

**MODELLING AND ANALYSIS OF ALGORITHMS
FOR EFFICIENT CONTENT DISTRIBUTION IN
NEXT-GENERATION CONTENT DELIVERY
SOLUTIONS USING FOG-CDN**

PRATEEK



**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
MAY 2025**

**MODELLING AND ANALYSIS OF ALGORITHMS
FOR EFFICIENT CONTENT DISTRIBUTION IN
NEXT-GENERATION CONTENT DELIVERY
SOLUTIONS USING FOG-CDN**

by

PRATEEK

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

*in fulfilment of the requirements of the degree of Doctor of Philosophy
to the*



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2025

This work is dedicated to...

my daughter for her joyful presence and unconditional love...

my wife for her patience, support, and advice...

my parents for their unwavering guidance...

&

in the memory of my late maternal grandfather (Retd. Hon. Sub. Hira Lal Yadav),

whose hard work still inspires.

CERTIFICATE

This is to certify that the thesis titled **Modelling and Analysis of Algorithms for Efficient Content Distribution in Next-Generation Content Delivery Solutions using Fog-CDN** submitted by **Prateek**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bonafide record of his research work under my supervision.

The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. Subrat Kar

Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016
India

ACKNOWLEDGEMENTS

I express my heartfelt gratitude to the invaluable individuals and friends whose proficiency, advice, and motivation have enabled the realization of this thesis.

To begin with, I am grateful to Prof. Subrat Kar, my supervisor, for taking me under his wing during my Ph.D. journey. His guidance and mentoring were invaluable in improving my critical thinking and research skills. I distinctly remember his words, “Frame your thoughts in simple and clear words,” which motivated me to excel in both research and writing skills. Even as I write this, I see what he meant. His contributions became even more evident when I transitioned to full-time academic pursuits. My heartfelt thanks to the members of my SRC committee: Prof. Sumantra Dutta Roy (Chairman), Prof. Seshan Srirangarajan, and Prof. Bhawani Shankar Panda. Their guidance and valuable inputs have contributed significantly to the depth and rigor of my thesis.

Academic Acknowledgments: My academic journey has been shaped by the invaluable contributions of numerous friends and colleagues. I extend my sincere appreciation to Dr. Ajay Yadav (super-simple! and now, my colleague), Dr. Meenakshi (a dedicated lab researcher and labmate), Dr. Dileep Baptala (sports enthusiast, hard-working, and my early research helper), Dr. Venkatesh Khammammetti (a super friend! and my first roommate in IITD) and Mr. Syed Bilal Qaisar Naqvi (an IEEE paper digger and publishing genius) for their unwavering support and camaraderie. I also want to thank Dr. Bodhibrata Mukhopadhyay, Dr. Navneet Pratap Singh (IIT Indore), Mr. Nitin Lohar, Mr. Manoj Sharma, Ms. Sonal Gupta, and Mr. Animesh Chattopadhyaya for their intellectual exchanges. A special thanks goes to Mr. Manoj Rana for his bits of help during the last years of my Ph.D. I thank Mrs. Sagarika Dutta Bishwas for her unwavering assistance in administrative tasks.

Lastly, I thank my friends from the Udaigiri hostel, with whom I played, roamed, and discussed during the initial Ph.D. journey.

Family and Friends: With heartfelt gratitude to my dear wife Pratibha, for her endless care and patience; to my wonderful daughter Ira, for being my source of joy and motivation; to my supportive parents, Ramesh Chandra Yadav and Savitri Yadav, for their unwavering guidance and encouragement; to my elder brothers, Piyush and Prasoon, for their unending support; and to my in-laws, Atma Yadav and Amba Yadav, for caring our newborn daughter Ira in her initial months.

My heartfelt thanks go to Dr. Sahil Anchal for being there when it was needed most. Thanks to Eswar Dhullipala (Nani) for all the years in and out of the campus we spent together as my campus confidante.

Finally, I am thankful to IIT Delhi for the resources and facilities provided to me during my Ph.D.

