

OPTIMIZATION OF ARQ ALLOCATION FOR ULTRA-RELIABLE AND LOW-LATENCY COMMUNICATION IN MULTI-HOP NETWORKS

JAYA



**BHARTI SCHOOL OF TELECOMMUNICATION TECHNOLOGY AND
MANAGEMENT**

INDIAN INSTITUTE OF TECHNOLOGY DELHI

MAY 2023

OPTIMIZATION OF ARQ ALLOCATION FOR ULTRA-RELIABLE AND LOW-LATENCY COMMUNICATION IN MULTI-HOP NETWORKS

by

JAYA

BHARTI SCHOOL OF TELECOMMUNICATION TECHNOLOGY AND MANAGEMENT

Submitted

in fulfillment of the requirements of the degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

May 2023

Dedicated
to
My Beloved
Parents and Sister -

who always inspire me to dream big!



Bharti School of Telecommunication Technology and Management
Indian Institute of Technology Delhi
Hauz Khas, New Delhi, India-110016

Certificate

This is to certify that the thesis entitled “**Optimization of ARQ Allocation for Ultra-Reliable and Low-Latency Communication in Multi-Hop Networks**”, submitted by **Jaya (aka Jaya Goel)** to the Bharti School of Telecommunication Technology and Management, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** has been carried out under my supervision. The work contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree.

Prof. Harshan Jagadeesh

Department of Electrical Engineering,
Indian Institute of Technology Delhi
Hauz Khas, New Delhi, India - 110016.
MAY 2023

Acknowledgments

First and foremost, thanks to the almighty God for giving me the wisdom, determination, and patience to explore the emerging world of wireless networks.

I would like to express my deep and sincere gratitude to my supervisor, Prof. Harshan Jagadeesh, for giving me the opportunity to work under his guidance. His tremendous patience, vision, sincerity, kindness, and motivation have been a source of inspiration to me. He always gave me the freedom to think and explore new research ideas. He has taught me the art of writing papers and presenting the results, along with the importance and values of good research. His assistance during all these years enabled me to complete the research successfully. It would never have been possible without his guidance and support. His pursuit for excellence and perfection has inspired me to be a better researcher and a better person. I am truly grateful to his support for all these years.

I would like to thank the Ministry of Education, Government of India, for providing financial support during my Ph.D. Also, I gratefully acknowledge the travel grant and work support from the contingency fund from IIT Delhi, Indigenous 5G Test Bed project, DoT, Government of India (GoI), and the Council of Scientific & Industrial Research (CSIR), GoI, which have given me the wonderful opportunity to participate in international conferences to present my work across the globe. Further, I would like to acknowledge the Bharti School of Telecommunications Technology and Management, IIT Delhi, for providing best research facilities. I would also like to thank IIT Delhi for providing me an opportunity to pursue graduate studies along with good hostel and mess facilities.

I would like to express my gratitude to Prof. Shankar Prakriya for allowing me to work in the DSP lab at IIT Delhi. I am grateful to Prof. Ranjitha Prasad, who gave me an opportunity to

work on a MEITY project (under GoI) for 3 months, at IIIT Delhi, and for very delicious south Indian food, many times, at her home.

I would like to extend my heartfelt thank to all my labmates Vivek, Aanad, Mayank, Kamal Agarwal, Bhupinder Kumar, Prateek Chakraborty, and Kamal Biswas, with whom I have enjoyed several discussions on work. Also, I would like to thank my friends Anjali Gupta, Amita Giri, Muskan Ahuja, Vishal Srivastava, Namrata Tiwari, Shravya, Kunal, Aadil Hussain, and Harikrishnan, at IIT Delhi, with whom I have shared a memorable time in the campus. I feel extremely lucky and privileged to have so many wonderful friends.

Most importantly, I shall be forever grateful to my parents, Sh. Prem Chand and Smt. Meena Rani, for supporting me with their heart and soul to pursue my academic career and have patiently nurtured me throughout my life. My special thanks to my sister, Neha Goel, for her endless support and affection. I would like to extend my thanks to my lifelong friend Nilaksh Bansal, who has been supportive in all my endeavors.

At last, I would like to pay my sincere gratitude to one and all who have directly or indirectly helped me throughout this journey.

