A Study on the Context-Aware Green Information-Centric Networking Model for Future Wireless Communications

将来の無線通信に向けたコンテキストアウェアグリーン情報指向ネットワークのモデル化に関する研究

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Waseda University

Graduate School of Fundamental Science and Engineering

Department of Computer Science and Communications Engineering,

Research on Ubiquitous Communication System

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NGUYEN Ngoc Quang

Department of Computer Science and Communications Engineering

Graduate School of Fundamental Science and Engineering

Faculty of Science and Engineering, Waseda University

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Credits and Declaration

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Nevertheless, I claim that this dissertation contains research work that has not been submitted previously, in whole or in part, and is solely my original research, except where acknowledged. The research work presented in this dissertation was carried at SATO Wireless Communication Systems Laboratory (SATO Lab), Department of Computer Science and Communications Engineering, Waseda University.

Abstract

Information-Centric Networking (ICN) has drawn substantial consideration over the past few years because its appearance introduced a new promising Internet architecture by deploying extensive cache structure to distribute and deliver the named content objects. Typically, ICN aims to redesign the Internet by letting users interact directly with the content objects, instead of indirectly through the hosts with the requested data. Though ICN has been shown as a potential Future Internet (FI) architecture to replace end-to-end communications and solve current host-centric Internet problems, conventional ICN design still has its drawbacks. These include caching, routing, forwarding, mobility and especially energy-efficiency (EE) problem due to additional energy consumption for Content Routers' caching capability. Particularly, due to the in-network caching feature, ICN incurs an extra caching cost: every node in the ICN interconnections network has to consume additional power whenever content data are cached, including extra cost for cache storage. This function then discourages the feasibility of ICN implementation as the network infrastructure for FI.

In this dissertation, we study the use of *green networking* in ICN to address its feasibility challenge and energy flaw for efficient wireless content access. Our goal is to build a concrete model of highly efficient and scalable ICN-based wireless access network within the context of Green Networking. In fact, a large portion of the huge consumed power consumption from the network resource, as we find out, can be saved with almost no impact on the network performance of the ICN system. Thus, the proposed Green ICN model minimizes the overall power consumption of the ICN system through optimizing the needed network resource utilization for maximized power savings, despite the extra power for caching capability in ICN. Typically, we propose a novel *Green ICN model* to optimize ICN network resource utilization for minimizing the network system power consumption in the three following aspects: (1) We eliminate unnecessary power consumption by adapting power consumption of both

Content Routers (CRs) and *Content Providers (CPs)* to their optimized utilization level according to network traffic and content popularity; (2) figuring out that *in-network caching* in ICN can be exploited to leverage the CR's power saving via the reduced traffic, we further save power at each content node by proposing smart caching strategies for context-based wireless content accesses; and (3) we study a case-study on a *game-theoretical model* corresponding to the proposed Green ICN system to study the interaction between an ISP and a network equipment company and analyze their economic incentives for deploying the proposed system.

Firstly, we find out that the optimal network device utilization, i.e., the utilization required to distribute all requested content items at one content node, can be achieved by ensuring sufficient link rate for serving content with highest popularity level. We therefore propose the cross-layer probabilistic power adaption in ICN nodes which is conducted through dynamically adjusting the link-rate corresponding to content popularity and traffic load to reduce the wasteful energy consumption of CRs. We also introduce four customized working power modes for CPs and policy for selecting the best operating mode to diminish their power consumption according to the request traffic to CP. We then formulate the rigorous energy models of the proposal and existing network systems as a concrete *Green ICN prototype* for the feasible ICN infrastructure deployment.

Having optimized Green ICN model by mapping network devices' utilization to their power consumption over the whole network, we then aim to further diminish each content node power consumption through minimizing the network traffic load. Towards this end, we observe that in the IP-based network, i.e., with the absence of caching mechanism, a considerable amount of data is transmitted multiple time from the content provider to users. This mechanism definitely produces a high number of packets needed for data exchanges, then consumes higher bandwidth, and results in sub-optimal delivery with high traffic load. In-network caching, on the other hand, realizes a more efficient content delivery by eliminating the need for getting content from content source only. This feature shows a great potential of taking advantage of caching scheme in ICN to optimize a CR's operating power via the lower traffic load.