Prateek

ABSTRACT

The ever-increasing demand for data necessitates the use of novel techniques in Content Distribution Networks (CDNs) to ensure efficient content delivery with guaranteed Quality of Service (QoS). One promising approach is the distributed fog-based CDN model, which relies on the optimal placement of fog nodes to meet these demands. Despite numerous academic efforts to develop CDN models, many critical aspects of CDN technology remain underexplored. These include the integration of fog computing with CDNs for localized processing, scalability challenges, efficient content distribution, improved adaptability to diverse user demand requirements, and cost-effective infrastructure management. This thesis addresses these issues by proposing various comprehensive approaches to build an efficient content distribution model.

First, we introduce the problem of deploying fog nodes and establishing the content distribution path to achieve guaranteed QoS, named the Fog-CDN problem. This NP-hard problem is a non-linear instance of the facility location problem. We construct this as an optimization problem by considering geographical regions, the locations of open public WiFi access points (OPWAPs), QoS, and cost to achieve three primary research objectives: strategic placement of fog nodes to process end-user requests, construction of a content distribution path with guaranteed QoS, and cost minimization when building a fog-based CDN model. We propose a framework with a heuristic for optimal fog node placement (*PFOLR*) and two approaches for content distribution, Greedy Performance-based Node Selection (*GPDS*) and Greedy Fog Node Selection Algorithm (*GFNSA*), to achieve these objectives. Our results demonstrate that the proposed methods outperform baseline techniques and provide near-optimal solutions.

Next, we propose the Joint Optimization Algorithm for Fog-node Placement and Content Distribution (*JFnP-CDA*) to jointly optimize fog-node placement and content distribution. Using a two-step procedure using clustering and the Voronoi method, along with a nonlinear programming method, we optimize the size of the geographi-

cal regions, the locations of OPWAPs, QoS, and the cost. We validate the effectiveness of the *JFnP-CDA* algorithm using real-world OPWAP data, demonstrating its validity over baseline methods. We optimize (jointly) the deployment and distribution factor and address the impact of fog node deployment on content distribution, a topic often overlooked in current research.

Next, we focus on factors such as space-time considerations, load balancing, and response time to enhance the Fog-CDN model capability. For this, we analyzed the locations of OPWAPs in two metropolitan cities of India (Mumbai and Chennai) by scraping and proposed a study to enhance the content distribution process within a Fog-CDN model, which coordinates numerous edge network hot spots near end users. To address the challenges of complexity and cost in Fog-CDN, we proposed a heuristic to optimize the problem objective. Our approach reduces service delays and costs by optimizing the Fog-CDN problem to build optimal service sub-regions and distribute content efficiently. We validate the effectiveness of this model by using real-world OPWAP data from metro cities, demonstrating that the proposed algorithm outperforms existing techniques in both cost and performance metrics.

Finally, to improve the Fog-CDN performance, we studied the Fog-CDN model to leverage cache deployments at various levels. Traditional CDNs have inherent limitations in effectively distributing content in densely populated areas. Therefore, the deployment of distributed fog node caches in Fog-CDN needs a closer look because it affects critical parameters: network resources (caching and storage), quality of service (QoS; latency), and costs (capital and operational expenditure). Consequently, we focused on analyzing those critical parameters by presenting an in-depth analysis of content popularity. For this, we have *scraped* and analyzed real-world data from YouTube to gain insights into content characteristics, which are crucial for minimizing QoS issues and costs. Additionally, we explore the deployment of micro-caches at the edge level, presenting various use cases to ensure low cost and high performance. We discuss the trade-offs between content popularity, caching, storage, and performance, demonstrating that our proposed model outperforms baseline CDN models in total cost and QoS guarantees.