Jaya

Abstract

Multi-hop networks comprising Line-of-Sight (LOS) dominated wireless channels have found attractive applications in wireless networks, such as in vehicular networks involving unmanned aerial vehicles. These applications are known to demand both high-reliability and low-latency features on communication links. While Automatic-Repeat-Requests (ARQs) or Hybrid-ARQs (HARQ) based decode-and-forward (DF) relaying strategies provide the high-reliability feature, they are known to incur delays owing to multiple re-transmissions of packets. To address the trade-off between the reliability and the low-latency features of ARQ-based or HARQ-based DF strategies, in this thesis, we impose a sum constraint on the total number of ARQs across the nodes as it captures an upper bound on end-to-end delay for packet transmissions. Subsequently, we solve the problem of optimally distributing the total number of ARQs across the nodes such that the end-to-end packet drop probability (PDP) is minimized under various non-cooperative, semi-cumulative, cluster-based, and fully-cumulative strategies. For each of the proposed strategies, we provide a set of necessary and sufficient conditions on the optimal ARQ distribution and use these conditions to synthesize low-complexity algorithms to obtain near-optimal solutions. In addition to the PDP metric, we also analyze the packet delay profiles to compare the latency of all the strategies and show that the packets reach the destination within the deadline with an overwhelming probability.

सार

मल्टी-हॉप नेटवर्क जिसमें लाइन-ऑफ-साइट (एलओएस) प्रमुख वायरलेस चैनल शामिल हैं, ने तार रहित नेटवर्क में आकर्षक अनुप्रयोग पाया है, जैसे मानव रहित हवाई वाहनों से जुड़े वाहन नेटवर्क में। ये अनुप्रयोग संचार लिंक पर उच्च-विश्वसनीयता और निम्न-विलंबता दोनों सुविधाओं की मांग करने के लिए जाने जाते हैं। जबकि स्वचालित-दोहराव-अनुरोध (एआरक्यू) या हाइब्रिड-एआरक्यू (एचएआरक्यू) आधारित डिकोड-एंड-फॉरवर्ड (डीएफ) रिलेइंग रणनीतियां उच्च-विश्वसनीयता सुविधा प्रदान करती हैं, उन्हें पैकेटों के एकाधिक पुनः प्रसारण के कारण देरी करने के लिए जाना जाता है। एआरक्यू-आधारित या एचएआरक्यू-आधारित डीएफ रणनीतियों की विश्वसनीयता और कम-विलंबता सुविधाओं के बीच व्यापार-बंद को संबोधित करने के लिए, इस थीसिस में, हम नोड्स में एआरक्यू की कुल संख्या पर एक बाधा डालते हैं क्योंकि यह एक ऊपरी सीमा को पकड़ता है। पैकेट प्रसारण के लिए एंड-टू-एंड देरी पर। इसके बाद, हम नोड्स में एआरक्यू की कुल संख्या को इष्टतम रूप से वितरित करने की समस्या को हल करते हैं जैसे कि एंड-टू-एंड पैकेट ड्रॉप प्रायिकता (पीडीपी) को विभिन्न गैर-सहकारी, अर्ध-संचयी, क्लस्टर-आधारित और पूरी तरह से कम किया जाता है। संचयी रणनीतियाँ। प्रस्तावित रणनीतियों में से प्रत्येक के लिए, हम इष्टतम एआरक्यू वितरण पर आवश्यक और पर्याप्त शर्तों का एक सेट प्रदान करते हैं और निकट-इष्टतम समाधान प्राप्त करने के लिए कम-जटिलता एल्गोरिदम को संश्लेषित करने के लिए इन शर्तों का उपयोग करते हैं। पीडीपी मीट्रिक के अलावा, हम सभी रणनीतियों की विलंबता की तुलना करने के लिए पैकेट विलंब प्रोफाइल का भी विश्लेषण करते हैं और दिखाते हैं कि पैकेट अत्यधिक संभावना के साथ समय सीमा के भीतर गंतव्य तक पहुंच जाते हैं।

Contents

Certificate	iii
Acknowledgements	iv
Abstract	vi
List of Figures	xii
List of Tables	xix
I Part: Prerequisites	1
1 Introduction	2
1.1 Motivation	2
1.2 Problem Statement and Research Objectives	5
1.3 Summary of the Contributions of this Thesis	6
1.4 Literature Review	9
1.5 Organization of the Thesis	10
2 An Overview of Multi-Hop Network under Consideration	12