Based on this observed insight, we propose novel caching mechanisms to further optimize a CR's power gained from lower network traffic. Typically, we design different caching mechanisms to leverage the efficiency of the proposed Green ICN model for wireless content accesses in distinguished contexts. Our first caching approach is an innovative *proactive-caching* technique in ICN providing the robust and effective content delivery to the mobile nodes (commuters) for the transportation system. We take into consideration the fact that the number of mobile devices increases rapidly day by day as well as the public transportation (e.g. train, bus, etc.) becomes more popular nowadays. Besides, mobile users may ask for different content interests via the Internet during the period when they are on the public transport vehicle. We then propose a wireless communication topology in ICN for the *Intelligent Transport System (ITS)* by utilizing the *smart scheduling algorithm* with a proactive-caching based strategy to deal with possible and practical situations of commuters (mobile content users). In our scheme, the dedicated CP proactively sends appropriate segments of the requested content (based on the chunk-level structure of content) to expected proximity Aggregation content nodes located at neighbor stations (future attachment points) on the moving path of the public transportation vehicle. By doing so, this caching scheme substantially enhances the mobile user's quality of experience (QoE) and network performance in ICN. However, the proactive-caching based technique is limited to a small scale for the specific scenario of the transportation system, and we did not consider the general communication means of WLAN, a much more popular and among the most widely-used wireless network access schemes. To match the content demand in WLAN, we propose a smart popularity-based caching strategy, called *Distinguished Caching Scheme* (DCS), with the introduction of *hot and cold-caching partitions* of ICN node's cache storage for popular and non-popular content objects, respectively. DCS improves the content diversity of the cache storage by adjusting, for each content, the number of chunks to be cached at ICN nodes based on its type and popularity level. DCS thus can further decrease the network system power consumption, thanks to its improved cache hit that reduces network traffic load. Also, towards the goal of realizing a context-aware green wireless network system with efficient content delivery, we also design a *Wi-Fi Direct based scheme* as an alternative approach to minimize power consumption and latency by sharing essential/important content objects via direct communications with power-saving mechanisms in the case that WLAN connections are not available. The simplified caching policy in Wi-Fi Direct lets the peer choose the highest-priority content to cache (i.e., the less popular content items are less likely to be stored) due to the limited battery capacity of wireless devices as an effective way to optimize the network resource for prolonging network lifetime.

Given the network topology, the evaluation results using analytical energy models in several distinct scenarios show that the *Context-Aware Green ICN Model (CAGIM)* can improve network efficiency by reducing both hop-count and power consumption considerably compared to existing wireless network systems with different relevant well-known caching schemes. These results also demonstrate that substantial power of an ICN system can be saved by exploiting the in-network caching feature.

We also develop a *game-theoretical model* to study the simplified interaction between an ISP and a network equipment company in the context of green networking. Specifically, we present the system concept and some demonstration results of game-based Green ICN model to analyze the economic incentives of players. Evidently, the case-study on the game-theoretical approach confirms the effectiveness of our proposed Green ICN model which can achieve a significant amount of power while still realizing high network performance. Moreover, we discuss ICN deployment and standardization challenges, then show that the proposal is robust, easy to deploy and practically relevant for the network players.

In short, in this study, we address the EE issue in ICN in an actual and relevant manner from both research and application perspectives with combined techniques by

integrating CP's optimal operating mode, CR's adaptive link-rate mechanisms, and priority-based content caching scheme as a potential context-based hybrid wireless network. Therefore, by integrating Green networking into ICN for achieving highly scalable, reliable and energy-efficient network performance, this proposal enables a flexible and efficient content delivery mechanism for future networks with various real-life wireless content access scenarios. We believe our studies, which offer insights into the way *green networking* improves content delivery and optimize its resource consumption and implementation, will contribute to the understanding of the subject and promote a wider deployment of ICN towards the migration to sustainable green future network deployment for fast and efficient content distribution.

We conclude the dissertation with a promising outlook for extending our results to facilitate content distribution in *network slicing*, a new active research field which is anticipated to build the future networks.

Keywords: Green networking, Future Internet (FI), Information-Centric Networking (ICN), in-network caching, Dynamic Power Scaling, D2D content sharing, Adaptive Link Rate (ALR), game-theory, next-generation wireless communications, Intelligent Transport System (ITS), standardization.