सारांश

डेटा की लगातार बढ़ती मांग के कारण सेवा की गुणवत्ता की गारंटी (क्यूओएस) के साथ कुशल सामग्री वितरण सुनिश्चित करने के लिए सामग्री वितरण नेटवर्क (सीडीएन) में नवीन तकनीकों के उपयोग की आवश्यकता होती है। एक आशाजनक दृष्टिकोण वितरित कोहरा-आधारित सीडीएन मॉडल है, जो इन मांगों को पूरा करने के लिए कोहरे नोड्स के इष्टतम स्थान पर निर्भर करता है। सीडीएन मॉडल विकसित करने के लिए कई अकादमिक प्रयासों के बावजूद, सीडीएन तकनीक के कई महत्वपूर्ण पहलुओं की अभी तक खोज नहीं की गई है। इनमें स्थानीयकृत प्रसंस्करण, मापनीयता चुनौतियों, कुशल सामग्री वितरण, विविध उपयोगकर्ता मांग आवश्यकताओं के लिए बेहतर अनुकूलनशीलता और लागत प्रभावी बुनियादी ढांचे के प्रबंधन के लिए सीडीएन के साथ फ़ॉग कंप्यूटिंग का एकीकरण शामिल है। यह थीसिस एक कुशल सामग्री वितरण मॉडल बनाने के लिए विभिन्न व्यापक दृष्टिकोणों का प्रस्ताव करके इन मुद्दों को संबोधित करती है।

सबसे पहले, हम इष्टतम क्यूओएस प्राप्त करने के लिए फ़ॉग नोड्स को तैनात करने और सामग्री वितरण पथ स्थापित करने की समस्या का परिचय देते हैं, जिसे फ़ॉग-सीडीएन समस्या के रूप में जाना जाता है। यह एनपी-हार्ड समस्या सुविधा स्थान समस्या का एक गैर-रेखीय उदाहरण है। हम भौगोलिक क्षेत्रों, खुले सार्वजनिक वाई-फाई एक्सेस प्वाइंट (ओपीडब्ल्यूएपी) स्थानों, क्यूओएस और तीन प्राथमिक अनुसंधान उद्देश्यों को प्राप्त करने की लागत पर विचार करके इसे एक संयुक्त अनुकूलन समस्या के रूप में बनाते हैं: अंतिम-उपयोगकर्ता अनुरोधों को संसाधित करने के लिए फ़ॉग नोड्स का रणनीतिक प्लेसमेंट, निर्माण गारंटीशुदा क्यूओएस के साथ एक सामग्री वितरण पथ, और कोहरे-आधारित सीडीएन मॉडल के निर्माण की लागत को कम करना। हम इन उद्देश्यों को प्राप्त करने के लिए इष्टतम फ़ॉग नोड प्लेसमेंट (पीएफओएलआर) और दो एल्गोरिदम, लालची प्रदर्शन-आधारित नोड चयन (जीपीडीएस) और लालची फ़ॉग नोड चयन एल्गोरिदम (जीएफएनएसए) के लिए एक दोहरे चरण की रूपरेखा का प्रस्ताव करते हैं। हमारे परिणाम दर्शाते हैं कि प्रस्तावित विधियाँ आधारभूत तकनीकों से बेहतर प्रदर्शन करती हैं और लगभग-इष्टतम समाधान प्रदान करती हैं।

इसके बाद, हम फ़ॉग-नोड प्लेसमेंट और सामग्री वितरण (जेएफएनपी-सीडीए) के लिए संयुक्त अनुकूलन एल्गोरिदम का प्रस्ताव देते हैं, जो संयुक्त रूप से फ़ॉग नोड प्लेसमेंट और सामग्री वितरण को अनुकूलित करता है। नॉनलाइनियर प्रोग्रामिंग के साथ-साथ क्लस्टरिंग और वीरोनोई पद्धति से जुड़ी दो-चरणीय प्रक्रिया का उपयोग करके, हमारा लक्ष्य भौगोलिक क्षेत्रों, ओपीडब्ल्यूएपी स्थानों, क्यूओएस और लागत को अनुकूलित करना है। हम वास्तविक दुनिया ओपीडब्ल्यूएपी डेटा का उपयोग करके जेएफएनपी-सीडीए एल्गोरिदम की प्रभावशीलता को मान्य करते हैं, जो आधारभूत तरीकों पर इसकी श्रेष्ठता को प्रदर्शित करता है। इस कार्य का उद्देश्य संयुक्त रूप से तैनाती और वितरण कारक को अनुकूलित करना, जिसे अक्सर वर्तमान शोध में अनदेखा किया गया है।