2.1	Introduction	12
-----	------------------------	----

II Part: ARQ Schemes for Achieving URLLC over Multi-Hop Networks **15**

3 Non-Cooperative ARQ Schemes in Multi-Hop Networks **16**

3.1	Introduction	16
3.2	Signal Model	17
3.2.1	Formulation of Optimization Problem	19
3.3	Sufficient and Necessary Conditions on the Optimal ARQ Distribution	20
3.4	Low-Complexity List-Decoding Algorithm	27
3.4.1	Towards Solving Problem 3.2 without Integer Constraints	29
3.4.2	List Generation using the Non-Integer Solution	30
3.5	Complexity Analysis and Simulation Results	31
3.5.1	Simulation Results on Delay Analysis	33
3.6	Summary	37

4 Cooperative ARQ Schemes in Multi-Hop Networks **38**

4.1	Introduction	38
4.2	Fully-Cumulative ARQ Scheme	39
4.3	Cluster based ARQ Schemes	44
4.3.1	Pair-wise Cooperative Scheme	45
4.3.2	Cluster based Cooperative Scheme	48
4.3.3	Algorithm for the Cluster based Cooperative ARQ Scheme	51
4.4	Complexity Analysis and Simulation Results	54
4.4.1	Pair-wise Cooperative ARQ Scheme	54

4.4.2	Cluster based Cooperative ARQ Scheme	58
4.4.3	Fully-Cumulative ARQ Scheme	61
4.4.4	Delay Analysis of Cooperative ARQ Strategies	61
4.5	Summary	65

III Part: One-Hop Listening ARQ Schemes for Achieving URLLC over Multi-Hop Networks 66

5	Semi-Cumulative ARQ Sharing Strategies in Multi-Hop Networks	67
5.1	Introduction	67
5.2	Semi-Cumulative Multi-Hop Network	69
5.3	PDP Expression of Semi-Cumulative Scheme	72
5.4	Optimal ARQ Distribution of the Semi-Cumulative Scheme	76
5.5	Low-Complexity Algorithms	79
5.5.1	List Generation using Multi-Folding	80
5.5.2	Multi-Folding based Greedy Algorithm	80
5.6	Simulation Results and Complexity Analysis	81
5.7	Summary	85
6	Cluster Based Semi-Cumulative ARQs Sharing Strategy in Multi-Hop Networks	86
6.1	Introduction	86
6.2	Cluster Based Semi-Cumulative Strategy	88
6.2.1	Theoretical Results for CSC Strategy	92
6.2.2	Complexity Reduction for Case-1 and Case-2	99
6.2.3	Complexity Reduction for Case-3	103
6.3	Low-Complexity Algorithms for CSC Strategy	104

6.3.1	List Generation using Multi-Folding for the CSC Strategy	104
6.3.2	Multi-Folding Algorithms for the CSC Strategy	106
6.4	Simulation Results on Cluster based Semi-Cumulative Strategy	108
6.5	Summary	113

IV Part: CC-HARQ Based Relaying Strategies for Achieving URLLC over Multi-Hop Networks **114**

7	CC-HARQ Strategies in Multi-Hop Networks under Slow-Fading Scenario	115
7.1	Introduction	115
7.2	CC-HARQ Based Multi-Hop Network Model	118
7.3	Analysis on the Optimal ARQ Distribution using CC-HARQ-SF	122
7.3.1	Approximation on the Marcum-Q function	122
7.3.2	Sufficient and Necessary Conditions on the Near-Optimal ARQ Distribution in CC-HARQ-SF Strategy	124
7.4	Low-Complexity List-Decoding Algorithm	129
7.5	Simulation Results	131
7.6	CC-HARQ-SF based Fully-Cumulative Network	135
7.7	Delay Analysis for CC-HARQ-SF based Non-Cumulative Network	140
7.8	Summary	144
8	CC-HARQ Strategies in Multi-Hop Networks under Fast-Fading Scenario	145
8.1	Introduction	145
8.2	CC-HARQ based Multi-Hop Network Model	147
8.3	Optimal ARQ Distribution in CC-HARQ-FF based Non-Cumulative Network	148
8.3.1	Approximation on the q_k -th Order Marcum-Q Function	149

8.3.2	Analysis on the Near-Optimal ARQ Distribution for CC-HARQ-FF based Non-Cumulative Network	152
8.3.3	Low-Complexity Algorithm for CC-HARQ-FF based Non-Cumulative Network	155
8.3.4	Simulation Results for CC-HARQ-FF based Non-Cumulative Network	160
8.4	CC-HARQ-FF based Fully-Cumulative Network	161
8.5	Simulation Results on Delay Analysis for CC-HARQ-FF Strategy.....	164
8.6	Summary.....	167
V	Part : Final Remarks	169
9	Conclusions and Future Directions	170
9.1	Conclusions	170
9.2	Future Directions	174
	Bibliography	175
	Appendix-I	180
	Biodata	182