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List of Acronyms

5G	Fifth-Generation
ACK	Acknowledgement
ALR	Adaptive Link Rate
CAGIM	Context-Aware Green ICN Model
CAPEX	CAPital EXpenditure
CCN	Content-Centric Networking
CDN	Content Delivery Network
CN	Content Node
CP	Content Provider
CR	Content Router
CS	Content Store
D2D	Device to Device
DCS	Distinguished Caching Scheme
DNS	Domain Name System
DONA	Data-Oriented Network Architecture
DoS	Denial of Service
EE	Energy Efficiency
FI	Future Internet
FIB	Forwarding Information Base
GNRS	Global Name Resolution Service
GUID	Global Unique Identifier
HD	High Definition
ICN	Information Centric Networking
ICS	Information and Communication System
ID	Identifier
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
i.i.d	independent and identically distributed
IoT	Internet of Things

IP	Internet Protocol
IRTF	Internet Research Task Force
ISP	Internet Service Provider
ITS	Intelligent Transport System
ITU	International Telecommunication Union
LPM	Longest Prefix Match
LRU	Least Recently Used
LTE	Long Term Evolution
NDN	Named Data Networking
ndnSIM	Named Data Networking Simulator
NetInf	Network of Information
ns-3	Network Simulator 3
NSF	National Science Foundation
P2P	Peer to Peer
PIT	Pending Interest Table
PKI	Public Key Infrastructure
PoA	Point of Attachment
PSI	Publish-Subscribe Internet
PSIRP	Publish-Subscribe Internet Routing Paradigm
PURSUIT	Publish Subscribe Internet Technology
QoS	Quality of Service
QoE	Quality of Experience
R&D	Research and Development
RN	Rendezvous Nodes
SAIL	Scalable and Adaptive Internet Solutions
SDN/NFV	Software Define Networking/Network Function Virtualization
SNS	Social Networking Service
TCP/IP	Transmission Control Protocol/Internet Protocol
UE	User Equipment
URL	Uniform Resource Locator
VoIP	Voice over IP
WLAN	Wireless Local Area Network

Chapter 1

Introduction

1.1 Dissertation Problem Statement

The Internet has become an essential infrastructure for our society since it plays an important part for all industries, economics and social activities of our daily lives. Current Internet architecture, which is introduced and appeared in the early 1970s, is based on The Internet Protocol suite, namely TCP/IP (Transmission Control Protocol/Internet Protocol). TCP/IP working principle focuses on resource sharing, network simplicity and speed by establishing the end-to-end communications between hosts for data transmission. However, the Internet has changed dramatically especially from the past decade, as content has taken the major part of today huge Internet traffic is from content-based services and applications. Specifically, we are now coping with Big Data issue, which is caused by numerous reasons, e.g., data generating from social media and social networking service (SNS) daily, mobile devices (location-tracking and pull-based services), scientific instruments for collecting, transmitting and processing data from satellites and Internet of Things (IoT) devices like sensors. In addition, in the near future, all the multimedia content exchanged via the Internet including video, audio, gaming or streaming will surpass our current standard Full HD (High Definition) or even the upcoming 4K resolution. Also, most of the software applications will become cloud-based services as almost every Internet user will store their data in the cloud. Hence, content access, especially in case of real-time access and high-resolution content, become a challenging issue of the existing host-to-host Internet architecture due to the bandwidth limitation and exponential growth of content demands. This issue gets more and more challenging since our current host-centric Internet suffers from various problems, including: security, content distribution, mobility and scalability.

These challenges raise the need for an Internet paradigm shift to match the key requirement of Future Internet (FI): from the host-centric network for remote resource accesses into the content-centric network for content accesses. To bridge the gap between current host-centric systems and actual content access demands, caching is an efficient methodology to improve network performance and currently utilized by Internet Service Providers (ISPs) through proxy-caches or Content Delivery Networks (CDNs). Although CDN improves content dissemination efficiency with lower latency by putting the content distribution function at the application layer, it is incomplete as CDN caches are simple caching solutions using small-scale distributed cache servers. In particular, CDN only enables persistent caches (CDN caches), not in-network caching where transient caches are promoted. Also, the caching elements in CDN are not exploited for content forwarding and routing process. Worse still, CDN caches endure high costs of resources (for bandwidth and storage), and their optimal geographical allocation requires a high degree of collaboration among ISPs corresponding to agreements with content providers, which make CDN undesirable for large-scale deployment. Peer-to-Peer (P2P) is another effort to match the new traffic tendency by enabling direct data transmission between the hosts in the network, namely peers, without the need for a central server. However, by promoting peers with roles of client and server at the same time for low latency, it is more difficult to coordinate the peer interconnections for data exchanges, compared to the host-to-host architecture.