फिर, हमने फॉग-सीडीएन मॉडल क्षमता को बढ़ाने के लिए स्पेस-टाइम विचार, लोड संतुलन और प्रतिक्रिया समय जैसे कारकों पर ध्यान केंद्रित किया। हमने स्क्रेपिंग के माध्यम से विभिन्न महानगरीय शहरों के ओपीडब्ल्यूएपी स्थानों का विश्लेषण किया है और फॉग-सीडीएन मॉडल के भीतर सामग्री वितरण प्रक्रिया को बढ़ाने के लिए एक अध्ययन का प्रस्ताव दिया है, जो अंतिम उपयोगकर्ताओं के पास कई एज नेटवर्क हॉट स्पॉट का समन्वय करता है। फॉग-सीडीएन में उच्च जटिलता और लागत की चुनौतियों का समाधान करने के लिए, हमने समस्या उद्देश्य को अनुकूलित करने के लिए एक अनुमान का प्रस्ताव रखा। हमारे दृष्टिकोण का उद्देश्य इष्टतम सेवा उप-क्षेत्रों का निर्माण करने और सामग्री को कुशलतापूर्वक वितरित करने के लिए फॉग-सीडीएन समस्या को संयुक्त रूप से अनुकूलित करके सेवा में देरी और लागत को कम करना है। हमने मेट्रो शहरों से वास्तविक दुनिया के ओपीडब्ल्यूएपी डेटा का उपयोग करके इस मॉडल की प्रभावशीलता को मान्य किया, यह प्रदर्शित करते हुए कि हमारा प्रस्तावित एल्गोरिदम लागत और प्रदर्शन मेट्रिक्स दोनों में मौजूदा तकनीकों से बेहतर प्रदर्शन करता है।

अंत में, फॉग-सीडीएन प्रदर्शन को बेहतर बनाने के लिए, हम फॉग-सीडीएन मॉडल पर एक अध्ययन प्रस्तुत करते हैं जो विभिन्न स्तरों पर कैश परिनियोजन का लाभ उठाता है। पारंपरिक सीडीएन में घनी आबादी वाले क्षेत्रों में सामग्री को प्रभावी ढंग से वितरित करने में अंतर्निहित सीमाएँ हैं। इसलिए, फॉग-सीडीएन में वितरित फॉग नोड कैश की व्यापक तैनाती के विश्लेषण पर बारीकी से नज़र डालने की ज़रूरत है जो महत्वपूर्ण मापदंडों को प्रभावित करता है: नेटवर्क संसाधन (कैशिंग और भंडारण), सेवा की गुणवत्ता (QoS ; विलंबता), और लागत (पूंजी और परिचालन व्यय)। परिणामस्वरूप, हमने सामग्री की लोकप्रियता का गहन विश्लेषण प्रस्तुत करके उन महत्वपूर्ण मापदंडों का विश्लेषण करने पर ध्यान केंद्रित किया। इसके लिए, हमने YouTube से वास्तविक दुनिया के डेटा को स्क्रेप किया और उसका विश्लेषण किया ताकि सामग्री विशेषताओं में अंतर्दृष्टि प्राप्त की जा सके, जो QoS मुद्दों और लागतों को कम करने के लिए महत्वपूर्ण हैं। इसके अतिरिक्त, हम कम लागत और उच्च प्रदर्शन सुनिश्चित करने के लिए विभिन्न उपयोग मामलों को प्रस्तुत करते हुए, किनारे के स्तर पर माइक्रो-कैश की तैनाती का पता लगाते हैं। अध्याय का समापन सामग्री लोकप्रियता, कैशिंग, भंडारण और प्रदर्शन के बीच व्यापार-नापसंद पर चर्चा करके होता है, तथा यह दर्शाता है कि हमारा प्रस्तावित मॉडल कुल लागत और QoS गारंटी में बेसलाइन सीडीएन मॉडल से बेहतर प्रदर्शन करता है।

