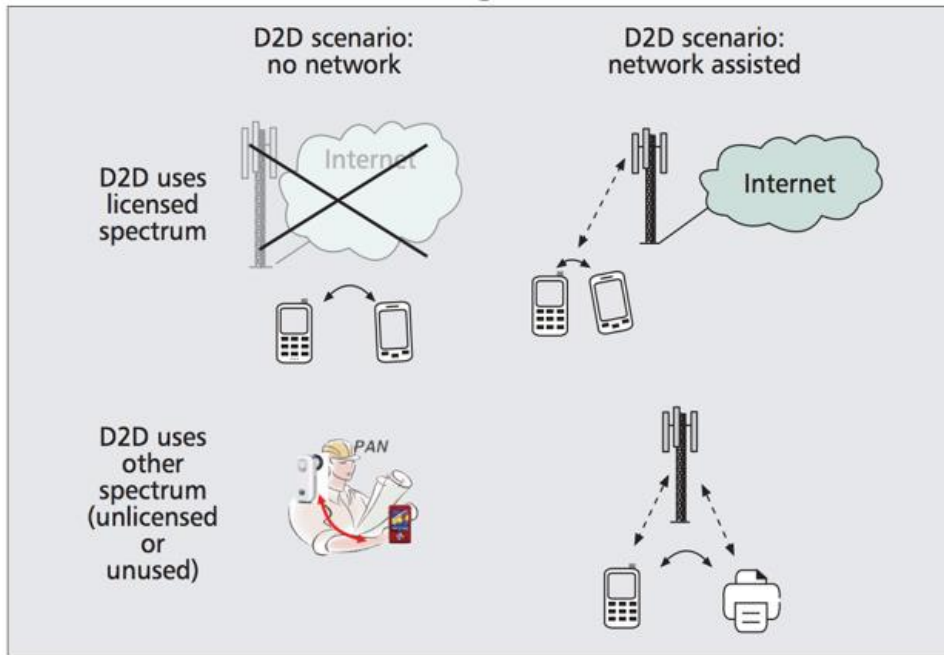


Figure 2.4: D2D communication utilizing licensed and unlicensed spectrum, with no assistance from the network and with network assistance [33].

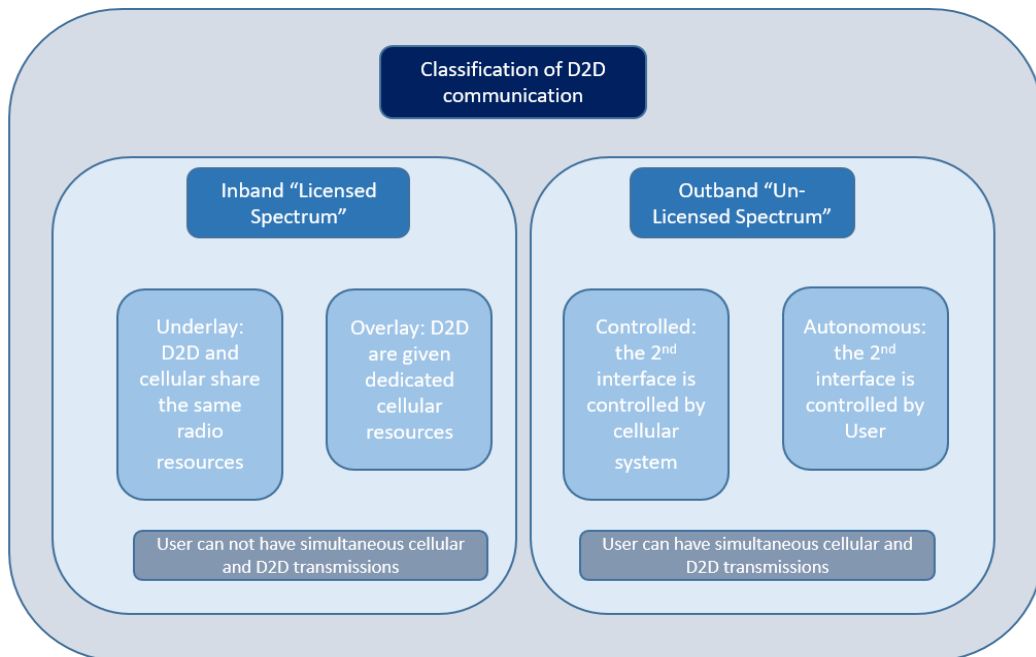


Figure 2.5: Classification of D2D communication.

2.2.1. Peer device discovery and communication. The process of peer discovery is quite significant for D2D communication, in such that the D2D link is discovered and established within the constraints of minimal latency of 10ms. In this

process the UE searches for a potential UE to connect with; if succeeded these two devices will form a D2D pair. Moreover, this process involves a number of messages that need to be exchanged between the UEs, and between the UE and the BS, to provide information related to the link qualities. D2D can always be done in a centralized or un-centralized manner, and there is always a trade-off between the efficiency, security, scalability and decentralization. After the two UEs discover each other, the actual communication between the two devices can start after the process of the mode selection, channel estimation, resource allocation, and the power control [34]-[36]. In the case that the BS tightly controls the device discovery, the process is called centralized framework for peer discovery. In contrast, the process where the device discovery is completed by the devices themselves using beacons is called as un-centralized framework for peer discovery. For two devices to be able to communicate, they must be in the same time, frequency, and space. The major challenge that faces the device discovery process is the consumption of great amount of energy that may end up draining the battery of the device [37]-[38].

2.2.1.1. Un-centralized framework for peer discovery. Several existing wireless technologies such as Bluetooth and WiFi-Direct depend on UE sends beacons as a mechanism for device discovery. Since the discovery is done without the involvement of the BS, the device will be responsible for the selection of resource and the transmission. The authors in [37] propose a process for the transmission of beacon between devices using Orthogonal Frequency Division Multiplexing (OFDMA), where UEs are divided into groups, and each group use different pattern for transmitting beacons [38]- [39].

2.2.1.2. Centralized framework for peer discovery. In the centralized peer discovery framework, the BS detects if the two pairs of devices are in the coverage, since the BS has the access to the physical location of the UEs. Thereafter, the network-directed transmission mode will be activated, and then the BS dynamically allocate resources to the UEs to establish a D2D transmission [38]- [39].

2.2.2. Interference management. The co-existence of both D2D communication and the cellular communication will cause interference, and hence a degradation in the performance of the cellular networks. Therefore, interference management is used to guarantee the users QoS and enhance the reliability of both

cellular and D2D communications. Interference management is divided into two categories, one is to guarantee QoS to the cellular UEs and the second one is to enhance the performance of D2D communication. Power control is one of the strategies used in minimizing the interference effect to the devices communicating using cellular links. When two D2D pairs communicate in the licensed spectrum causing an interference to the cellular links, the BS can control the transmission power of the two devices, both statically and dynamically. In the static power control case, the BS sets a fixed power for transmission regardless of the transmission channel fluctuations, while on the dynamic power control the BS adjust the transmission power of the two devices dynamically based on the Channel State Information (CSI) [40]. Another strategy for controlling the interference effect is the resource allocation, under the assumption that the D2D communication is in the licensed spectrum; in this case, there will be an adequate amount of interference generated by the D2D pair to the cellular network, unless the BS assigns a dedicated radio resource to the D2D communication. This strategy allocates both the spectrum and the transmission power to the D2D pair, in a way that satisfy the SINR requirements of the cellular users [41].

2.2.3. D2D communication over WiFi Direct. The invention of the use of the existing WiFi Direct and Bluetooth technologies in the field of D2D communication forms a real-solution to the market of telecom industry. These technologies work in the unlicensed band and could be powered by the cloud services. One of the challenges in the implementation of the WiFi Direct in file transmission between any pair of devices is the manual pre-authentication process for the transmission. Therefore, researchers have been investigating the need to develop a solid infrastructure to semi-automate the process and to support the process, especially in the process of device discovery and authentication. Clearly, there will be an argument on the ability of the current network technologies to accommodate such demands; hence, we will need to discuss the potential design schemes that could enable the use of the existing WiFi Direct technology.

The authors in [76], made a valuable comparison between the use of WiFi Direct, the Bluetooth, and the Inband D2D communication, in terms of the spectrum, the interference management, the user preference of the QoS, the delivery process, and the transmission range, as listed in Table 2.2.

Table 2.2: Comparison of the different D2D communication technologies [76].

Technology	WiFi Direct	Bluetooth	In-band D2D
Spectrum	Unlicensed	Unlicensed	Licensed
Interference Management	No	No	Yes
QoS	No	No	Yes
Device Discovery	Two-steps asynchronous messages	Pairing manually	Devices podcast their services at the physical layer
Transmission Range	Up to 100 meter	Tens of meters	Up to 500 meters

The authors in [42], stated that the use of the unlicensed band technologies suffers from the energy consumptions in the process of device discovery, it also suffers from the unexpected interference and unscheduled channel access. They proposed the idea of evolving the network in a way that the device receives help from the MNO to manage the unlicensed band D2D communication. MNO can also interfere to resolve the issues of peer discovery. If clients are already under the MNO coverage, the BS can define the user device's location to a range of few meters, if the GPS services are available. This service will allow the BS to know without any overhead signalling if any two devices are in the proximity of each other, then BS can inform them and assist in the establishment of the D2D connection, the power control, and the mode switching between the D2D mode and the cellular connectivity mode [42]- [46]. In contrast, in the decentralized structure, the role of the network is kept to minimum only in the synchronization between the D2D pairs [47].

2.2.4. High Mobility devices communication in D2D. D2D communication is used in short range communications, to achieve higher data rates and lower transmission power. The mobility capability of both the Transmitter (Tx) and the Receiver (Rx) will result in an increase in the Doppler spread and shadowing. Zhi Wang et. al in [48], proposed a model to transfer the social content by making replica of the

files, while utilizing the D2D connectivity as the users move in arbitrary directions within the cellular network coverage. In the work authored by Yerragudipadu et. al in [49], they have proposed a distributed stochastic geometry model which enables the analysis of the mobility-aware D2D communication.

2.2.5. D2D communication in HetNet. A HetNet consists of a MBS and multiple SBS deployed inside the MBS. The SBS role is to provide signalling for the D2D communication between users, while the role of the MBS is to transmit the requested files, i.e. provide the data traffic. Two-tier HetNet is extensively studied in literature [50]- [52]. Figure 2.6 depicts the signalling and data transfer in a two-tier HetNet that consists of SBSs in addition to the MBS.

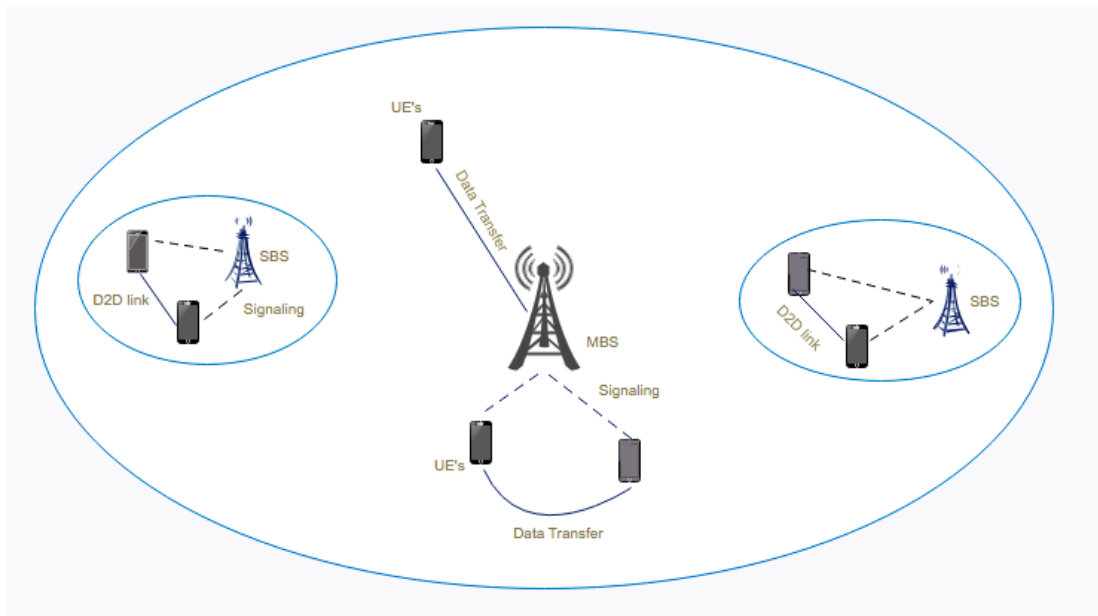


Figure 2.6: D2D communication in a Two-tier HetNet, consisting of MBS, SBS, and D2D links. SBS provide signalling for D2D communication, MBS provide data transfer. Solid lines represent data transfer while dash lines represents signalling.

2.3. Caching Techniques in 5G Networks

Caching the most popular files at the network edge is a promising technique that will be utilized heavily in the era of 5G. It is used to reduce the need for accessing the data directly from the origin server at the content provider end, which will reduce the core network congestion and reduce the latency, while increasing the transmission data rate and the user hit probability. The idea of caching goes back to the sixties of the last

century, since then the idea of storing the most used files in nearby memory locations and delete the no longer used files has been utilized in many systems. As a result caching will help in reducing the network load by storing the most popular files at the network nodes such as the EPC core network, RAN access network, at the BS and at UEs, at the off-peak hours and serve the requests. Caching at the UEs exploits the D2D links between user terminals. The key factor of success in this operation is to pick the perfect set of files based on their popularities so that the request of users can be satisfied directly at the network edge without the need of using the congested backhaul link to the Content Provider (CP) [53]. Different types of file caching and offloading are expressed in the Figure 2.7, where self-offloading depicts the scenario of a certain user requests a file that is already available in its storage; in such case, the request can be directly offloaded and the request is then satisfied. Another scenario is a user requests a file that is available at any neighboring device, then the request can be satisfied by utilizing the D2D communication between the two devices. The device who requests a content file will be denoted as the content requester, while the device who has the requested file and can serve the request will be denoted as the potential content provider. For any request there may be more than one potential provider, in such case the requester can make a multiple D2D (MD2D) links with the multiple providers to satisfy the request and the problem could be extended into how to select a proper content sharing mode in an interpretable manner [16], [54], [64]. In the 3rd scenario, the network is a HetNet with two-tier network that consists of the SBS and the MBS. In such case the SBS forms a cache helper, and the user request is directly satisfied by the SBS as in [55]. The authors in [56] have divided the cell into several virtual clusters and if the content file is not available within the cluster, the MBS will satisfy the request by getting the file from any neighboring cluster and then deliver the file. In their work, they analyse both the centralized and distributed cache schemes within a certain collaborative distance. They pointed out that the random cache placement, where the location of the devices is unknown a priori, shows only minimal loss in the performance.