List of Figures

2.1	Depiction of LOS dominated N -hop network, where $0 \leq c_k \leq 1$ represents the LOS component of the k -th link, and $q_k \in \mathbb{Z}_+$ denotes the number of ARQs allotted to the transmitter of the k -th link, for $1 \leq k \leq N$	13
3.1	Depiction of LOS dominated N -hop network, where $0 \leq c_k \leq 1$ represents the LOS component of the k -th link, and $q_k \in \mathbb{Z}_+$ denotes the number of ARQs allotted to the transmitter of the k -th link, for $1 \leq k \leq N$	18
3.2	An illustrative example with $N = 2$: The LOS components and the SNR of the two links are such that $P_1 = 0.4$ and $P_2 = 0.25$. With $q_{sum} = 8$, our approach generates a list consisting 2 ARQ distributions, whereas the size of the search space is 7.	30
3.3	List size for $N = 4$ and $N = 6$ at $R = 1$	32
3.4	PDP for $N = 4$ and $N = 6$ at $R = 1$. With uniform distribution, each link is first allotted $\lfloor \frac{q_{sum}}{N} \rfloor$ ARQs, whereas the remaining ARQs are equally shared by the first $q_{sum} \bmod N$ links.	33

3.5	Simulation results using a 4-hop network with LOS vector $\mathbf{c} = [0.7, 0.3, 0.1, 0.5]$, $q_{sum} = 8$ at $R = 1$ and various values of SNR. Plots show delay profile of the non-cooperative ARQ strategy and a hybrid ARQ strategy when $T = 1$ microsecond is the time taken for packet transmission, and $T_{NACK} = 0.1$ microsecond is the time taken for NACK.	34
3.6	Simulation results using a 4-hop network with LOS vector $\mathbf{c} = [0.7, 0.3, 0.1, 0.5]$, $q_{sum} = 8$ at $R = 1$ and various values of SNR showing plots on the average delay and PDP of the non-cooperative ARQ along with that of a hybrid ARQ scheme and a repetition strategy.	36
4.1	An illustrative example of 4-hop network employing (i) the non-cooperative strategy, (ii) the one-pair based cooperative scheme, (iii) the one-cluster based cooperative scheme, and (iv) the fully-cumulative scheme.	40
4.2	Plots depicting the improvement in the PDP when using a one-pair (1p) cooperative scheme.	54
4.3	Plots depicting the PDP of the one-pair (1p) scheme when the ARQ distribution is computed using exhaustive search and the proposed algorithm.	55
4.4	Complexity of the one-pair (1p) cooperative scheme.	56
4.5	Plots depicting the improvement in the PDP when using a two-pair (2p) cooperative scheme.	57
4.6	Plots depicting the improvement in the PDP when using a cooperative strategy with one-cluster (1c) scheme by combining 3 links.	58
4.7	Plots depicting the improvement in the PDP when using a cooperative strategy with two-cluster (2c) scheme wherein each cluster is formed by combining 3 links.	59
4.8	Complexity of the cooperative strategy with one-cluster (1c) scheme by combining 3 links.	60

4.9	Complexity of the cooperative strategy with two-cluster (2c) scheme wherein each cluster is formed by combining 3 links.	60
4.10	Plots depicting the improvement in the PDP when using a fully-cumulative strategy wherein one cluster is formed by combining all the links in the network.	62
4.11	Simulation results using a 4-hop network with $\mathbf{c} = [0.7, 0.3, 0.1, 0.5]$, $q_{sum} = 8$ at various values of R and SNR. At the top: Delay profiles of the proposed schemes when $T = 1$ microsecond is the time taken for packet transmission each time in the network. Plots on PDV as a function of α , where α captures the complexity parameter to update the counter. The legends "NC", "1p", "1c" and "FC" represent the non-cooperative, one-pair cooperative, one-cluster cooperative, and fully-cumulative strategies, respectively.	63
4.12	Simulation results using a 4-hop network with $\mathbf{c} = [0.7, 0.3, 0.1, 0.5]$, $q_{sum} = 8$ at various values of R and SNR. Plots on PDV as a function of α , where α captures the complexity parameter to update the counter. The legends "NC", "1p", "1c" and "FC" represent the non-cooperative, one-pair cooperative, one-cluster cooperative, and fully-cumulative strategies, respectively.	64
5.1	Illustration of an N -hop semi-cumulative scheme with channels dominated by LOS components.	69
5.2	Variation of average delay on the packets and the deadline violation parameter (η) for various τ_{NACK} when using the SC strategy.	83
5.3	PDP plots when using an SC strategy with exhaustive search (no fold), 1-fold, 2-fold and greedy strategies with $\mathbf{c}_1 = [0.1, 0.3, 0.1, 0.5, 0.2]$, $\mathbf{c}_2 = [0.5, 0.5, 0.5, 0.5, 0.5]$, $\mathbf{c}_3 = [0.9, 0.2, 0.4, 0.7, 0.1, 0.5]$ and $\mathbf{c}_4 = [0.3, 0.3, 0.3, 0.3, 0.3, 0.3]$ at SNR = 10 dB and rate $R = 1$	84