Contents

ACKNOWLEDGEMENTS	1
ABSTRACT	3
LIST OF TABLES	11
LIST OF FIGURES	15
ABBREVIATIONS	16
1 Introduction	1
1.1 Overview	1
1.2 Challenges	2
1.2.1 Building an Efficient Content Distribution Model using Resources near End Users	3
1.2.2 The Effect of Placement Strategies on Scalability and Cost .	4
1.2.3 How does the Effective Content Distribution Approach Con- tribute to the Overall Cost-effectiveness?	4
1.3 Summary of Contributions of the Thesis	5
1.3.1 Fog-CDN: A Cost-Efficient Content Distribution Model for CDN	5
1.3.2 A Joint Optimization Algorithm for the Content Distribution Model	6
1.3.3 Improved Fog-CDN Model with Space-Time Considerations	7
1.3.4 Cache Deployment Strategies in Fog-CDN Model	7
1.4 Literature Review	8
1.4.1 Review of the Existing Studies in Fog-based CDNs: Introduc- tion and background	9
1.4.2 Existing Methods in Fog Node Deployments	11
1.4.3 Enhanced Fog-CDN Model with Response Time and Load Bal- ancing	13
1.4.4 Cache Deployments, QoS, and Cost in CDNs	14

1.5	Organization of the Thesis	16
2	Building Clouds on the Ground for Content Distribution Networks	19
2.1	Introduction	19
2.2	The Fog-CDN Model	21
2.2.1	Model and Problem Definitions	21
2.2.2	Problem Objective	23
2.3	The Proposed Algorithms	24
2.3.1	An Algorithm for Placing Fog-node in Optimal Locations of a Region (PFOLR)	26
2.3.2	Novel Algorithms for Fog Node Selection	28
2.3.2.1	Greedy Performance-based Node Selection (GPDS)	28
2.3.2.2	Greedy Fog Node Selection Algorithm (GFNSA)	29
2.3.2.3	Discussion on the Fog Node Selection Algorithms	29
2.4	Comparison of the GPDS and GFNSA with Existing Algorithms . .	30
2.4.1	Simulation Setup and Evaluation of the Model	30
2.4.2	Performance Evaluation of the Algorithms	34
2.5	Chapter Summary	42
3	A Joint Optimization Algorithm for Fog-based Content Delivery Network	44
3.1	Introduction	44
3.2	The Fog-CDN Model with Sub-regions	45
3.2.1	Problem Formulation	45
3.2.2	Definition of Problem Objective	48
3.2.3	NP-hardness Proof	49
3.3	Joint Optimization Algorithm for the Fog-node Placement and Content distribution (JFnP-CDA)	52
3.4	Comparison of the JFnP-CDA with Existing Algorithms	56
3.4.1	Evaluation Parameters	57
3.4.1.1	Regions and Locations	57
3.4.1.2	Fog Nodes, Replica Size, Delay, and Cost	58
3.4.2	Analysis and Discussion of Results	59
3.4.2.1	Comparison of the Performance Evaluation of the Algorithms on the Optimal Placement of Fog Nodes	60

3.4.2.2	Comparison of the Performance Evaluation of the Algorithms with Varying Model Parameters	60
3.5	Chapter Summary	71
4	Enhanced Fog-based Content Distribution Model with Space-Time Characteristics	72
4.1	Introduction	72
4.2	The Fog-CDN Model with Space-Time Characteristics	73
4.2.1	Definitions	73
4.2.2	System Model	75
4.2.3	Problem Objective	78
4.3	A Novel Algorithm for Optimizing Fog Node Deployment and Content Distribution (FogOpt)	79
4.4	Comparison of the FogOpt with Existing Algorithms	83
4.4.1	Evaluation Parameters	84
4.4.2	Evaluation of the Algorithms on the Optimal Fog Node Placement and the Load Balancing Factor	86
4.4.3	Impact of Deploying the Algorithms on the Sub-regions, Fog Nodes, Replica Size, and Associated Cost	89
4.5	Chapter Summary	96
5	Impact Analysis: Cache Deployment in Fog-CDNs	97
5.1	Introduction	97
5.2	Component Models of the Proposed Fog-CDN	98
5.2.1	Network Model	98
5.2.2	Video-On-Demand Model	99
5.2.3	Content Popularity Model	100
5.2.4	Fog Node Cache Deployment and Cost Model	102
5.2.5	Performance Measurement for the Cache Deployment in Fog-CDN Model	103
5.3	Evaluation Parameters	105
5.3.1	Comparison of the Fog-CDN model with the Traditional CDN Models	105
5.3.2	Simulation Parameters	106
5.3.3	Illustrative Numerical Evaluations and Discussion	107
5.3.3.1	Case 1: Edge CDN with All Caching	111