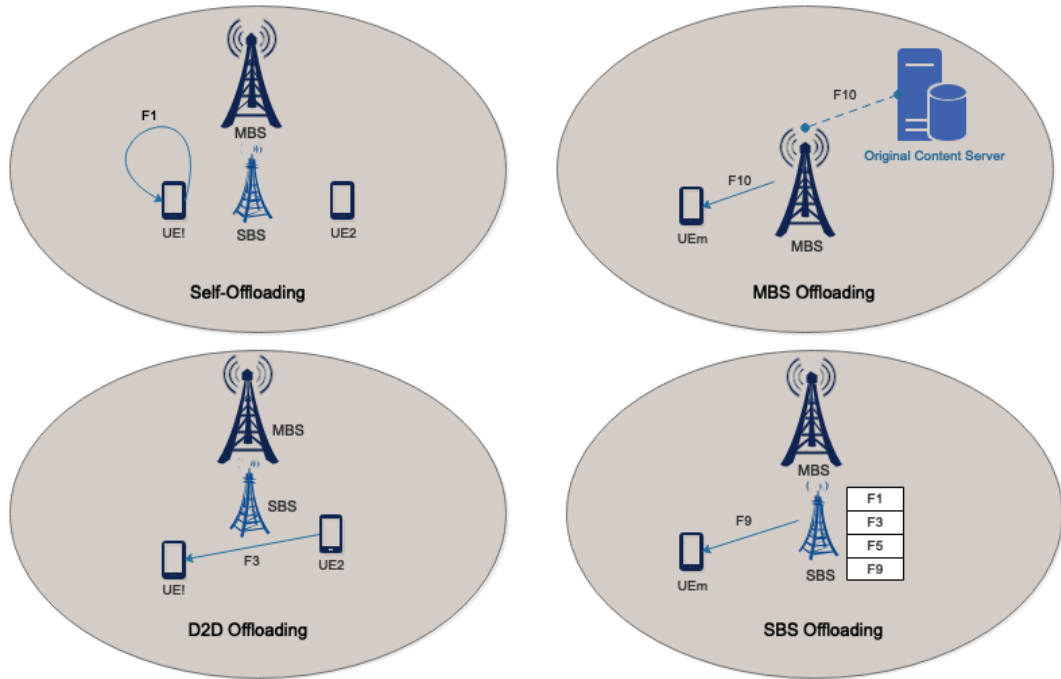


Figure 2.7: Different types of requests off-loading in 5G networks.

2.3.1. Caching in a Multi-Tier HetNet. A two-tier and three-tier HetNet are used extensively in the real-world implementation of cellular networks. Le Thanh et. al in [57], proposed a joint optimal cache placement and resource allocation for a two-tier HetNet where the cache is implemented at the edge of the network. The network throughput was optimized by the means of cache placement. Furthermore the authors in [58] proposed the use of Femtocells as a cache helper and optimally assign the popular files to it, with the goal of minimizing the files download time.

2.3.2. Content popularity model. The content cache problem has many issues that needs to be addressed; the usually asked questions are where to cache i.e. at which nodes in which location in the network, what to cache which is associated with the process of files selection based on a pre-stated criterion, taking into account the spatial and temporal content popularity, and how to cache by using a specific algorithm to implement the caching process. When the cache decision is made it must be targeting the goal of maximizing the content hit probability [59]. The most commonly studied and used popularity distribution model was observed in web caching, which was the Zipf distribution. The probability distribution function of the Zipf distribution is shown in Figure 2.8.

Zipf distribution allowed for the accurate determination of the cache decision, in which the files that has the highest popularity should be intensively cached in the network edge, while the files that has the lowest popularity should be discarded from the cache system [60]- [61].

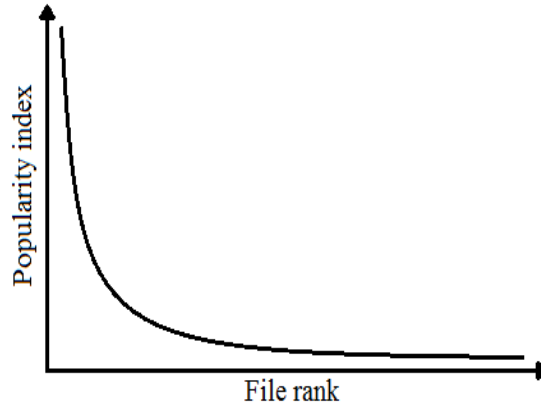


Figure 2.8: Zipf Probability Distribution Function.

2.3.3. Content cache placement. The content cache placement phase is crucial in determining the success of the content caching scheme. Precisely, an optimal placement of the content files at the UEs could be the driving success to ensure a high offloading gain in the system under implementation. In the work authored by Somayeh et. al in [74], and [75], they proposed an optimal cache placement scheme that takes into consideration the device ability to establish a D2D communication. In their first work they look into the offloading probability that is affected by the proposed scheme, while in the second work they look into the effect of the joint optimization problem in terms of the caching gain. Cache placement at the network edge can be divided into two categories, centralized caching or distributed caching.

2.3.3.1. Centralized caching. The transmission power and the cache decision is under the control of the BS. Many researchers adopted the centralized caching scheme due to its optimality in the cache decision and the cache distribution between the UEs as compared to the distributed caching scheme. The centralized caching scheme suffers from the signalling overhead to synchronize and deliver user's requests. Furthermore, this scheme does not encounter the mobility behaviour of the users [62]- [66].

2.3.3.2. Distributed caching. To overcome the issues of the centralized caching schemes, some authors proposed a novel distributed caching scheme, where UEs decide whether to cache a file or not based on the popularity index, randomly, independently and without the central control of the BS. Distributed cache comes with its own flaws in term of the duplication of cache content which degrades the efficiency of the cache process [62]- [66].

2.3.4. Content cache replacement. The replacement algorithms that are used in web caching could be extended to the file content replacement. The most commonly used algorithms are Least Recently Used (LRU), and the Least Frequently Used (LFU). The authors in [67], proposed a novel cache replacement policy, named the Lowest Relative Value (LRV). LRV replaces the file based on its relative value (V), which is proportional to the time from the previous file access among many other parameters, and it is computed adaptively. They proved that LRV outperformed the traditional LRU.

2.3.5. Incentive-based caching in D2D networks. Many researchers posed the question of whether the users will accept to participate in the D2D cache-aided communication in the later times. Previously, researchers assumed that network users are willing to participate in the D2D network and they are willing to share their content files. The assumption is valid in the case of the social networks where users are related to each other somehow. But practically speaking, users will not consume their resources and drain their batteries in such communications unless this behaviour is rewarded. The incentive based D2D communication has been studied in many researches. In [68] each user can select which content to cache in a way that maximize its incentive profit while minimize its cost and interference at the same time. In this scheme the BS subtracts the interference that the D2D link introduces to the network from the calculated incentive to provide the total profit for each participating device.

Chapter 3. System Model

In this chapter, we formulate the problem of content caching and sharing in three different domains namely the network model, the cache model, and the transmission model.

In our proposed work, we assume that the D2D communication does not interfere with the communication between the base station (BS) and other users. This assumption is justified if the D2D communications occurs in the unlicensed frequency band (e.g., WiFi). We henceforth, do not need to consider explicitly the BS and its associated communications. We assume that groups of mobile devices collaborate to exchange files via D2D communications. We can say that clusters of collaborating devices “pool” their caching resources to provide a “central virtual cache” (CVC), controlled by the BS, and a user can select from a multiple devices to form a D2D pair.

When a UE first joins the network and requests for a content file, it directs its request to the BS, which keeps a 2D matrix that contains the cached files ID and the owner of that file. The BS sends the requester the information about the possible content owners, and then the requester attempts to connect to one of the possible owner that falls in the connectivity range and the communication channel has the highest SINR value. The proposed model is a hybrid content caching assisted D2D communication, since the BS is partially involved in the process. The model takes into account user’s mobility in addition to the randomness nature of users’ behaviour for arrivals, departures, and disconnection.

3.1. Network Model

We consider a network cell that consists of the MBS and a set of UEs which are distributed under the coverage of the MBS using the independent homogeneous Poisson point process (PPPs) with density of λ in the unit of number of users per unit area (users/ m^2) as shown in Figure 3.1. A pair of UEs will discover each other and establish a D2D communication channel in the downlink to exchange the cached contents. The distance between the D2D transmitter and receiver is limited to 50m as stated in the 3GPP standard Release 12 [69]. We assume that the D2D is operating in the autonomous outband “unlicensed spectrum”, and using the WiFi interface. We assume a D2D peer discovery is done using LTE Direct technology available at many smart

phones. The MBS is equipped with only one antenna for transmission and reception and each user is also equipped with only antenna which is used for both transmission and reception of the signals. We investigate the operation of mode selection for each D2D pair, where each pair could operate either in the D2D mode or in the cellular mode; In our work we focus only on the D2D mode of operation, and hence the set of D2D devices is denoted as $UE = \{UE_1, UE_2, UE_3, \dots, UE_N\}$. The selection of one of the modes or another depends on the specified criterion. The first and the most important criteria to be met is the availability of the requested content at the transmitter's cache memory, if the content was available then a possible D2D pair is established between the transmitter and the receiver of the content. In such cases when the requested content is unavailable, the request will be directed to the BS and the mode will be switched to the cellular mode. We consider the case where the network is a dense auditorium or university campus, and the users are trying to access the content files from the network, and hence the interference is high and the network is congested with the download requests. In our solution we use WiFi Direct-based D2D communication to reduce the load on the network as done in [70].

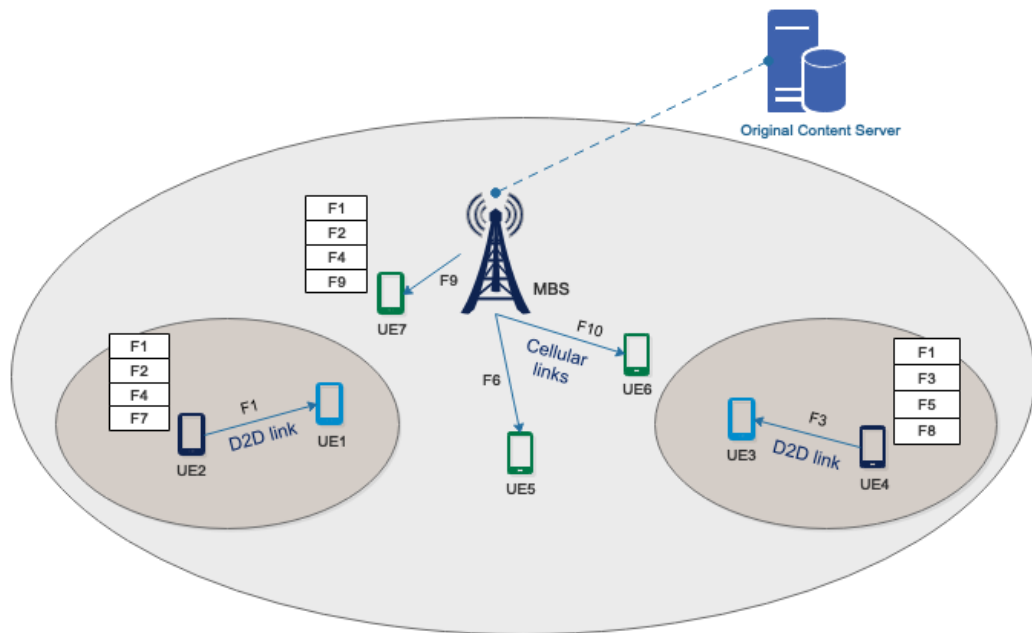


Figure 3.1: The proposed 5G network architecture consisting of one MBS and a number of users distributed using homogenous PPPs. When a user UE_1 requests a file f_1 that is cached in any neighbouring device, the file f_1 is transmitted by the user UE_1 . While when UE_7 requests a file f_9 that is not cached in any neighbouring device, the file is fetched from the original content server and the request is served via the MBS.

3.2 Cache Model

For the cache placement problem, we assume a set of content which is denoted as $F = \{f_1, f_2, f_3, \dots, f_M\}$ and the size of the content file is S_i for each file content f_i , where $i \in [1, 2, \dots, M]$. For simplicity we assume all files are of the same size, and if not they will be divided into a set of an equal size files. The whole file set is also cached at the BS, portion of the set is distributed to be cached at some of the UEs. The UEs has a limited cache storage capacity C in terms of the number of files, which satisfies the condition $C \ll M$, which means that not all the files can be cached in the UEs. Furthermore, the BS keeps track of which files are cached at which device using a binary matrix M_{BS} which has $M \times N$ dimensions, where M represents the number of the content files and N represents the number of UEs in the cell. The matrix M_{BS} is used to denote the cache placement decision where each binary element v_{mn} indicates whether a certain file is cached at a specific UE; specifically, $v_{mn} = 1$ if the file f_m is cached at the user device UE_n , otherwise $v_{mn} = 0$ if the file f_m is not cached at the user device. From the above mentioned storage capacity limitation, clearly, $\sum_{m=1}^M v_{mn} \leq C$, $\forall UE$, this implies that the cache placement, i.e. which file to be cached at which UE , is a vital issue.

3.2.1. Self-offloading mode. If the requested content file is already available at the requesting device cache memory, there will be no need to connect with any neighbouring device and the request will be served immediately. This is the case where a user is revisiting a previously requested content.

3.2.2. D2D mode. In the case that the requested content file is available at one or more of the neighbouring device, which forms the potential content providers, and the connection can be established to connect with one of the content providers. The requester then sets up a one-to-one connection between itself and the content provider, and the request is then satisfied.

3.2.3. B2D mode. The content is not available at any of the neighbouring device, and it is only available at the BS, then the device utilizes the cellular link to establish a one-to-one connection between itself and the BS. If the requested content is also not available at the BS, which is the worst-case scenario, then the BS utilizes the backhaul link to bring the requested content from the content service provider. In our

work we assume that the requested content has been already fetched from the remote server and hence the associated communication is not considered.

3.3. Transmission Model

The requested file is transmitted to the content requester from the content provider who cached the requested content. The transmitter is selected by using a mechanism to increase the signal to interference plus noise ratio (SINR), by selecting a channel that provide the highest value for the SINR. If the requested file is cached at any UE, which means $\sum_{m=1}^M v_{mn} \geq 1$, the received signal at the content requester is given by [79]:

$$P_{Rx} = P_{Tx} G_{Tx} G_{Rx} \left(\frac{c}{4\pi f_c d} \right)^2 \quad (3.1)$$

where P_{Rx} is the received power of the D2D receiver.

P_{Tx} is the transmitting power of the D2D transmitter.

G_{Tx} is the antenna gain of the D2D transmitter.

G_{Rx} is the antenna gain of the D2D receiver.

c is the velocity of the propagating signal.

f_c is the carrier frequency.

d is the separation distance between the transmitter and the receiver.