Along this line, the appearance of Information-Centric Networking (ICN) [1][2] has drawn substantial considerations over the past few years as a promising FI design that matches the current huge generated content demands. ICN, equipped with in-network caching and name-based routing based on unique content name, provides considerable benefits over the current IP-based Internet which suffers from several serious problems regarding content dissemination, security, mobility support, and scalability. Firstly, ICN matches the Internet usage and content access pattern from user demands by focusing on the content name (What) rather than its location (Where), then ICN can utilize network resource more efficiently for content distributions, compared to current Internet design. Also, ICN realizes a more flexible forwarding scheme via its in-network caching implementation by deploying extensive cache structure and provides content security, not communication channel level as of IP-based network, which is very sensitive to Denial of Service (DoS) attacks from the malicious attackers. Particularly, different from IP-based networks where dedicated communication channel between two IP address of two hosts is maintained and secured, ICN aims to assure the integrity of content by securing content itself (i.e., built-in security measure). Sending malicious request packets to a host then becomes difficult because ICN cares only about content, not hosts. ICN guarantees whether a content is what it meant to be or not by offering each content a unique name (named content), instead of IP address in the TCP/IP architecture. ICN therefore can provide content users a new communication paradigm with higher reliability and effectiveness compared to the IP-based system as named content can be retrieved not only from the original source but also from caches via the content name look-up strategy. ICN also supports mobility better by maintaining connectivity regardless of their Point of Attachments (PoAs). Another critical issue of IP-based Internet is we are now facing with the fact that IPv4 address allocations are exhausting (due to the huge number of IP addresses needed to assign to the host network interface, given a rapid increase in mobile and wireless devices) while IPv6 address still has a long way to be adopted and implemented all over the world. These innovative working mechanisms make ICN become a pioneer for the FI architecture to solve the existing host-centric Internet serious problems of inefficiency and security.

Even though ICN is regarded as a promising global-scale FI (Future Internet) architecture, its in-network caching capability raises EE (Energy Efficiency) problems due to the additional power consumption required for the caching capability of content routers. However, there is not much work about EE in ICN, especially in the wireless environment. Currently, ICN concept [1][3] has been studied extensively, but most of the existing wireless ICN researches dealt with content consumers and publishers mobility, revealing that ICN has better support for mobility compared to the current IP-based Internet. Integrating Green Networking with ICN for the wireless access network, however, has not been received adequate exploration yet. The EE problem becomes more challenging with the rapid increase in price for energy consumption, number of broadband wireless network users, as well as growing demand of the content users in the future network. This issue emphasizes the need for a wireless energy-efficient ICN-based platform for future communications, given that energy consumption is a primary concern in the design of wireless communications for the future network [4].

1.2 Research motivation and Aims

In fact, little attention has been carried out to combine ICN concept and Green Networking, despite power consumption is a primary concern for the design and real-world deployment of future networks, due to its impact on economic and environment. Currently, the energy consumption of the Internet is estimated to be about 10% of total world energy, and this ratio keeps increasing as a tendency [5]. One of the primary reasons for the high network system power consumption is that a large amount of unnecessary power is consumed by unused network devices and links because existing Internet designs are typically over-provisioned for the worst cases, e.g., very high traffic load and fault protection cases. For instance, an AP (Access Point) normally operates with full power capacity though it can take up to hour-long idle times without traffic load in an enterprise wireless network [6]. This policy then produces a considerably unnecessary power consumption for redundant network resources as network nodes rarely operate at full-utilization. Worse still, as mentioned, in-network caching capability in ICN also raises new challenges, especially Energy Efficiency (EE) issue because caching itself introduces additional costs for both caching storage and power consumption. Specifically, if ICN operates in the same way as existing IP-based architecture, ICN approach will consume higher power for network deployment due to additional power for caching feature. These key challenges and significant facts motivate us to establish a common EE ICN-based platform for FI implementation, especially given that electricity prices, number of content users and growing demand of big-size content objects are increasing day by day.