5.3.3.2	Case 2: Edge CDN with 80:20 Caching	113
5.3.3.3	Case 3: Cloud-based CDN with No Caching	113
5.3.3.4	Case 4: Presented Fog-CDN Approaches	113
5.4	Chapter Summary	115
6	Conclusion and Future Work	116
6.1	Conclusion	116
6.2	Future Work	118
	Bibliography	119
	List of Publications Arising Out of the Thesis	132
	Brief Profile of the Author	133

List of Tables

2.1	Notations (used in Chapter 2)	25
2.2	Some examples of the fog node	31
2.3	Example of typical cloud CDN charges	32
2.4	Summary of simulation parameters for Fog-CDN model (used in chapter 2)	32
3.1	Notations (used in Chapter 3)	50
3.2	Summary of simulation parameters for Fog-CDN model (used in chapter 3)	59
3.3	A summary of the efficiency comparison among algorithms TS^2P-CDA , OS^2P-CDA , $Mk-MS^2P-CDA$, RS^2P-CDA , MS^2P-CDA , and $JFnP-CDA$	67
4.1	Notations (used in Chapter 4)	80
5.1	Notations (used in Chapter 5)	104
5.2	Different properties (metadata traces) of the collected dataset	107
5.3	Hit ratio and storage relation for the <i>Harvard</i> dataset	111
5.4	Hit ratio and storage relation for the <i>MIT OpenCourseWare</i> dataset	111

List of Figures

1.1	Overview of the two-tier content distribution network model. In this, the origin server distributes content with the help of distributed edge servers, which are closer to end-users.	2
1.2	Organization of the Thesis	17
2.1	Schematic representation of the Fog-CDN model.	20
2.2	The CDF of the optimal cost in the simulation runs.	34
2.3	The effect of Algorithm 2.1 PFOLR on a region for optimal fog node placements in a sample of geo-distributed OPWAPs.	35
2.4	Simulation results show the performance of all the fog node selection algorithms (proposed; <i>GPDS</i> , <i>GFNSA</i> , and existed; <i>GRA</i> , and <i>RRA</i>) (a) present the relative cost achieved by the algorithms, (b) the corresponding error bars, where highly significant means the difference between the mean relative costs of the two proposed algorithm is less than 0.001 in a t-test.	36
2.5	Simulation results for the variation of relative cost with the number of regions in the Fog-CDN model (a) Relative cost achieved for number of regions = 5, 6, 7, . . . , 20, and (b) the corresponding performance error bars	37
2.6	Simulation results for the variation of relative cost with the fog nodes per region (FNPR) in the Fog-CDN model (a) Relative cost achieved for FNPR = 40, 41, . . . , 100, and (b) the corresponding performance error bars	38
2.7	Simulation results for the variation of relative cost with the delay in the Fog-CDN model (a) Relative cost achieved for delay (ms) = 10, 11, . . . , 500, and (b) the corresponding performance error bars	39
2.8	Simulation results for the variation of relative cost with the replica size in the Fog-CDN model (a) Relative cost achieved for replica size (MB) = 2, 3, . . . , 10000, and (b) the corresponding performance error bars	40
2.9	Simulation results for the variation of relative cost with the update frequency in the Fog-CDN model (a) Relative cost achieved for update frequency (%) = 10, 11, . . . , 20, and (b) the corresponding performance error bars	41
3.1	Schematic representation of the Fog-CDN model with sub-regions.	46
3.2	A sample problem scenario for fog node placements and content distribution.	48