3.3.1. Channel model. The channel model was built based on the WiFi wireless technology, which has around 14 channels. The channels operate in the frequency range of 2.400 GHz to 2.483 GHz which is equivalent to 83.5 MHz of total frequency as per the 802.11b standard. As it can be seen in Figure 3.2 the WiFi technology consists of 3 non-overlapping channels in the 2.4 GHz frequency band, namely, channel 1, 6, and 11. An example of the channels frequency band with a bandwidth of 11 MHz:

Channel 1:= The central frequency = 2.412.

Range: = 2.401 => 2.423.

Channel 6:= the central frequency = 2.437.

Range: = 2.437 => 2.44.

Channel 11:= the central frequency = 2.462.

Range: = 2.451=> 2.473.

Since WiFi is a half-duplex communication system, which means only one device can transmit at a given time on one channel. The use of non-overlapping will be beneficial in the process of interference management [72]. In our system we implemented the channel assignment in Round Robin fashion (RR), the system will assign channel 1 followed by channel 6 and then channel 11. In case more than 3 devices are transmitting simultaneously, the system will then assign channel 2, channel 7, and then channel 12. In the case where all the 6 channels are transmitting simultaneously, channel 3, 8 are assigned, followed by the assignment of channel 4 and 9. This way of implementation helps in minimizing the effect of the interference. We assumed a total of 12 channels in our implementation.

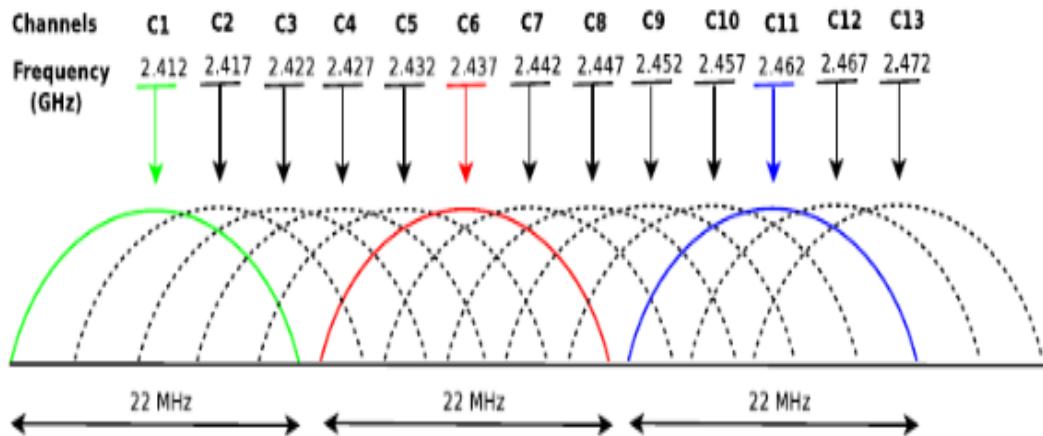


Figure 3.2: WiFi Channel frequency distribution with 12 channels and a bandwidth of 22 MHz each [73].

3.3.1.1. Path loss model. The path loss model used in the D2D communication, is assumed for in the outdoor to indoor and pedestrian communication environment [78]. The path loss is given by:

$$PL = 4 \alpha \log_{10} R + 30 \log_{10} f + 49 \quad (3.2)$$

where PL is the path loss for the non-line of sight (NLOS) measured in dB.

α is the propagation decaying exponent which is set to 4 in this model.

R is the separation distance between the transmitter and the receiver measured in km.

f is the carrier frequency measured in MHz.

3.3.1.2. Shadow fading. The attenuation and fluctuation around the path loss due to the obstacles in the non-line of sight (NLOS) model, which describes the worst-case propagation is assumed to be log-normal and has a standard deviation of 10 dB in the indoor environment [78].

3.3.2. SINR calculation and receiver sensitivity.

The resource allocation is based on the value of the signal to interference plus noise ratio, which is given by:

$$SINR = \frac{P_{Tx}}{N+I} \quad (3.3)$$

where P_{Tx} is the signal power at the transmitter.

N is the Additive white Gaussian Noise (AWGN).

I is the interference in the D2D mode of operation.

The calculation of the interference is based on the information of the WiFi channel allocation. For instance if the 3 non-overlapping channels are assigned for communication, the interference is to any of the 3 simultaneously transmitting devices is the power received from the other 2 devices who are transmitting simultaneously after deducting the values of the channel noise and the Pathloss. This is also valid for any number of transmitting devices by knowing the number of WiFi channels which are active simultaneously.

3.3.3. Arrival of requests. The arrival of requests has been modelled as a homogeneous Poisson Point Process (PPPs) with rate λ_r in the unit of number of requests per unit time (request /s), and it is given by:

$$P_{(n)} = \frac{(\lambda_r)^n}{n!} e^{-(\lambda_r)} \quad (3.4)$$

where $P_{(n)}$ is the probability of the arrival of the n^{th} request.

3.3.4. Transmission rate. The transmission rate in the system follows the Shannon's capacity theorem, which is used to predict the maximum rate of information transmitted through a channel. The transmission rate S_r is given by:

$$S_r = B \log_2(1 + SNR) \quad (3.5)$$

where B is the bandwidth, and SNR is the signal to Noise ratio.

Chapter 4. Methodology

In this chapter, we formulate the problem of content caching and sharing in a collaborative D2D cellular communication system. We present the proposed algorithms for a distributed and decentralized content sharing between UEs by utilizing the available D2D links. We will present the implementation of the proposed network architecture along with the employed algorithms for the cache-assisted D2D communication problem.

4.1. D2D Pair Selection

The process of mode selection has the objective of maximizing the offloading probability based on the cached content availability. We proposed an algorithm, which is called Maximum SINR with distance threshold (MSDT), to select the perfect D2D pair to communicate with, based on the maximum SINR and the minimum distance between the two UEs. If two devices are within the communication range and one of them offers a higher SINR on the communication channel, then the algorithm will select the one with the higher SINR. Regardless of the distance between the two devices, as long as the distance will allow for the D2D communications. The SINR is an indicator of the channel quality and it is calculated within a *UE* [71]. The proposed algorithm is shown in Figure 4.1. Where N stands for the number of devices, SINR is the signal to noise plus interference ratio, and D_t is the threshold distance which is set by the algorithm to determine the maximum allowable distance for transmission.

4.1.1. Distance between any D2D pair. The distance between any two D2D devices is shown in Figure 4.2. It is assumed to be the Euclidean distance in the Cartesian coordinates, and it is given by:

$$D_{d2d} = \sqrt{(r_{d1}^2 + r_{d2}^2 - 2r_{d1}r_{d2}\cos\theta)} \quad (4.1)$$

where D_{d2d} = the distance between T_x and R_x .

r_{d1} = the distance between T_x and the BS.

r_{d2} = the distance between R_x and the BS.

$\theta = [0, 2\pi]$

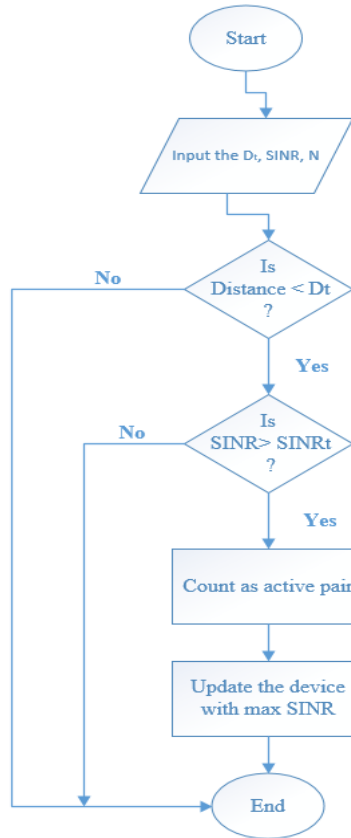


Figure 4.1: The proposed MSDT algorithm.

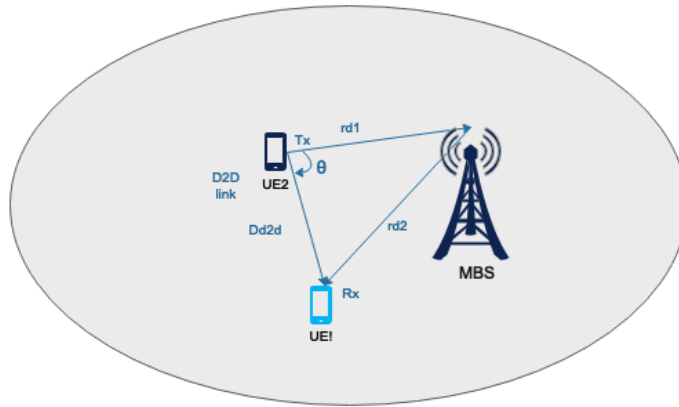


Figure 4.2: Distance Calculation between two D2D devices UE_1 and UE_2 .

4.2. Cache Assisted D2D Communication

Based on the availability of the requested content file cached at one or more neighbouring devices, a potential mode of operation will be selected, either the self-offloading mode, the D2D mode or the B2D mode. The former (B2D) will be selected only if the content could not be found in any user proximity, and its associated

communication is neglected in our work. The proposed system algorithm that describes in details the process of the cache placement phase in addition to the delivery phase is shown in Figure 4.3.

4.3. Cache Placement and Replacement Strategies

On the occurrence of a request of a new content file, the request is placed by the user to the BS. The BS serves the request using the congested backbone network, and the file is then cached at the BS. The file is then transmitted to the file requester, and then the requester caches the file as well. Based on how many times the file is requested by other users, the file popularity index is calculated locally at the content owner. The replacement of the file in the existing cache storage is done primarily using the Least Frequently Used (LFU) algorithm. After sorting the files in a stack of descending order based on the popularity index, the last file in this stack will be replaced. The proposed algorithm of the cache placement and replacement is shown in Figure 4.4.

4.4. Random Cache Algorithm (RCA)

In the random cache scheme, each user caches files independently and at random. Since the BS has a minimal influence on the cache decision strategy and each user decides to cache files randomly, there may be duplicates of the cached files at different user's cache storage. This duplication will definitely affect the cache decision efficiency. Hence, the performance will be reduced when compared to other caching scheme [77].

4.5. Popular Cache Algorithm with LFU Replacement (PCA)

In the popular cache scheme each user caches the most popular files only. In this scheme, we assume that the files popularity follows the Zipf distribution with skewness of η . However, the user's preference may vary from time to time due to the change of interest of users; for instance the users in a library will have a different content request other than the users resident in the sport complex. In our work we assume that users have the same content files preference which implies that users are interested in the same set of popular content files. The proposed cache replacement algorithm is the LFU, where content files are sorted in a stack in a descending order based on the content files popularities. Then the files that have the least popularity, which means the files that are least frequently used, will be replaced with the new requested files [77].

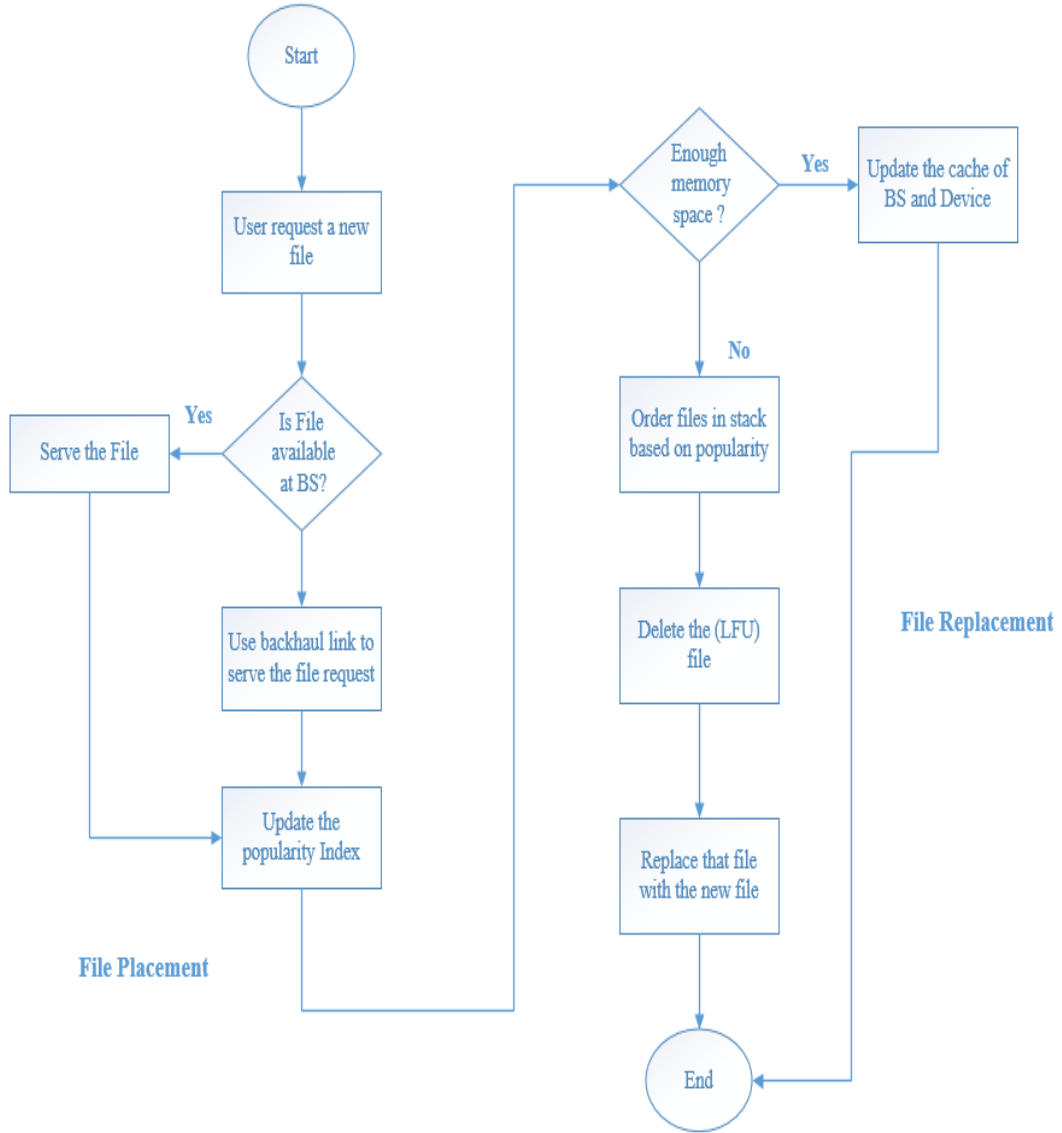


Figure 4.4: The proposed Cache Placement and Replacement strategies.