-
- 5.4 List sizes for an SC strategy with exhaustive search, 1-fold, 2-fold and greedy strategies with $\mathbf{c}_1 = [0.1, 0.3, 0.1, 0.5, 0.2]$, $\mathbf{c}_2 = [0.5, 0.5, 0.5, 0.5, 0.5]$, $\mathbf{c}_3 = [0.9, 0.2, 0.4, 0.7, 0.1, 0.5]$ and $\mathbf{c}_4 = [0.3, 0.3, 0.3, 0.3, 0.3, 0.3]$ at SNR= 10 dB and rate $R = 1$ 85
- 6.1 An illustrative example of a 5-hop network where a cluster is formed by grouping 3 consecutive nodes: (i) the cluster at the beginning (Case-1), (ii) the cluster at an intermediate position (Case-2), and (iii) the cluster at the end (Case-3). 89
- 6.2 PDP comparison: Case-1 (first three hops constitute cluster), Case-2 (third hop to fifth hop forming a cluster) and Case-3 (fourth hop to sixth hop forming a cluster) with $\mathbf{c}_1 = [0.9, 0.2, 0.4, 0.7, 0.1, 0.5]$ and $\mathbf{c}_2 = [0.3, 0.3, 0.3, 0.3, 0.3, 0.3]$ at rate $R = 1$ 110
- 6.3 Plots depicting the PDP comparison for Case-1 (first three hops constitute cluster) and Case-2 (third hop to fifth hop forming a cluster) with no-fold, 1-fold, 2-fold and greedy strategies where $\mathbf{c}_1 = [0.9, 0.2, 0.4, 0.7, 0.1, 0.5]$ and $\mathbf{c}_2 = [0.3, 0.3, 0.3, 0.3, 0.3, 0.3]$ 111
- 6.4 On the left: Plots illustrating the PDP comparison for Case-3 with no-fold, 1-fold algorithm where $\mathbf{c}_1 = [0.9, 0.2, 0.4, 0.7, 0.1, 0.5]$ and $\mathbf{c}_2 = [0.3, 0.3, 0.3, 0.3, 0.3, 0.3]$, SNR = 10 dB, rate $R = 1$. In this case, the last three hops constitute the cluster. On the right: Plots depicting the reduction in list size for Case-3 with exhaustive search, and 1-fold algorithms. 112
- 6.5 Plots depicting the reduction in list size for Case-1 (first three hops constitute cluster) and Case-2 (third hop to fifth hop forming a cluster) with no fold, 1 Fold, 2 Fold and Greedy strategies where $\mathbf{c}_1 = [0.9, 0.2, 0.4, 0.7, 0.1, 0.5]$ and $\mathbf{c}_2 = [0.3, 0.3, 0.3, 0.3, 0.3, 0.3]$ 112