3.3	Effect of algorithm <i>JFnP-CDA</i> (proposed) and <i>MS²P-CDA</i> (existing) on the placements of fog nodes for the Delhi dataset (a) Geo-distribution of OPWAPs in Delhi dataset, and (b) the optimized fog node placement locations with sub-regions achieved by the <i>JFnP-CDA</i> (each dot represents the optimal placement location in each sub-region). Finally, (c) the observed grids achieved for the fog node placement using <i>MS²P-CDA</i>	61
3.4	Effect of algorithm <i>JFnP-CDA</i> (proposed) and <i>MS²P-CDA</i> (existing) on the placements of fog nodes for the NYC dataset (a) Geo-distribution of OPWAPs in NYC dataset, and (b) the optimized fog node placement locations with sub-regions achieved by the <i>JFnP-CDA</i> (each dot represents the optimal placement location in each sub-region). Finally, (c) the observed grids achieved for the fog node placement using <i>MS²P-CDA</i>	62
3.5	Effect of algorithms <i>JFnP-CDA</i> , <i>OS²P-CDA</i> , <i>Mk-MS²P-CDA</i> , <i>RS²P-CDA</i> , <i>TS²P-CDA</i> , and <i>Mk-MS²P-CDA</i> simulation results on the corresponding Delhi dataset (a) showing the variation of the overall cost with different fog nodes per sub-region , and (b) the impact of these algorithms on the overall cost to build Fog-CDN model in a region	64
3.6	Effect of algorithms <i>JFnP-CDA</i> , <i>OS²P-CDA</i> , <i>Mk-MS²P-CDA</i> , <i>RS²P-CDA</i> , <i>TS²P-CDA</i> , and <i>Mk-MS²P-CDA</i> and results of the simulation of the variation of overall cost against the content replica size.	65
3.7	Effect of algorithms <i>JFnP-CDA</i> , <i>OS²P-CDA</i> , <i>Mk-MS²P-CDA</i> , <i>RS²P-CDA</i> , <i>TS²P-CDA</i> , and <i>Mk-MS²P-CDA</i> simulation results on the corresponding Delhi dataset showing the variation of (a) the overall cost against delay, and (b) the variation of the overall cost with content update frequency.	66
3.8	Trade-off analysis on Cost-to-Delay ratios with default delay set to 50 ms.	67
3.9	Trade-off analysis on Cost-to-‘Content update frequency’ ratios on the default set to 20% of storage update.	68
3.10	<i>Algorithms statistical performance for parameter content replica size against overall cost. Post hoc tests reveal <i>JFnP-CDA</i> (proposed) superiority ($p_{adj} < 0.001$) against other benchmark algorithms, <i>MS²P-CDA</i> performs worst.</i>	68
3.11	<i>Algorithms statistical performance for parameter delay against overall cost. In this, <i>JFnP-CDA</i> achieves significantly lower overall cost with $p_{adj} < 0.05$ than all benchmarks algorithms.</i>	69
3.12	<i>Algorithms statistical performance for parameter content update frequency against overall cost. Post hoc tests reveal <i>JFnP-CDA</i> (proposed) superiority ($p_{adj} < 0.001$) against other benchmark algorithms.</i>	69

3.13	<i>Algorithms statistical performance for parameter FNPSR against overall cost. The analysis shows limited significant differences against the benchmark algorithms (MS^2P-CDA and OS^2P-CDA with $p=0.029$ and $p=0.042$, respectively).</i>	70
4.1	Schematic representation of the Fog-CDN (as in Fig. 3.1).	76
4.2	Effect of algorithm <i>FogOpt</i> (proposed) and $mMx\mathcal{R}_kA$ (existing) on the placement of fog nodes for the Mumbai City dataset, showing (a) geo-distribution of the OPWAPs, (b) the optimal fog node locations observed in every sub-region by <i>FogOpt</i> , and (c) the grids identified for fog node placement by $mMx\mathcal{R}_kA$.	87
4.3	Effect of algorithm <i>FogOpt</i> (proposed) and $mMx\mathcal{R}_kA$ (existing) on the placement of fog nodes for the Chennai City dataset, showing (a) geo-distribution of the OPWAPs, (b) the optimal fog node locations observed in every sub-region by <i>FogOpt</i> , and (c) the grids identified for fog node placement by $mMx\mathcal{R}_kA$.	88
4.4	The load balancing factor of the fog nodes in a region, showing (a) the impact on various nodes through proposed <i>FogOpt</i> and (b) the effect on various fog nodes through existing $mMx\mathcal{R}_kA$.	89
4.5	Simulations results of algorithms $mT\mathcal{R}_kA$, $mO\mathcal{R}_kA$, $mR\mathcal{R}_kA$, $mMx\mathcal{R}_kA$ (existing), and <i>FogOpt</i> (proposed) on fog node per sub-region (FNPSR) and number of partitioned sub-regions on the Mumbai City dataset, showing impact on (a) deployment of fog nodes and corresponding total cost, and (b) the number of partitioned sub-regions in a region and the corresponding total cost.	90
4.6	Simulations results of algorithms $mT\mathcal{R}_kA$, $mO\mathcal{R}_kA$, $mR\mathcal{R}_kA$, $mMx\mathcal{R}_kA$ (existing), and <i>FogOpt</i> (proposed) on content replica size, overall response time, and content update frequency on the Mumbai City dataset, showing the effect of (a) content replica size on the corresponding total cost, and (b) the overall response time on the total cost, and finally (c) the impact of content update frequency on the total cost.	91
4.7	<i>Algorithms statistical performance for parameter content replica size against Total cost. <i>FogOpt</i> demonstrates robust performance ($p_{adj} < 0.001$) over all benchmarks.</i>	94
4.8	<i>Algorithms statistical performance for parameter overall response time against Total cost. <i>FogOpt</i> outperformed other benchmarks algorithms with $p_{adj} < 0.05$.</i>	94
4.9	<i>Algorithms statistical performance for parameter content update frequency against Total cost. <i>FogOpt</i> shows robust performance for ($p_{adj} < 0.001$).</i>	95
4.10	<i>Algorithms statistical performance for parameter FNPSR against Total cost. <i>FogOpt</i> matches leading benchmarks ($p > 0.05$) while significantly outperforming $mMx\mathcal{R}_kA$ ($p = 0.026$).</i>	95