4.6. Popular Cache with LFU plus Instantaneous Popularity Index (PCLIA) Algorithm

In the popular cache scheme each user caches the most popular files only. In this scheme we assume that the files popularity follows the Zipf distribution with skewness of η . However, the proposed scheme will take into account the significance of the cache storage capacity in affecting the system offloading gain. In this proposed scheme the replacement method depends not only on the LFU but also it checks the number of owner, to the least frequently used file. The LFU file is only cached by one UE it will not be replaced, and the algorithm will keep looking into a file that has a

higher popularity that is owned by more than one UE. this process will insure that the files which has only one owner will not be removed from the cache system; on the other hands the files which resides in more than one user cache storage will be replaced since it has more than one replica. This proposed scheme will increase the overall system efficiency, and hence will increase the system overall caching gain.

4.7. Content Popularity Distribution

The content popularity distribution normally follows a Zipf distribution, which is widely used to model the multimedia content popularity [63]. In Zipf distribution the contents that has a small value of k tend to show a higher popularity, while the contents that corresponds to a high value of k tend to show a lower popularity.

Zipf distribution is given by:

$$P_k = \frac{k^{-\eta}}{\sum_{l=1}^k l^{-\eta}} \quad (4.2)$$

where P_k is the popularity index of k^{th} file.

The parameter η indicates the skewness of the Zipf distribution, which is the case that the popularity does not follow the exact normal distribution.

The content popularity enables a good estimation of the potential value of the received content to any potential requester, and provides an estimation of to which extent the neighboring devices will benefit from this cached content.

4.8. Disconnection Rate

In order to provide a realistic model that simulates the real-life events, we proposed a scheme that takes into account the randomness of user behavior in disconnection. Due to certain circumstances such as the dead battery or the fact that the user is no longer interested in the cache collaboration, users can suddenly disconnect from the system while carrying valuable information, such as the instantaneous popularity of a specific file. In the case that the user was the only owner of some files, the loss of such information could be vital to the system overall offloading gain, and hence decrease the cache hit probability. The Disconnection rate α_r could be low where only few users leave the communication cell, while in the medium disconnection rate around half of the users leave the communication cell, on the high disconnection rate

most of the users leave the communication cell due to sudden changes in the communication or in emergency situations.

4.8.1. Low disconnection rate. In the case that the percentage of devices leaving the communication cell, or switching to B2D mode of operation without being further involved in the D2D communication is low. The Disconnection rate α_r is assumed to be 10% of the total number of devices in the communication cell.

4.8.2. Average disconnection rate. In the case that the percentage of devices disconnecting from the D2D mode of operation is averaged to 50% of the total number of devices in the communication cell.

4.8.3. High disconnection rate. In the case that the percentage of devices disconnecting from the D2D mode of operation, or entirely leave the communication cell is assumed to be really high. The Disconnection rate α_r is assumed to be 90% of the total number of devices in the communication cell. The sudden change in the device connectivity is due to the sudden change in the communication cell's parameters, system faults, or due to an emergency situation.

4.9. Mobility Model

In order to provide a realistic model that simulates the real-life events, we proposed a scheme that takes into account the mobility of the users. The unpredictable users mobility affect the cache hit probability and the cache offloading mode i.e. D2D mode and B2D mode. The proposed model is called the Random Walk Model (RWM) and it has been investigated in the literature in [80]-[82]. In this model, the node starts moving from the starting point toward the next point by setting the direction and the speed of movement. The angle range is $[0, 2\pi]$, and the speed range is $[0, v_m]$. The node moves for a fixed time interval t , which is set to 1 second in this model. After 1 second, the node selects a new direction and a speed for the next move. In the case, that one node reaches the boundary of the cell the direction will be reversed, to keep the nodes inside the cell boundaries.

The offloading probability is used as a metric to show the effect of device mobility, since mobility will affect the offloading mode from D2D to B2D and vice-versa.

Chapter 5. Results and Analysis

In this chapter, we present the simulation results achieved for the implemented collaborative cache assisted-D2D scheme. We consider a single macro communication cell with a radius of 1500 m. The users are distributed in the cell using the homogenous Poisson point process (PPPs) with intensity λ (number of users per unit area). We also evaluate the performance of the proposed cache placement algorithms in terms of the caching hit probability in the random caching algorithm (RCA), the popular caching algorithm (PCA), and the popular cache with LFU plus instantaneous popularity index algorithm (PCLIA). The caching hit probability is defined as the percentage of requests that has been served using the self-offloading mode plus the D2D mode rather than served by the BS. Moreover, the system performance is measured by varying the network parameters in terms of the user's intensity and the D2D collaboration distance. In addition, the Zipf parameter and its effect on the caching scheme is considered when evaluating the overall system performance.

5.1. Simulation Setup and Main Parameters

We have implemented the proposed algorithms by fixing up the main parameters to calculate the SINR. In order to get reliable parameters the results were averaged over 500 runs with a total simulation duration time of 1×10^6 seconds. The main parameters for the system implementation and the channel model are listed in table 5.1. The simulation was run on MATLAB R2018a. The Matlab code appears in Appendix A.

Based on the LTE standards in [83], the transmission power of the UE is set to 24 dBm. The macro urban channel model is used for the simulation and the Additive White Gaussian Noise (AWGN) is assumed to be -117 dBm. The content library size, cache storage size and the size of content are assumed similar to the research in [74]. The SINR threshold is the minimum value that the communication channel can take, otherwise the communication channel is rejected, and the transmission is directed to the B2D mode. The same argument is used for the receiver sensitivity and the D2D cooperation distance.

Table 5.1: System main parameters.

Parameter	Value
Cell radius	1500 m
Channel Model	Macro Urban
D2D Distance Threshold	50 m
Density of users λ	$5 \times 10^{-5} / \text{m}^2$
Request rate \mathcal{S}_r for the system	0.5 request/s
Transmit power of user	24 dBm
Content library size \mathcal{F}	100 files
Cache storage size \mathcal{C}	10 files
Size of content \mathcal{S}	1 Mbits
Carrier frequency for D2D f_c	2.4 GHz
Bandwidth \mathcal{B} D2D	22 MHz
Transmission time \mathcal{S}_r	3 ms
Path loss exponent α	4
Zipf distribution parameter	2
SINR threshold	15 dB
Receiver sensitivity	-100 dBm
AWGN noise \mathcal{N}	-117 dBm

5.2. Simulation Results

The cell structure is considered to be in a hexagonal shape where the outer circle radius of the hexagon is set to 1500 m. Figure 5.1 shows the cell structure where the BS is assumed to be at the center of the cell, and the user distribution follows the homogenous PPPs with density $\lambda = 5 \times 10^{-5} / \text{m}^2$.

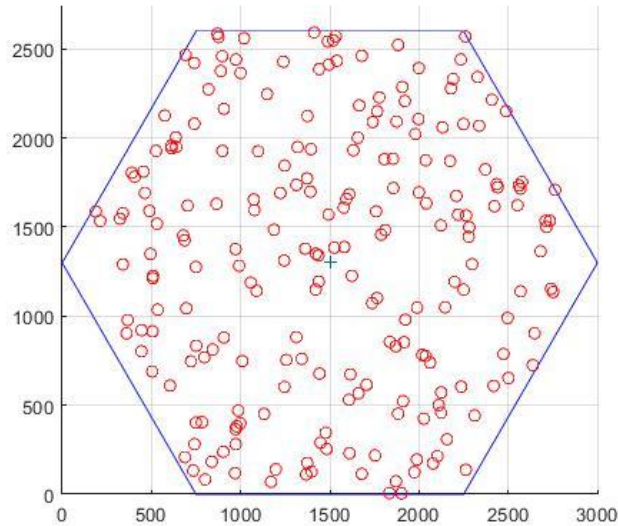


Figure 5.1: A sample cell structure with one MBS at the centre and the users are distributed using PPPs with density $\lambda = 5 \times 10^{-5} / \text{m}^2$.

The proposed MSDT algorithm is able to detect user's locations and measure the distances between a specific device and all the other devices in the cell, in addition to the SINR values for potential D2D pairs, and then compare the pairs based on the maximum SINR and the minimum distance between any potential pairs. The distance between any device and the others for 10 devices is shown in Figure 5.2. From this figure it can be clearly seen that the distance between any device and itself is equal to zero, also the matrix is mirrored around the diagonal, thus it implicitly prove that the distance from a particular device to the other is the exact distance from the other device to this particular device. The argument is also valid for the SINR calculations, in the case of SINR calculation of the device with itself, on contradictory, the SINR calculation between a particular device and the other device differs than the SINR calculation from the other device to this particular one, since it depends on the device transmitted power. The distances values are extremely large since there are only 10 devices distributed in the area of the communication cell.

Figure 5.3 shows the SINR values in dB for 10 devices as implemented by the MSDT algorithm. The values are very small since the distances between the devices are extremely large, and apparently none of these devices will be able to successfully make a D2D connection.

Table 5.2: Distance in km between 10 D2D devices as implemented by MSDT Algorithm.

0.0000	2.7664	2.3984	2.9042	0.9501	0.9048	3.3847	1.8833	1.6713	2.3228
2.7664	0.0000	9.1270	1.4582	2.1894	1.0894	1.2826	0.9160	1.3020	0.4481
2.3984	9.1270	0.0000	2.2208	1.5968	1.6885	2.1774	0.6900	1.4820	0.7591
2.9042	1.4582	2.2208	0.0000	2.7975	2.0584	0.6698	1.7685	1.3000	1.4630
0.9501	2.1894	1.5968	2.7975	0.0000	0.8824	3.1144	1.2786	1.5075	1.7695
0.9048	1.0894	1.6885	2.0584	0.8824	0.0000	2.4945	1.0656	0.7796	1.4592
3.3847	1.2826	2.1774	0.6698	3.1144	2.4945	0.0000	1.9024	1.7158	1.4897
1.8833	0.9160	0.6900	1.7685	1.2786	1.0656	1.9024	0.0000	0.8033	0.4912
1.6713	1.3020	1.4820	1.3000	1.5075	0.7796	1.7158	0.8033	0.0000	0.9257
2.3228	0.4481	0.7591	1.4630	1.7695	1.4592	1.4897	0.4912	0.9257	0.0000

Table 5.3: SINR calculations in dB between 10 D2D devices as implemented by MSDT Algorithm.

0.0000	9.5121	19.3706	17.3050	17.6160	23.7220	18.6681	15.4088	15.5589	19.4457
20.5730	0.0000	17.3370	16.8180	12.5731	22.8194	19.9914	9.5022	23.7020	20.8821
17.4215	15.8198	0.0000	13.2448	20.2551	18.8062	18.5980	21.7693	21.2246	17.4327
22.8213	16.0085	19.5178	0.0000	13.7650	16.5442	23.3108	15.3204	22.3106	19.5172
13.6658	16.3120	29.5755	17.5330	0.0000	20.5442	17.6172	23.0465	29.3112	17.6682
15.5730	25.4450	22.5560	17.8180	21.8820	0.0000	19.2231	21.1560	23.6023	24.9982
21.8812	19.7552	24.3230	19.2813	21.7560	24.2833	0.0000	17.5062	23.2312	16.6278
12.7814	15.5160	27.6760	19.8812	19.8890	17.0650	21.7560	0.0000	19.6682	27.9382
17.4129	15.1560	19.5368	24.7123	23.3204	18.0546	23.3160	15.9596	0.0000	23.6810
20.1566	16.6570	19.0377	17.0920	17.5003	21.0560	18.0156	24.6053	23.1565	0.0000

5.2.1. Impact of varying network parameters. In Figure 5.2 we compare the hit probability against the number of users while varying the sending time threshold t for sending the file content. The figure depicts the fact that as the user density λ increases the hit probability decreases, because as the density increases the number of device in a specific area also increases and hence an increased number of simultaneous cache enabled D2D links are formed. As a result, the interference among these active links will also increase. These devices also compete for the resources taking into account the limited number of WiFi channels dedicated for the D2D communication. One more thing to be noted is the increase of the hit probability when we increase the threshold value of the sending time. The threshold sending time t is the maximum time allowed for transmitting the requested content. The value of the time needed to transmit any file is calculated based on Shannon's formula, and this time should be less than the threshold time t for a successful transmission, otherwise, the B2D mode will be used to serve the request. As seen from the figure, the longer the sending time threshold will allow for more devices to transmit the requested files, as expected. These results implies that the user density λ can be considered as the main factor that affects the hit probability.

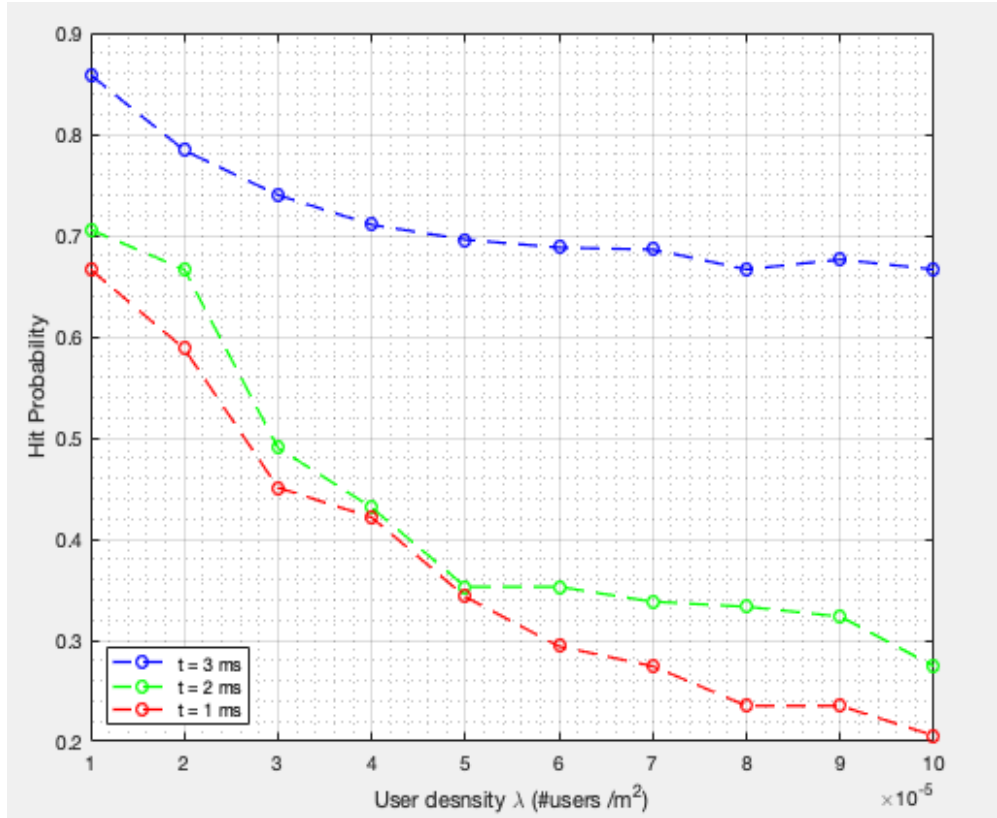


Figure 5.2: The hit probability versus the user density λ in (users /m^2) with different sending time threshold t (ms).