6.6	Simulation results on probability of deadline violation using a 6-hop network with $\mathbf{c} = [0.9, 0.2, 0.4, 0.7, 0.1, 0.5]$, at rate $R = 1$ and SNR = 10 dB with 10^6 packets. For comparison, we have Case-1, Case-2, Case-3 and the SC strategy (with no cluster).	113
7.1	Illustration of an N -hop network with a source node (S), the relay nodes $R_1, \dots, R_{N-1}$ and the destination node (D) follow the CC-HARQ protocol at each intermediate link. Also, each intermediate link can be characterized by an LOS component $c_k \forall k \in [N]$	119
7.2	Comparison of original expression of Marcum Q-function with its proposed approximation at different values of SNR.	123
7.3	Illustration on the average delay on packets and deadline violation parameter (η) for several values of $\tau_{NACK} = \{0.05, 0.2, 0.8\}$ microseconds while implementing CC-HARQ-SF strategy.	132
7.4	Comparison of list size between exhaustive search and the proposed low-complexity algorithm with and without Theorem 7.2.	132
7.5	PDP comparison in CC-HARQ-SF based non-cumulative network between (i) exhaustive search using original PDP expression, p_d , (ii) exhaustive search using approximated PDP expression, $\tilde{p}_d$, (iii) proposed low-complexity algorithm (given in Algorithm 7), and (iv) uniform ARQ distribution along with ARQ distribution in a non-HARQ strategy (as discussed in Chapters 3, 4). With uniform distribution, each link is first distributed with $\lfloor q_{sum}/N \rfloor$ ARQs, and the remaining ARQs are equally shared by the first $q_{sum} \bmod N$ links.	133
7.6	An illustration for a CC-HARQ-SF based fully-cumulative network.	135

7.7	Comparison of the minimum PDP, denoted by p_d , for : (i) CC-HARQ-SF based non-cumulative network, (ii) CC-HARQ-SF based fully-cumulative network, and (iii) non-hybrid ARQ strategy	137
7.8	Variation of average delay on the packets and the deadline violation parameter (η) for various τ_{NACK} in CC-HARQ-SF based strategies at SNR= 0 dB.	141
7.9	Simulation results on delay profiles for CC-HARQ-SF based strategies using a 5-hop network with $\mathbf{c} = [0.1, 0.5, 0.1, 0.3, 0.7]$ and $q_{sum} = 12$ at rate $R = 1$ and SNR= 5dB with 10^6 packets wherein some packets are dropped either due to outage and some are dropped due to deadline violation, denoted by $W_{deadline}$ (marked in the rectangle).	143
7.10	Illustration on PDV for non-cumulative and fully-cumulative network while implementing CC-HARQ-SF strategies for different τ_{NACK} and α values.	143
8.1	Illustration of an N -hop network with a source node (S), the relay nodes $R_1, \dots, R_{N-1}$ and the destination node (D) follow the CC-HARQ protocol at each intermediate link. Also, each intermediate link can be characterized by an LOS component $c_k \forall k \in [N]$ and the non-LOS component captures fast varying behavior of the channel.	147
8.2	Comparison of an original expression of q_k -th order Marcum Q-function with its proposed approximation (in (8.4)) at different SNR.	150
8.3	PDP comparison in CC-HARQ-FF based non-cumulative network between (i) exhaustive search using original PDP expression, p_d^f , (ii) exhaustive search using approximated PDP expression, $\tilde{p}_d^f$, (iii) proposed FTML low-complexity algorithm (given in Algorithm 8), and (iv) uniform ARQ distribution. With uniform distribution, each link is first distributed with $\lfloor q_{sum}/N \rfloor$ ARQs, and the remaining ARQs are equally shared by the first $q_{sum} \bmod N$ links.	161

8.4	Comparison of list size between (i) exhaustive search in original PDP expression, p_d^f (in (8.1)), (ii) exhaustive search in approximated PDP expression, $\tilde{p}_d^f$ (in (8.6)), and (iii) the proposed FTML low-complexity algorithm (given in Algorithm 8) for CC-HARQ-FF based non-cumulative network.	162
8.5	Comparison of PDP for the CC-HARQ-FF based non-cumulative network and fully-cumulative network at various values of q_{sum}	163
8.6	Variation of average delay on the packets and the deadline violation parameter (η) for various τ_{NACK} in CC-HARQ-FF based strategies at SNR= 0 dB.	165
8.7	Simulation results on delay profiles (in %) for CC-HARQ-FF based strategies using a 5-hop network with $\mathbf{c} = [0.1, 0.5, 0.1, 0.3, 0.7]$ and $q_{sum} = 12$ at rate $R = 1$ and SNR= 5 dB with 10^6 packets wherein some packets are dropped either due to outage and some are dropped due to deadline violation (marked in the rectangle).	166
8.8	Illustration on PDV for non-cumulative and fully-cumulative network implementing the CC-HARQ-FF strategy for different τ_{NACK} and α values.	167

List of Tables

6.1	Binary sequence based PDP expression for $\tilde{N}$ -hop CSC network	100
9.1	Summary of various protocols presented in this thesis	173