5.1	The Fog-CDN network model.	99
5.2	Dataset distribution of (a) the <i>Harvard</i> videos dataset, and (b) the <i>MIT OpenCourseWare</i> videos dataset.	108
5.3	Goodness fit test on datasets, test results on (a) the <i>Harvard</i> dataset, and (b) the <i>MIT OpenCourseWare</i> dataset.	109
5.4	Popularity measurement for the two datasets, on the (a) <i>Harvard</i> dataset, and (b) <i>MIT OpenCourseWare</i> dataset.	110
5.5	Total cost of cache deployments in Fog-CDN model for varying values of popularity exponent α (a) at $\alpha = 0.88$, and (b) at $\alpha = 0.66$	112
5.6	Variation of Capital expenditure against performance for popularity exponent $\alpha = 0.66$ and $\alpha = 0.88$	114

ABBREVIATIONS

ABR	Adaptive Bit Rate
APs	Access Points
CCP	Cloud-based Content Provider
CDN	Content Distribution/Delivery Network
COTS	Commercial Off-The-Shelf
CSP	Cloud Service Provider
DPI	Deep Packet Inspection
ES	Edge Servers
FOG-CDN	Fog-based Content Distribution Network
FNPP	Fog Node Placement Problem
GUI	Graphical User Interface
HTTP	Hypertext Markup Language
IaaS	Infrastructure as a Service
ICN	Information Centric Network
IoT	Internet of Things
IPTV	Internet Protocol Television
ISP	Internet Service Provider
MANO	Management and Orchestration
MIP	Mixed Integer Programming
MILP	Mixed Integer Linear Programming
MLS	Mobile Live Streaming
NAT	Network Address Translation
NFs	Network Functions
NFV	Network Function Virtualization
NFVI	Network Function Virtualization Infrastructure
NIST	National Institute of Standards and Technology
NS	Network Service
O&M	Orchestration and Management

OSS/BSS	Operational Support System/Business Support System
OPWAPs	Open Public WiFi Access Points
PoD	Point of Deployment
PoP	Point of Presence
QoE	Quality of Experience
QoS	Quality of Service
RTT	Round Trip Time
RO	Resource Orchestration
SaaS	Software as a Service
SDN	Software Defined Network
SE-B	Semi-Edge-Broadcast
SE-U	Semi-Edge-Unicast
SFC	Service Function Chaining
SLA	Service Level Agreement
UAV	Unmanned Aerial Vehicle
UDN	Ultra Dense Network
VoD	Video-on-Demand
VAS	Value-added Service
WAN	Wide Area Network
WOA	Whale Optimization Algorithm