In Figure 5.3, we compare the hit probability against different values of the D2D distance threshold. D2D distance threshold is the maximum allowable cooperative distance between any two D2D devices. From the figure it can be clearly seen that the hit probability increases with the increase in distance and then stabilizes after 50m. This is due to the fact that a large communication distance will allow more devices to communicate and hence introduce additional interference to the system. Furthermore, the increase in the communication distance will affect the channel quality which will result in many connection failures. On the other hand, for small values of D2D distance the increase on the Zipf parameter η increase the hit probability, since an increase in the Zipf parameter will increase the probability that the file is cached in one of the devices. As a result, the requester will have a higher chances in getting the requested file from nearby devices.

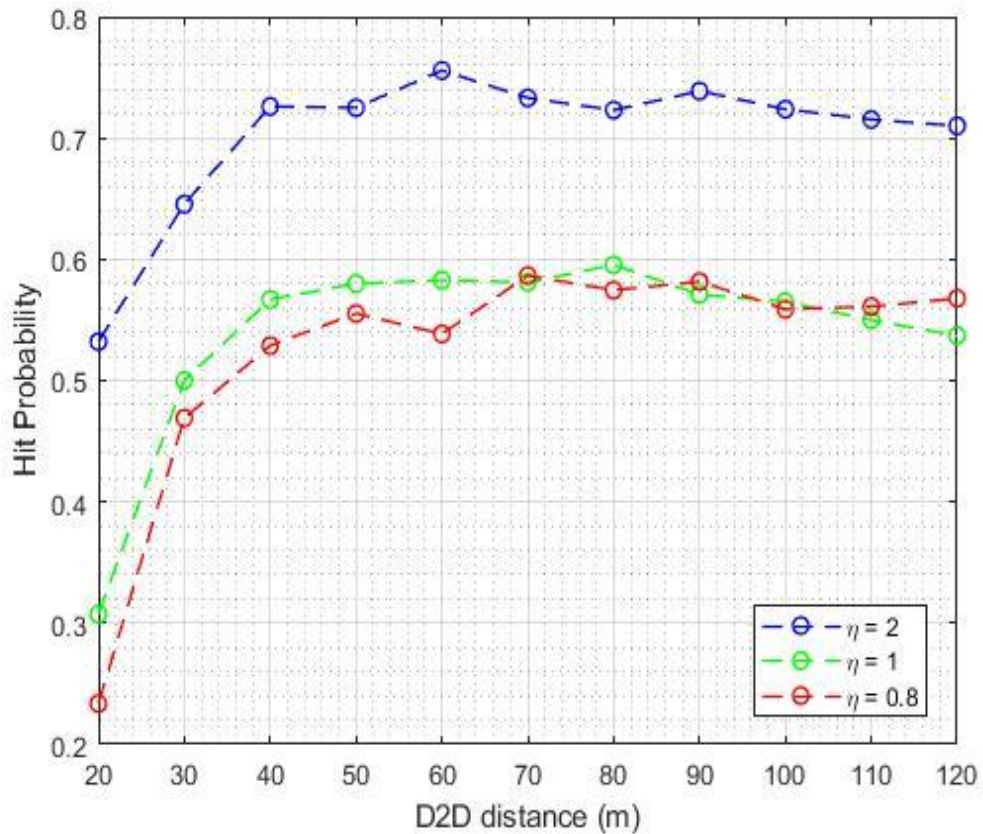


Figure 5.3: The hit probability versus the D2D distance (m) with different Zipf parameter η .

5.2.2. Impact of varying the Zipf parameter in popular caching schemes.

In Figure 5.4, for the purpose of comparing the different values of the Zipf parameter η , the cache decision probability have higher values for the lower indices contents, and this value decreases monotonically for the lower indices values. It can be clearly seen from the figure that the higher values of the Zipf parameter ($\eta=2$) will positively impact the hit probability in caching the most popular files in the popular caching scheme. The content cache decision probability for contents with high popularity is much higher when compared to the contents with lower popularity. It can also be seen from the figure that for lower values of the Zipf parameter, the content popularity distribution will have almost similar behavior.

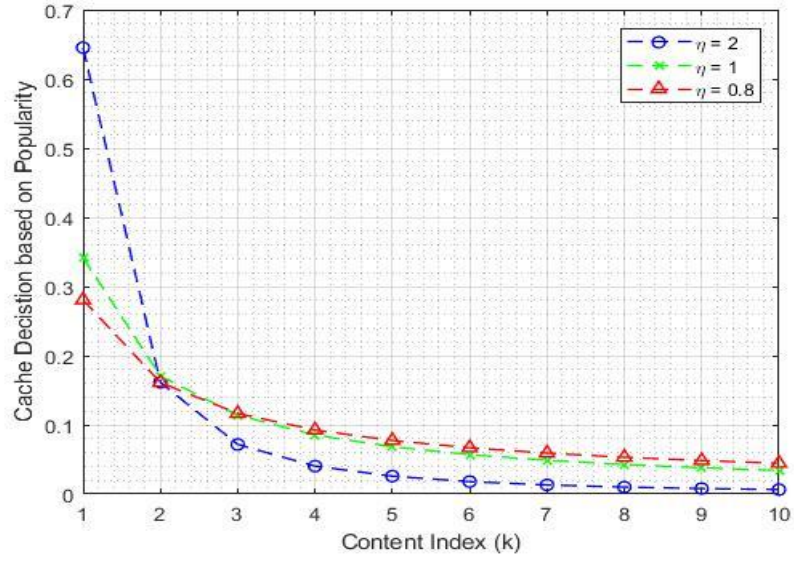


Figure 5.4: The cache decision under different values of the zipf parameter η .

In Figure 5.5, we compare the hit probability against different values of the Zipf parameter, while varying the cache size. From the figure it can be clearly seen that the hit probability increases as the cache storage size increases. This is due to the fact that increasing the Zipf parameter will increase the cache decision probability. Moreover, the large cache capacity will improve the chances that a requested file is cached in the cache storage, which in turn increases the cache hit probability. As a result, more requests will be offloaded from the D2D link rather than from the BS.

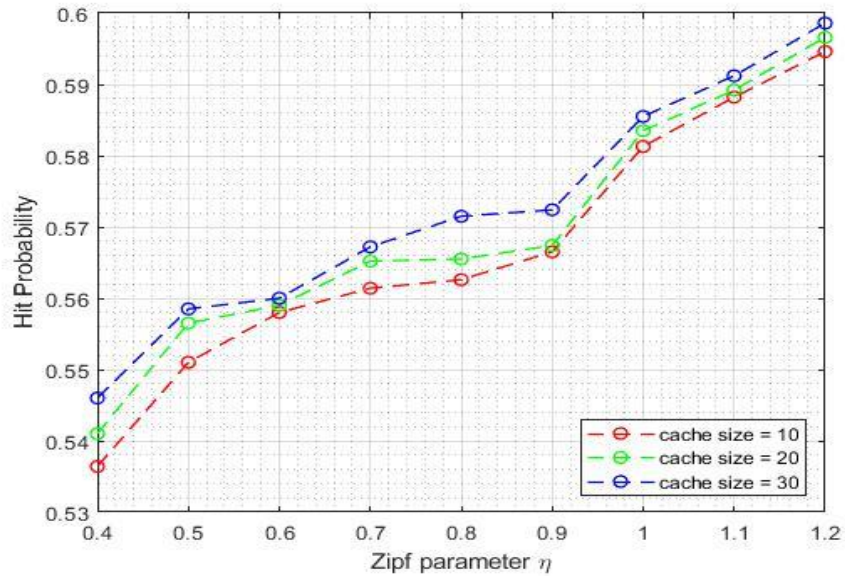


Figure 5.5: The cache hit probability versus different values of the Zipf parameter η with different cache storage capacity.

5.2.3. Performance of the proposed caching algorithms in terms of the cache hit probability.

In Figure 5.6, we compare the three caching algorithms against the cache storage capacity by varying the number of files each device can cache. As expected the hit probability of the all three algorithms increased while increasing the number of files cached at each UE. Moreover, the random cache algorithm has shown a monotonically increase in the cache hit probability with the increase of the cache capacity. This is due to the fact that the random caching cache files at random and the increase of the cache capacity increases the chance that the requested file could be found in one of the UEs. On the other hand, when comparing the Popular Cache Algorithm (PCA) and the Popular Cache Algorithm plus Instantaneous Popularity Index (PCLIA), we can see clearly from the figure that both has the same behavior in changing slowly due to the change in the cache size, but the PCLIA has a higher hit probability due to the selective cache replacement implementation, while this effect tends to disappear for the large cache capacity.

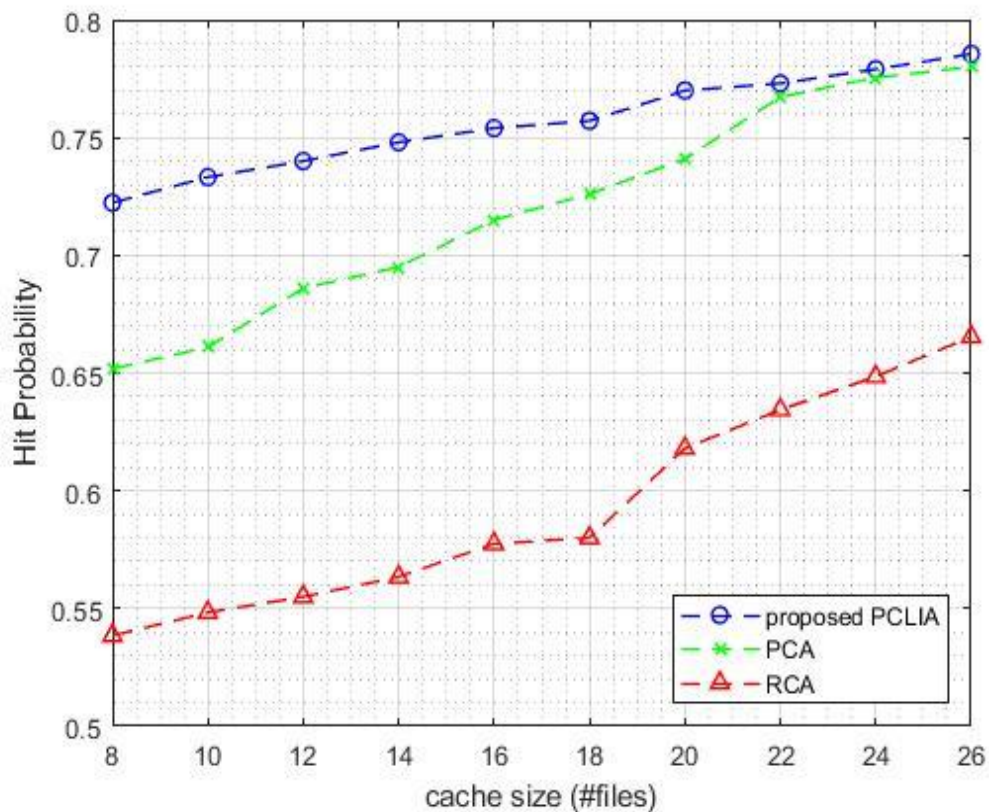


Figure 5.6: Performance evaluation of the three caching algorithms under different values of the cache storage capacity.

In Figure 5.7, we compare the hit probability against different values of the D2D distance threshold. From the figure it can be clearly seen that the hit probability increases with the increase in distance at first and then stabilizes after 50m, since the large communication distance allow for more UEs to form D2D pairs. As a result, the interference introduced to the system is much greater which in turns decreases the number of pairs succeed in making D2D transmission, and the cache hit probability decreases. It can also be clearly seen that the PCLIA algorithm outperformed the random caching algorithms and the popular caching scheme by 20% and 9.4% respectively.

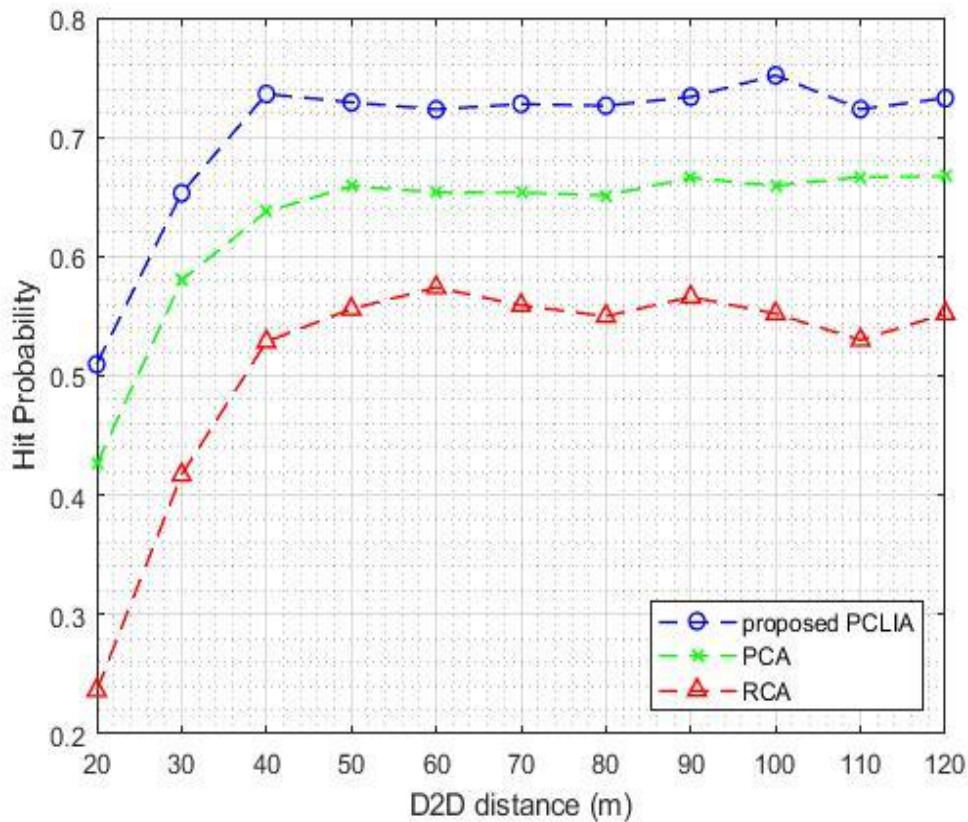


Figure 5.7: Performance evaluation of the three caching algorithms under different values of the D2D cooperation distance (m).

In Figure 5.8, the value of the sending time was fixed to 3 milliseconds, and the D2D cooperation distance threshold is set to 50m, while varying the value of the user's density λ . The three algorithms are compared based on the performance on the cache hit probability. This figure confirms the fact that the PCLIA algorithm outperforms the other two algorithms, and the RCA algorithms shows the lowest performance boundary. As stated before the value of the hit probability decreases when considering higher

user's density λ , due to the severe interference that the systems suffers from, and the fact that these users are competing for the resources to establish a D2D communication link.

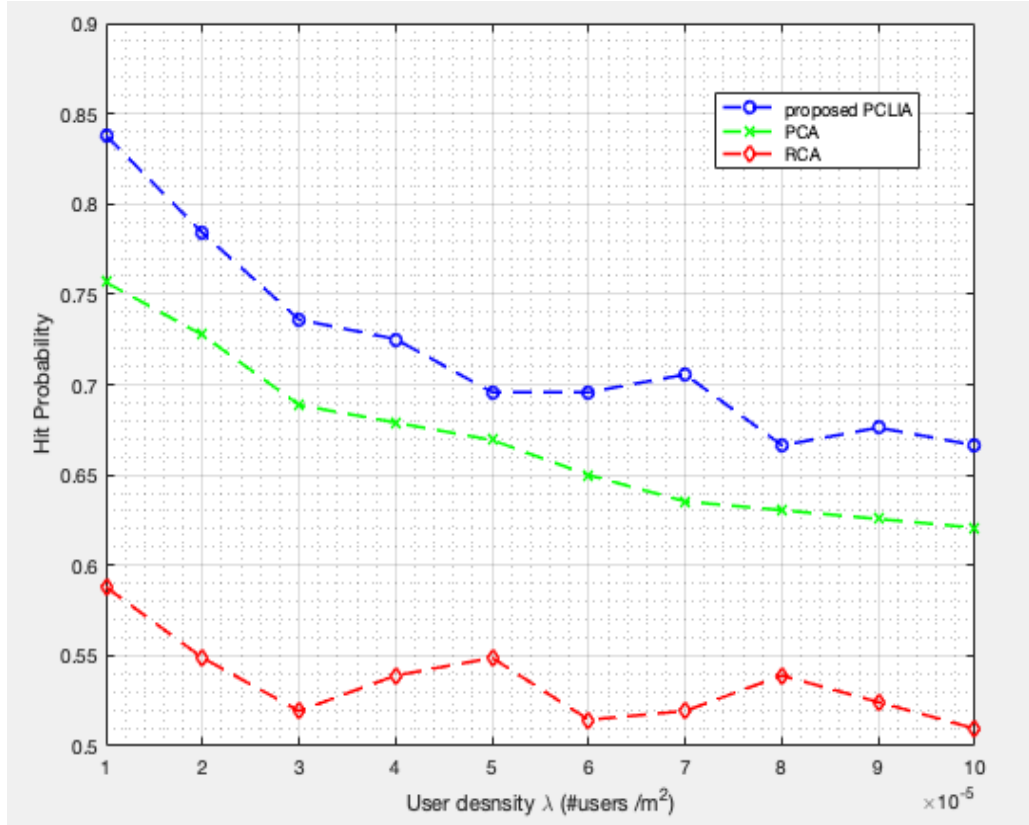


Figure 5.8: Performance evaluation of the three caching algorithms under different values of the user density λ (users /m²).

5.2.4. Impact of considering D2D alone in the calculation of the cache hit probability.

In Figure 5.9, the value of hit probability is calculated by considering the percentage of requests offloaded using D2D communications, while ignoring the self-offloaded requests. The figure shows that the cache hit probability while considering D2D alone has dropped to almost 39.7% of the cache hit probability considering D2D requests offloading in addition to self-offloading in the PCLIA algorithm. This result emphasizes on the fact that self-offloading is considered as the first solution for traffic offloading, since it does not require resource allocation and it does not introduce any interference to the system.

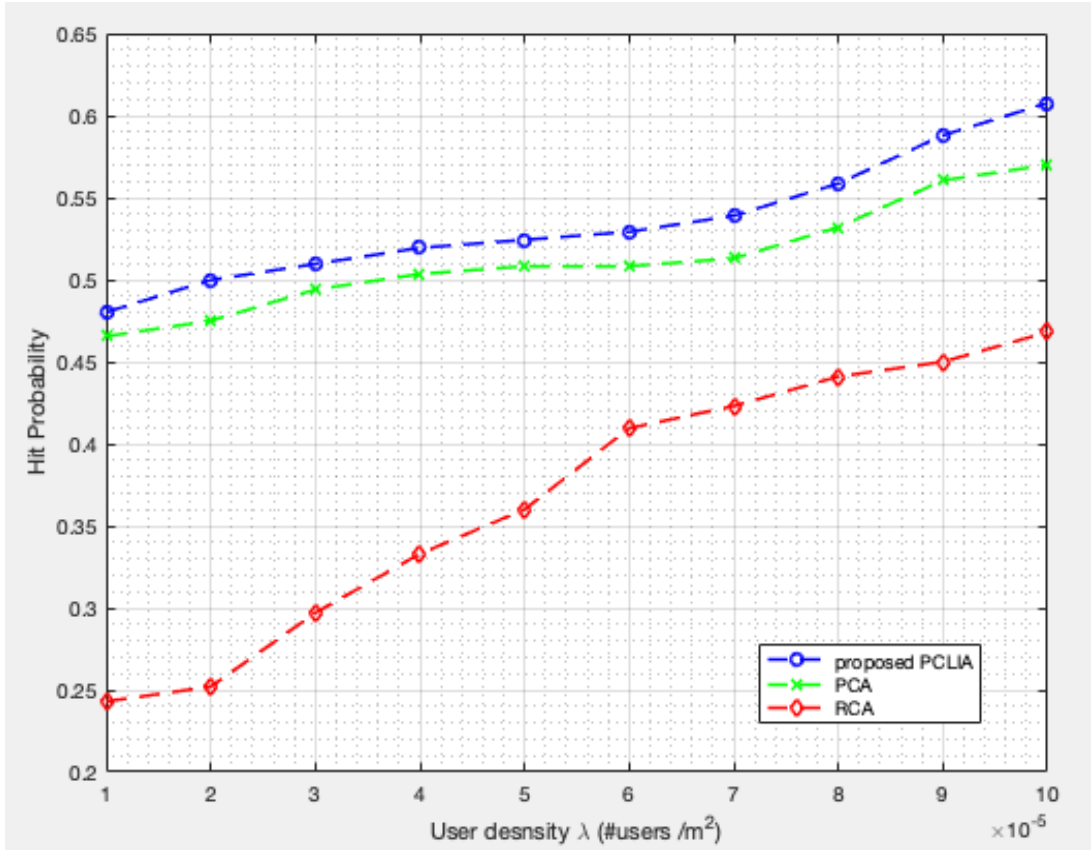


Figure 5.9: Hit probability using D2D traffic offloading for the three caching algorithms under different values of the user density λ (users / m^2).

5.2.5. Impact of varying the disconnection rate in the PCLIA algorithm.

To study the effect of user's unpredicted disconnection from the communication cell, Figure 5.10 shows the values of the hit probability using the PCLIA algorithm without any disconnection, with low disconnection rate α_r of 10%, with average disconnection rate α_r of 50% and with a very high disconnection rate α_r of 90%. The effect of user's disconnection on the hit probability is severe in the average and high values of α_r , as a result there should be a mechanism to minimize the degradation in performance due to the users disconnection. One of the proposed solutions as discussed earlier is the cache incentive-based mechanism to encourage users to continue participating in the cache-assisted D2D communication.

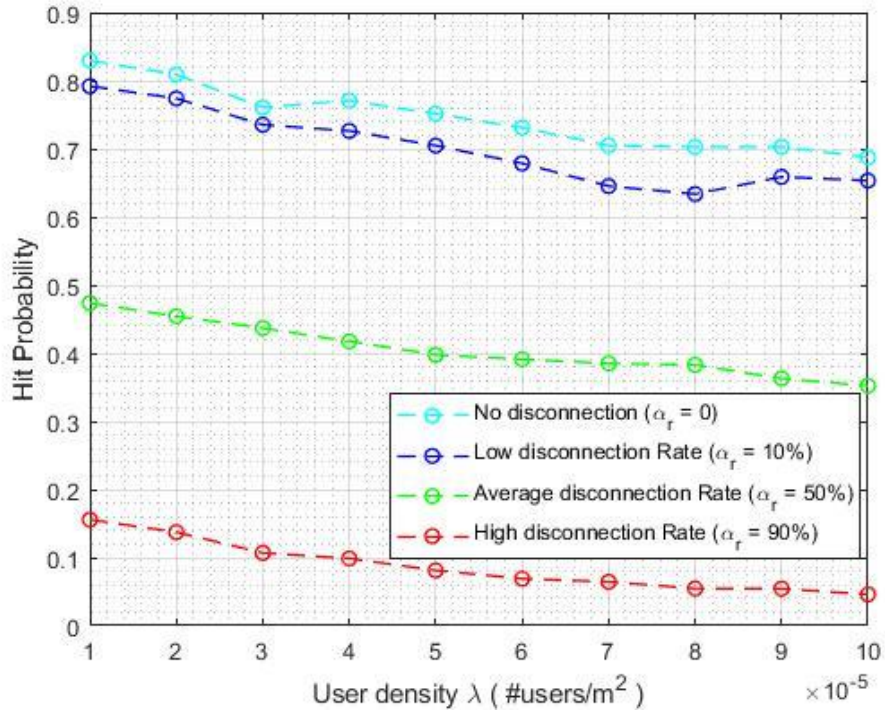


Figure 5.10: The impact of user’s disconnection as implemented by the PCLIA algorithm under different values of the user density λ (users / m^2).

5.3. Mobility Model

The impact of device mobility to the systems overall offloading gain has been investigated. The device movement using the Random Walk Model (RWM) has been captured in Figure 5.11. As shown in the figure, the first and last points are marked in red. The effect of mobility in the offloading gain is minimal in small speeds till 10 km/h. The percentage of requests offloaded using D2D connection increases as the speed increases. At a low speed of 3 km/h the offloading probability was found to be 60%, this percentage increases to 89% when the speed reaches 40 km/h. The low speed of 3 km/h simulates the average speed of a pedestrian, while the moderate speed of 40 km/h simulates the average speed of a user riding a bicycle. The increase of user’s speed makes the user appears in many locations, allowing more chances for other users to communicate with and avail the content. One approach could be used to fully utilize user’s mobility, is to allow the users moving in high speeds to cache a more diversity of the content files, while users who are static or moving in low speed to cache the most popular files only. The effect of user’s mobility in the cache offloading gain is demonstrated in Figure 5.12.

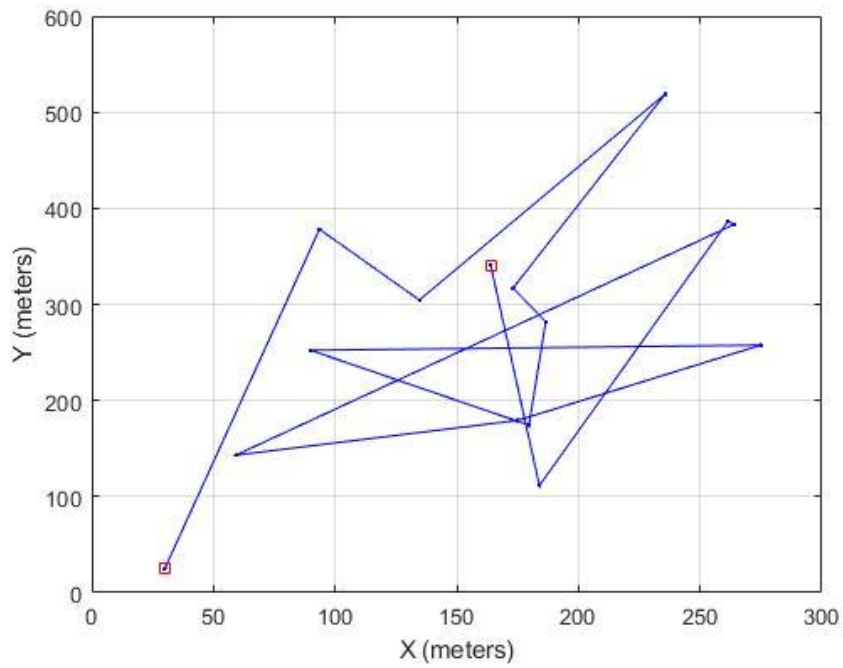


Figure 5.11: Node movement in RWM model.

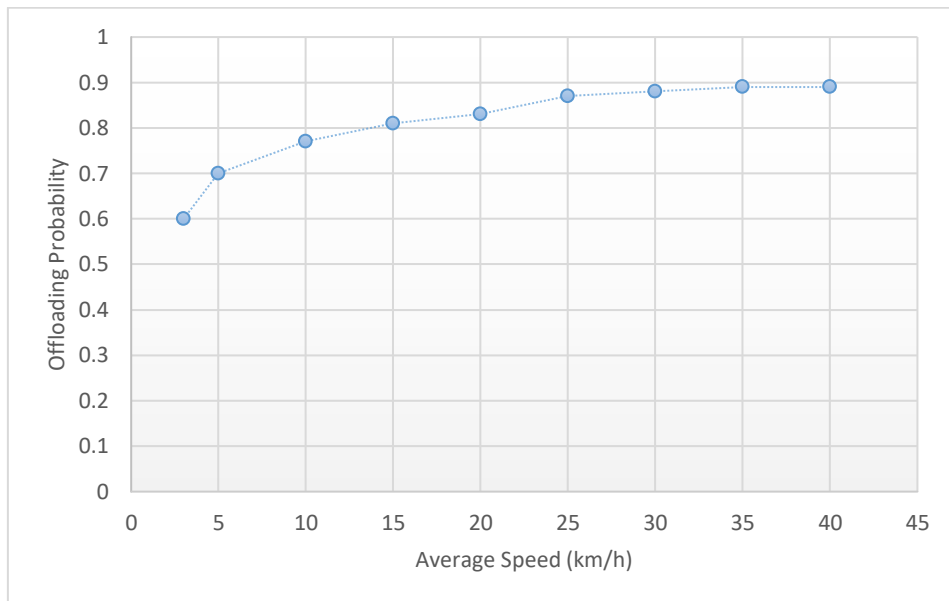


Figure 5.12: The impact of mobility on the offloading probability.

Chapter 6. Conclusion and Future Work

6.1. Conclusion

Caching at the edge of the network with the assistance of D2D communication is presented as an emerging strategy in 5G networks to cope with the ever increasing demand in multimedia services. The main goal behind this technology is to increase the cache hit probability which in turn increases the overall offloading gain. We mainly focus on the challenges and opportunities on what to cache and how to cache in a way that maximize the total system offloading gain.

By looking in to the concept of popularity index, which aims to cache the highly demanded files, we try to formulate a hybrid collaborative cache scheme that focuses on cache placement and cache replacement processes and the decisions involved in each process. Moreover, the mode of operation in D2D communication is formulated as an interchange between self-offloading, D2D offloading, and B2D to obtain the optimal cache delivery strategy. We further propose a popular caching scheme that intelligently selects the no longer needed files for replacement by looking into the instantaneous popularity index of the file and the possible owners of that file.

Based on the availability of the requested content and possibility of transmitting the content, the model carefully takes into account the channel condition, and selects a compatible D2D pair for the communication, in a way that assures the highest possible signal to interference plus noise ratio. In addition, a maximum value for the sending time is set, and if exceeded due to the poor channel quality or due the user's disconnection, the mode switches from the D2D mode into the B2D mode of operation.

The experimental results give indicators that the proposed popular caching with LFU plus instantaneous popularity index (PCLIA) improves the performance in terms of the cache hit probability. When PCLIA is compared to both the random cache algorithm (RCA) and the popular cache algorithm (PCA), the cache hit probability increases with 13% and 10%, respectively.

Furthermore, in order to simulate real-environment scenario, the proposed model takes into account user's mobility. We found that for low speed mobility the offloading gain was not affected, while moderate speed mobility severely impacted the offloading gain.

Moreover, the proposed model takes into account the unpredicted user's behaviour in disconnection for various reasons such as the dead battery. The model exhibits three disconnection rate, from low, average to severe disconnection rate; and the later found to decrease the system performance poorly, and should be avoided if possible.

6.2. Future Work

This research can be extended in various ways. Firstly, the proposed system model can be extended from a single cell to a system of multi-cell that takes into account the handoff process. Additionally, a more complex multi-tier heterogeneous network could be used by utilizing the concept of using small base stations as relays. Furthermore, heuristic studies could be implemented in order to optimize the cache placement scheme. Moreover, machine learning models could be used to predict the future contents preferences, in a way that allow for caching these content in advance.

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Appendix A: Source Code

```
clc;

close all;

clear all;

%----- Delete the result matrix form previous sessions -----%

if isfile('test1.mat')

    delete('test1.mat');

end

%----- User Input for the simulation time and no of users -----%

Max_simulation_time = input('Please enter the max simulation time');
%simulation time in seconds, 0.5 request/sec;

lamda_requests = input('Please enter the lamda of requests');
%request rate per seconds, 1000;

lamda = input('Please enter the number of lamda D2D users');

zipf_parameter = input('Please enter the zipf distribution
parameter');

sending_time = input('Please enter the sending time in seconds');

Dt = input('Please enter the distance threshold in km');

alpha_r = input('Please enter the disconnection rate [0, 0.1, 0.5,
0.9]');

Max_files = input('Please enter the maximum cache size');

C_scheme = input('Please enter the caching scheme [RCA, PCA,
PCLIA]');
```

```

%----- Simulation Parameters -----%
%   s = rng;
%
%   rng('default');
%
%   rng(0);

ind_S=0; % index for the S matrix which is the time matrix

m=1; % no of hexagonal cells

R=1500;

len=3000;

wid=3000;

%D2D=randi([3 10],1);% no of D2D devices

AWGN= -117; % -117dBm

alpha=4;

pi=3.14159;

fc=2.4e9;

BW=22e6; % bandwidth is 22 MHz

GTx=1;

GRx=1;

```

```

NoF = 100; % No of files

R_sensitivity = -100; % in dBm

SINRt = 15; % in dB

File_size = 1e6;

channel_count = 0; % counter to check how many channels are active

par1_RAT = 5; % Request Arrival Time (0s -> 10s)

par1_HT = 8*3600; % 8 hours

No_channel = 12; % Number of communication channels

Tot_t = 10; % total simulation time is 10s

R_Request_t = rand(N,1);

Ind = 0;

Ind2 = 0;

%----- User's distributed based on PPP -----%

r=1500;

areaTotal=pi*r^2;

% lamda=0.0005;

numPoints=poissrnd(areaTotal*lamda);

D2D=numPoints;

if D2D<1

```

```

        D2D = randi(100,1);
end

%----- Initialization of the Arrays -----%

popularity = zeros(NoF,D2D);

BS = zeros(NoF , D2D);    % Base Station Directory "which has all the
files"

I_popularity = zeros (NoF, D2D);

UserStack = zeros(NoF,D2D);    % The stack of files for each user

channel= zeros(1,12);    % The number of channels in WiFi (12
channels)

I = zeros(D2D,D2D);

sinr = zeros(D2D,D2D);

PTx = zeros(D2D,D2D);

arrv_request = zeros(1,No_requests);

%----- Load the saved file -----%

if isfile('test1.mat')
    load('test1.mat');
end

%----- Print the results into a text file -----
%

fileID = fopen('result_table.txt', 'w');

```



```

fprintf(fileID,'%6s %6s %8s \t %6s
%6s\r\n','Requester','Provider','Time(S)','File#','Hit_prob');

hit_prob =0; % Number of hits before every request period

%----- Call the Request Rate function to return the time of
request -----%

[arrv_request,ic2,holdTime] =
request_rate_v2(No_requests,arrv_request,No_channel,Tot_t,parl_RAT,pa
r1_HT);

rate = floor(D2D*alpha_r); % Rate for the disconnection rate (low
rate = 10%)

disconnected_users = randi(D2D,1,rate);

time_to_disconnect = randi(No_requests,1,rate);

for iter=1:length(inter_arrival_time) %No of Request in the total
simulation time

    %ind_S = ind_S+1;

    %----- Create Hexagon Cell -----%

    nx11=len/(2*R);

    nx=round(nx11); % x size

    ny1=wid/(2*R);

    ny=round(ny1); % y size

    % one hexagon coordinaties:

```

```

al=0:((2*pi)/6):2*pi;

xh=R*cos(al);

yh=R*sin(al);

xcell=[];

ycell=[];

hold on;

% one hexagons set:

x0=R;

y0=sqrt(3)*R/2;

Si=x0;

y=y0;

for nxc=1:m

    for nyc=1:m

        plot(Si+xh,y+yh,'b');

```

```

        plot(Si,y,'+');
        xcell=[xcell Si]; %recording cell coordinates

        ycell=[ycell y];

        y=y+sqrt(3)*R;

    end

    Si=Si+3*R;

    y=y0;

end

%----- Users Distribution (random, unifrom)----- %
%----- binomial point process -----%

    D2Dxuser=rand(1,D2D).*(len/50); % scale the x and y coordinates
to be inside the cell coordinates

    D2Dyuser=rand(1,D2D).*(wid/50);

%----- Calculating the distance between users -----%

    distD2D1 = zeros (D2D,D2D);

    for i=1:1:length(D2Dxuser)

        for j=1:1:length(D2Dxuser)

            if i==j

```

```

        distD2D1(i,j) = 0;

        else

            distD2D1(i,j)=sqrt((D2Dxuser(1,i)-D2Dxuser(1,j))^2 +
(D2Dyuser(1,i)-D2Dyuser(1,j))^2);

        end

    end

end

distD2D=(distD2D1./1000);

xcell_i= [750,2250,3000,2250,750,0]; %recording cell x
coordinates

ycell_i=[0,0,1299,2598,2598,1299]; %recording cell y coordinates

D2Dxuser1=rand(1,D2D).*(len); % scale the x and y coordinates to
be inside the cell coordinates

D2Dyuser1=rand(1,D2D).*(wid);

in = inpolygon(D2Dxuser1,D2Dyuser1,xcell_i,ycell_i); %return the
scaled points

axis equal;

axis([0 len 0 wid-250]);

grid;

hold on;

```

```

%----- Returns points inside the hexagon-----
--%

numel(D2Dxuser1(in)); %no of D2D users inside cell

figure1= plot(D2Dxuser1(in),D2Dyuser1(in),'ro');

if( iter~= No_requests)

    %           pause(0.25);

    close Figure 1;

end

%           plot(D2Dxuser(~in),D2Dyuser(~in),'r+') %points outside

%----- Generating Transmitted power for each device -----
--%

rng('default');

rng(0);

PTxmin=20;

PTxmax=25;

for i=1:1:D2D

    for j=1:1:D2D

        if i~=j

            PTx(i,j)=randi([PTxmin PTxmax]); %dBm

```

```

        end

    end

end

%----- minimum distance -----%

DD=min(distD2D(distD2D>0));

%----- Calculate the Pathloss -----%
%----- Call function to calculate the attenuation -----%

[PL]= channel_model(distD2D,fc,alpha); %dB

%----- Call cal_received_signal function to return the power of
the received signal -----%

[Sin] = cal_received_signal(D2D,PTx,PL);

%----- SNR calculations to be used in calculating the
transmission rate -----%

N = AWGN - 30; %from dBm to dBW % AWGN

snr = zeros(D2D,D2D); % Pre-allocation

for i=1:1:D2D

    for j=1:1:D2D

        if i==j

            snr(i,j)=0;

        else

            snr(i,j) = Sin(i,j) - N; %dBW

```

```

        end

    end

end

%----- Call cal_shannon_rate function to return the link
capacity based on Shannon's Formula -----%

[C] = cal_shannon_rate(D2D,BW,snr);

%---- Shuffle the popular files request every 100 request -----%

if mod(No_requests,50)==0

    New = D2D/2 + 1;

else

    New = D2D/2;

end

%----- SINR calculations -----%

[I,sinr] =
cal_sinr(I,sinr,Sin,D2D,requester_save,User_requester,provider_save,N
,ic2);

%----- Calculate the popularity and hit probability for
Caching Scheme -----%

%S_save=S(ind_S);

rng('shuffle');

User_requester = randi(D2D,1); % The user who request a file
from the set of D2D

switch C_scheme

```

```

        case 'RCA'

Request = randi(NoF,1);          % randomly choose the requested file

        otherwise

Request = zipf_rand(NoF,zipf_parameter,1);    % the requested
file follows zipf distribution

        end

        %----- condition to make sure that users and requested files are
in the range -----%

        while ((User_requester>D2D) | (User_requester<1) |
(ismember(User_requester,disconnected_users))) % ismember to check if
a scalar value is element of an array

            User_requester = randi(D2D,1);

        end

        while ((Request>NoF) | (Request<1))

            Request = randi(NoF,1);

        end

        Ind = find(UserStack(Request,User_requester) == 1);

        if(Ind ~= 0)                % Resource found in user stack " Self-
offloading"

            MSG1=['Resource found available on the current user stack
','Requester# ',num2str(User_requester),' File# ',num2str(Request)];

            disp(MSG1);

            User_provider = User_requester;

            popularity(Request,User_requester) =
popularity(Request,User_requester) +1; % Increase popularity

            hit_prob = hit_prob +1;          % increare the hit
probability

            fprintf(fileID,'%6s\t',num2str(User_requester));

            fprintf(fileID,'%6s\t',num2str(User_requester));

            fprintf(fileID,'%6s\t',num2str(Request));

```



```

        fprintf(fileID, '%6s\r\n', num2str(hit_prob));

%
print_to_excel(User_requester, Request, User_provider, hit_prob, S_save);
%
%           S;

%----- Sending time per request calculations -----%

        sending_time_req = 0;    % Self-offloading case; the sending
time is zero

        MSG5=['Sending time for the request
', num2str(sending_time_req)];

        disp(MSG5);

%
print_to_excel_Sending_time_req(User_requester, Request, User_provider,
hit_prob, S_save, sending_time_req)

else

%----- Different Caching Schemes -----%

switch C_scheme

        case 'RCA'

                %-- "random" function to make sure that each user cache a
maximum of 10 files

                [UserStack, BS, popularity] = random_replacement(UserStack,
BS, User_requester, popularity, Max_files);

        case 'PCA'

                %-- "popular" call the function to make sure that each user
cache a maximum of 10 files

                [UserStack, BS, popularity] = popular_replacement(UserStack,
BS, popularity, Max_files, User_requester);

        case 'PCLIA'

                %-- "popular" call the function to make sure that each user
cache a maximum of 10 files

                [UserStack, BS, popularity] =
popular_replacement_PCLIA(UserStack,
BS, popularity, Max_files, User_requester);

```

```

end

Ind2 = find(BS(Request,:) == 1);

if (Ind2 ~= 0)

    % resource is available in another UE "choose one pair
(D2D)"

    Dt_local = zeros(1,length(Ind2)); % Pre_allocation
    SINR_local = zeros(1,length(Ind2));
    Sin_local = zeros(1,length(Ind2));

    for m=1:length(Ind2)
        xx = (Ind2(m));
        Dt_local(m) = distD2D(User_requester, (xx));
        SINR_local(m) = sinr(User_requester, (xx));
        Sin_local(m) = Sin(User_requester, (xx));
    end

    end

    [index_max] = find(max(SINR_local));

    User_provider = Ind2(index_max); % choose the pair with
the maximum SINR value

    %----- Check Receiver Sensitivity, cooperation Distance
and SINR for all the potential providers -----%

    if (Sin_local(index_max) > R_sensitivity) &&
(SINR_local(index_max) > SINRt) && (Dt_local(index_max) < Dt)

        % received signal should be greater than receiver
sensitivity

        % SINRt threshold min SINR for connection

        % Dt threshold max distance for cooperation

        Ind2

        MSG2=['Resource found available on another user stack
','Requester# ',num2str(User_requester),' ,Provider#
',num2str(User_provider),' ,File# ',num2str(Request)];

        disp(MSG2);

```

```

        popularity(Request,User_requester) =
popularity(Request,User_requester) +1; % Increase popularity

        hit_prob = hit_prob +1; % increare
the hit probability

        BS(Request,User_requester) = 1; % Reflect on
the BS Directory

        UserStack(Request,User_requester) = 1; % Reflect on
the UserStack

        fprintf(fileID, '%6s\t', num2str(User_requester));
        fprintf(fileID, '%6s\t', num2str(User_provider));
        fprintf(fileID, '%6s\t', num2str(Request));
        fprintf(fileID, '%6s\r\n', num2str(hit_prob));

%
print_to_excel(User_requester,Request,User_provider,hit_prob,S_save);
%
%           S;

        %----- Sending time per request calculations -----%

        sending_time_req =
File_size/(C(User_requester,User_provider)); % D2D-offloading case;
calculate the sending time

        MSG6=['Sending time for the request
',num2str(sending_time_req)];

        disp(MSG6);

        %----- Time limit for the D2D connection -----
-----%

        if sending_time_req>sending_time

            User_provider=911;

            MSG4=['Connection Timed Out use Cellular
connection ', 'Requester# ', num2str(User_requester), ' ,File#
', num2str(Request)];

            disp(MSG4);

            hit_prob = hit_prob -1; % reduce the hit
probability

        end

```

```

%
print_to_excel_Sending_time_req(User_requester,Request,User_provider,
hit_prob,S_save,sending_time_req)

    else

        MSG3=['Resource found available from BS
','Requester# ',num2str(User_requester),' ,File# ',num2str(Request)];

        disp(MSG3);

        User_provider = 911;

        popularity(Request,User_requester) =
popularity(Request,User_requester) +1; % Increase popularity

        BS(Request,User_requester) = 1; % Reflect on
the BS Directory

        UserStack(Request,User_requester) = 1; % Reflect on
the UserStack

        fprintf(fileID,'%6s\t',num2str(User_requester));

        fprintf(fileID,'%6s\t','BS');

        fprintf(fileID,'%6s\t',num2str(Request));

        fprintf(fileID,'%6s\r\n',num2str(hit_prob));

%
print_to_excel(User_requester,Request,User_provider,hit_prob,S_save)
%
%           S;

%----- Sending time per request calculations -----%

        sending_time_req = 911; % B2D-offloading case; the
sending time is infinity

        MSG7=['Sending time for the request
',num2str(sending_time_req)];

        disp(MSG7);

%
print_to_excel_Sending_time_req(User_requester,Request,User_provider,
hit_prob,S_save,sending_time_req)
    end

    else

        MSG3=['Resource found available from BS ','Requester#
',num2str(User_requester),' ,File# ',num2str(Request)];

```

```

disp(MSG3);

User_provider = 911;

popularity(Request,User_requester) =
popularity(Request,User_requester) +1; % Increase popularity

BS(Request,User_requester) = 1; % Reflect on the
BS Directory

UserStack(Request,User_requester) = 1; % Reflect on the
UserStack

fprintf(fileID, '%6s\t', num2str(User_requester));

fprintf(fileID, '%6s\t', 'BS');

fprintf(fileID, '%6s\t', num2str(Request));

fprintf(fileID, '%6s\r\n', num2str(hit_prob));

%
print_to_excel(User_requester,Request,User_provider,hit_prob,S_save)
%
%          S;

%----- Sending time per request calculations -----%

sending_time_req = 911; % B2D-offloading case; the
sending time is infinity

MSG7=['Sending time for the request
',num2str(sending_time_req)];

disp(MSG7);

%
print_to_excel_Sending_time_req(User_requester,Request,User_provider,
hit_prob,S_save,sending_time_req)

end

end

provider_save(1,iter)= User_provider;

requester_save(1,iter)= User_requester;

%----- SINR calculations -----%

```

```

[I, sinr] =
cal_sinr(I, sinr, Sin, channel_count, D2D, requester_save, provider_save, N)
;

%----- Delete the record of the disconnected users -----%
%----- call the disconnection rate function -----%

for iii = 1:rate

    if (time_to_disconnect(1,iii)==iter)

        [UserStack,BS,popularity] =
disconnection_rate(iii,disconnected_users,UserStack,BS,popularity);

        MSG_disconnection=[ 'User#
',num2str(disconnected_users(1,iii)), ' was disconnected'];

        disp(MSG_disconnection);

    end

end

%----- Call wifi_channel function to assign a channel for
communication -----%

    if User_provider ~= 911 && User_provider ~= User_requester    % if
the case is not B2D or self-offloading assign channel

        if (sum(channel)>=12) % 12 channels for communication

            [timerVal] =
time_to_release(sending_time,sending_time_req);

            if timerVal <= sending_time

                [~,channel1] = release_channel (channel);

                [fc,channel_assigned,channel] =
wifi_channel(channel1);

                channel_assigned

            end

        elseif (sum(channel)<12)

            [fc,channel_assigned,channel] = wifi_channel(channel);

```

```

        channel_assigned

        channel_count = channel_count+1;

    end

end

%----- Call Initialization Function to return popularity and hit
probability for Caching scheme -----%

MSG_hit_prob=[ 'hit probability on the# ',num2str(iter),' is
equal to# ',num2str(hit_prob)];

disp(MSG_hit_prob);

end

for No_channel=1:12

    [timerVal] = time_to_release(sending_time,sending_time_req);

    if timerVal == sending_time

        [channel_assigned1,channel1] = release_channel(channel);

        channel = channel1;

    end

end

for ii=1:No_requests

    fprintf(fileID,' %8.4f \r\t\n',S(ii));
    fprintf(fileID,' %8.4f \r\t\n',Max_simulation_time(ii));

end

%----- close the result text file-----%

fclose(fileID);

%----- Save all the variables into a file-----%

```

```

filename = 'test1.mat';

save(filename);



---



function [S,inter_arrival_time]=
request_rate(lamda_requests,Max_simulation_time)

%Function that return the users request time based on poisson
distribution

%=====
% The Max simulation time is total time the simulation is running,
The
% arrival times are generated based on the poisson distribution, the
inter
% arrival time has an exponential distribution. The average of
requests is
% assumed to be 0.5 req/sec
%=====
=====

T=-log(rand)/lamda_requests;

n=0;

inter_arrival_time = 0;

while inter_arrival_time < Max_simulation_time % Total simulation
time is 1000 seconds

    n=n+1;

    S(n)= T;

    T= T-log(rand)/lamda_requests;

    inter_arrival_time=cumsum(S);

end

S(1)=S(1)+0.001;

disp(n)

disp(S(1:n))



---



function [PL]= channel_model(distD2D,fc,alpha)

```



```

% Function that calculate the Path Loss in dB

PL = zeros(length(distD2D),length(distD2D)); % Pre-allocation

fc = fc*10^-6 ; % from 2.4e9 Hz to MHz
for i=1:1:length(distD2D)

    for j=1:1:length(distD2D)

        if i==j

            PL(i,j) = 0;

        else

            PL(i,j)= 10*alpha*log10(distD2D(i,j))+30*log10(fc)+49;
% distnace is in km    % fc is in MHz

        end

    end

end

end

```

```

function [Sin] = cal_received_signal(D2D,PTx,PL)

% function to calculate the received signal in dB

Sin = zeros(D2D,D2D); % Pre-allocation

for i=1:D2D

    for j=1:D2D

        if i==j

            Sin(i,j) = 0;

        else

            %use the path loss model to calculate the received signal
            %instead of Friss Formula

            Sin(i,j) = PTx(i,j)-30- PL(i,j); %PTx form dBm to dBW

            %Sin(i,j) = 10^((PTx(i,j)-30)/10) - 10^(PL(i,j)/10); % in
watts

            %Sin(i,j) = 10*log10(Sin(i,j)); % in dB

```

```

        end
    end
end

```

```

function [C] = cal_shannon_rate(D2D,BW,snr)

% function to calculate the maximum capacity of the link
C = zeros(D2D,D2D); %Pre_allocation
snr_w = zeros(D2D,D2D); %Pre_allocation

for i=1:D2D
    for j=1:D2D
        if i==j
            C(i,j) = 0;
        else
            snr_w(i,j) = 10^((snr(i,j))./10);
            C(i,j) = (BW*log2(1+snr_w(i,j))); %BW in Hz snr in w
        end
    end
end
end

```

```

function [UserStack,BS,popularity] = random_replacement(UserStack,
BS,User_requester,popularity,Max_files)

% Function that replace files for random caching => replace the FIFO
" replace the 1st file "

if (sum(UserStack(:,User_requester))>= Max_files) % any user can
cache up to 10 files only

    Index = find(UserStack(:,User_requester) ~= 0,1,'first'); %
find the 1st cached file

    UserStack(Index,User_requester)= 0;

```

```

    BS(Index,User_requester)= 0;

    popularity(Index,User_requester)= 0;

end

end

```

```

function [UserStack,BS,popularity] = popular_replacement(UserStack,
BS,popularity,Max_files,User_requester)

% Function that replace the least popular file for popular caching =>
Zipf Distribution

if (sum(UserStack(:,User_requester))>= Max_files)      % any user can
cache up to 10 files only

    popularity_one = popularity (:,User_requester);    % Requester
popularity, coloumn vector

    Stack_Ind = UserStack(:,User_requester);          % Non-zero
indicies

    popularity_temp = popularity_one(Stack_Ind);        % the
popularity of full-cahsed user (should be non zeros)

    [~,Ind] = min(popularity_temp);                    % find the
index least popular that is cached

    % delete the least popular file and its record in the BS matrix
and in the UserStack matrix

    UserStack(Ind,User_requester) = 0;

    BS(Ind,User_requester) = 0;

    popularity(Index,User_requester)= 0;

end

end

```

```

function [UserStack,BS,popularity] =
popular_replacement_PCLIA(UserStack,
BS,popularity,Max_files,User_requester)

```

```

% Function that replace files for popular caching PCLIA => Zipf
Distribution
%=====
=====
% The function takes look into the file with the least popularity
then how
% many owners of that file. if there are more than one owner it
replaces
% this file, otherwise the algorithm deletes the least popular file
and
% continoue looking for a 2nd least popular file taking into account
the
% number of owners of that file and replace it.
%=====
=====

if (sum(UserStack(:,User_requester))>= Max_files)           % any user
can cache up to 10 files only

    popularity_one = popularity (:,User_requester);         % Requester
popularity, coloumn vector

    Stack_Ind = find (UserStack(:,User_requester));         % Non-zero
indicies

    popularity_temp = popularity_one(Stack_Ind);             % the
popularity of full-cahsed user (should be non zeros)

    BS_temp = BS(Stack_Ind,:);                               %
corrosponding BS for the requesters' files

    for j=1:Max_files

        [~,Ind] = min(popularity_temp); % repeat the min till find
the least popular that is cached in more than one user

        num_file_owners = sum(BS_temp(Ind,:));

        if num_file_owners > 1 % if the file is cached at more than
one user in the system

            % delete the least popular file and its record in the BS
matrix and in the UserStack matrix

            UserStack(Ind,User_requester) = 0;

            BS(Ind,User_requester) = 0;

            popularity(Ind,User_requester) = 0;

            break;

        else

            popularity_temp(Ind) = []; % delete the current least
popular since it's not saved in any other device
        end
end

```

```

    end

end

end

```

```

function x = zipf_rand(N, expn, M)

% Generate numbers based on Zipf distribution
% N      Number of Elements
% expn   Exponent
% M      Number of sample to be generated
% Example: zipf_rand(3,1,4)
% ans = 3 2 1 1

if nargin == 2

    M = 1;

end

ranks = 1:1:N;

pmf = (ranks.^(-expn))/sum(ranks.^(-expn));

samples = rand(1,M);

p = cumsum(pmf(:));

[~,x] = histc(samples,[0;p/p(end)]);

end

```

```

function [arrv_request,ic2,holdTime] =
request_rate_v2(No_requests,arrv_request,No_channel,Tot_t,par1_RAT,pa
r1_HT)

%----- Compute request arrival times -----%

arrv_request(1) = 0.01; %First request arrives at time = 0.01

%----- Poisson distribution for the request arrival times -----%

Req_arrv_time =poissrnd(par1_RAT,No_requests-1,1);

for k = 2:No_requests

```

```

arrv_request(k) = Req_arrv_time(k-1);

%requests arrive at an instant t that ensures some of the request
%arrives at the same time, i,e more than two D2D connection
coexist
end

%----- Function to return the D2D requests that starts at the
same time (coexist) -----%

[~,~,ic2] = unique(arrv_request,'stable');

%----- exponential distribution for the holding time of the requests
-----%

holdTime = exprnd(par1_HT,No_requests,1);    % Holding time for
requests.

%----- Compute request termination time -----%

termTime = zeros(No_requests,1);    % Termination array

for k = 1:No_requests
    termTime(k) = arrv_request(k) + holdTime(k);    %Termination time
= arrivalofrequest + holdingTime
end

Serviced = 0;

Blocked = 0;

flagServed = 0;    % Flag is 1 if serviced

channels = zeros(No_channel,1);    %Channel array

channel_usage = No_channel*ones(No_requests,1);

%-----Determine : Serviced, Blocked requests-----%

for i = 1:No_requests
    for k = 1:No_channel
        if( channels(k) < arrv_request(i))
            Serviced = Serviced + 1;
            flagServed = 1;
            channels(k) = termTime(i);
            break;
        end
    end
end

% Check remaining channels

if(k < 12 )
    for j = k+1:12
        if(channels(j) < arrv_request(i))

```

```

        channels(j) = 0;           % If request have been
terminated clear the channels
        end
    end
elseif (flagServed == 0)
    Blocked = Blocked + 1;
end

flagServed = 0; %Reset Flag

for x = 1:No_channel
    if (channels(x) == 0)
        channel_usage(i) = channel_usage(i) - 1; % to make sure
that the channels are cleared after serving the request
    end
end
end

return

```

```

function [I,sinr] =
cal_sinr(I,sinr,Sin,D2D,requester_save>User_requester,provider_save,N
,ic2)

% function to calculate the inerference in dB

% Initialize the Interference vector

for i=1:1:length(ic2)

    for j=1:1:10

        % Interference vector: All devices that transmit at channels
        % other than the 4 non-overlapping channels

        if (ic2(i)==j) % implies that the devices that are
transmattng at the same time

            sum_Sin=0;

            if (provider_save(i)~= 911) &&
(i==requester_save(i)) && (j==provider_save(i)) %911 is a code for
the BS

                sum_Sin = sum_Sin +
Sin(requester_save(i),User_requester); % The received signal from
other devices

            end

```

```

        I(i,j) = I(i,j) + sum_Sin;
    end
end
end

for i=1:1:D2D
    for j=1:1:D2D
        if i==j
            sinr(i,j)=0;
        else
            sinr(i,j) = Sin(i,j)- (N + I(i,j)); %in dB
        end
    end
end
end
end

```

```

function [UserStack,BS,popularity] =
disconnection_rate(iii,disconnected_users,UserStack,BS,popularity)

%----- Delete the record of the disconnected users -----%

disconnected_users_i = disconnected_users(1,iii);

UserStack(:,disconnected_users_i)=(0);

BS(:,disconnected_users_i)=(0);

popularity(:,disconnected_users_i)=(0);

end

```

```

function [fc,channel_assigned,channel] = wifi_channel(channel)

```



```

% Assign a channel for each User request

channel_assigned = find(channel<1,1,'first');

if channel_assigned==1
    fc=2.412e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==2
    fc=2.437e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==3
    fc=2.462e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==4
    fc=2.417e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==5
    fc=2.422e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==6
    fc=2.467e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==7

```

```

        fc=2.422e9;

        channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==8

    fc=2.447e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==9

    fc=2.472e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==10

    fc=2.427e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==11

    fc=2.452e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

if channel_assigned==12

    fc=2.477e9;

    channel(channel_assigned)=channel(channel_assigned)+ 1;
end

end

end



---


function [channel_assigned1,channel1] = release_channel(channel)

```

```
% Release the channel after the User request

channel1 = channel;

channel_assigned1 = find(channel==1);

for ii=1:length(channel_assigned1)

    channel1(1,ii)=channel1(1,ii)- 1;

end

end
```

Vita

Ansam Elfadel was born in 1992, in Khartoum, Sudan. She received her primary and secondary education in Khartoum, Sudan. She received her B.Sc. degree in Electrical and Electronic Engineering from the Khartoum University in 2014. From 2015 to 2017, she worked as an Account Manager in Etisalat, UAE.

In September 2017, she joined the Computer Engineering master's program in the American University of Sharjah as a graduate teaching assistant. Her research interests are in mobile networks, machine learning and cloud computing.