Therefore, in this dissertation, we build an adaptive ICN model by jointly optimizing *Green Networking* and *caching strategy in ICN* to enhance the efficiency of access networks for FI. To realize a power-awareness system with practical significance, we propose a cross-layer network design approach to enable dynamic rate adaptation on a given link of a content node in ICN which matches network traffic and content demand according to the provisioned rate needed to serve different content popularity levels. This approach is feasible under a reasonable assumption that network devices consume less power when operating at lower rates. We also design CP's customized operating modes and propose optimal operating mode selection scheme according to traffic to each traffic to each CP to minimize its power consumption. Besides, as content caching also can reduce link utilization in ICN interconnections, we aim to build a dynamic provisioning approach which can minimize content node power consumption by proposing distinguished innovative caching policies in different wireless access contexts to improve cache diversity. In this way, the proposed Green ICN system lets the node operate with lower rate due to higher cache efficiency, then realizes high caching performance and low power consumption at the same time. We then establish a case-study on a *game-theory-based model* for the proposed Green ICN model to analyze the economic incentives for deploying the proposal. This approach shows that we can exploit in-network caching capability in ICN to further diminish the overall power consumption while still gain high network performance for content dissemination, despite the additional power required for caching capability in ICN.

1.3 Outline of the Proposed Approach and Contributions

Given that and EE is a key factor in designing a feasible new feasible networking model for future communications, we build an ICN model, namely *CAGIM* (*Context-Aware Green ICN Model*), which can provide highly energy-efficient content delivery with good network performances at the same time to realize ICN as a practical architecture for the future wireless access network deployment. Suppose that network devices can adapt their operating power consumption to link rate values (i.e., power-aware devices), CAGIM uses adaptive operating schemes for both content nodes and content providers to minimize power consumption of network system. Additionally, CAGIM employs a hybrid caching policy instead of ICN default caching scheme to reduce hop count in WLAN (Wireless Local Area Network). This caching scheme diminishes network traffic and workload in ICN, which in turn further reduces the network system power consumed by supporting power-aware network nodes. In case that WLAN is not available, we design a Wi-Fi Direct based D2D (Device to Device) communication which enables important content sharing to optimize power savings. We also design a proactive-caching based policy to efficiently transmit content data to wireless/mobile users in the specific case of Intelligent Transport System (ITS). We then present a simplified non-cooperative game in the proposed Green ICN model to study a case-study where the ISP is motivated to cache content and build network infrastructure for the goal of highly energy-efficient networks towards FI deployment.

The study is conducted in a comprehensive manner including the theoretical concepts and network definition, the proposed mathematical model for energy estimation, the description of the implementation algorithms and a case-study on game-theory based Green ICN framework, simulation setup, and results and discussion of the results. The detailed contributions of the proposal are six-fold as follows:

1- The proposal aims at EE issue in ICN in the context that energy efficiency has not been stated clearly in the current ICN standardization procedure of major international standardization bodies including: ITU, IETF and IRTF. As this issue is getting more critical in the era of IoT in the case of ICN due to the fact that ICN needs additional power consumption for caching energy, we propose novel solutions to minimize the power consumption of the entire ICN system infrastructure, instead of considering only a few network components. In particular, the system dynamically adapts all network links and nodes to optimized link rates and optimal operating mode, respectively to save unnecessary operating power while still ensuring full connections for effective content dissemination with adaptive network resource utilization;

2- We design a fault tolerance and dynamic wireless communication system via different network access technologies to realize a context-aware ICN system, in which the wireless devices can switch between different network interfaces corresponding to the requested content objects and current network status;

3- CAGIM utilizes widespread availability and recent advances in Wi-Fi technologies to save network system energy consumption and reduce hop counts from content users to the closest content source that matches user requests. Besides, the synergy of WLAN based ICN system and emerging Wi-Fi Direct D2D communications realizes a context-aware Green ICN model based on network status and content types to enhance the migration process feasibility and ubiquity of Next-Generation wireless communications in the Big Data era. This lays down the foundation of practical EE deployment for wireless communications to save expensive mobile data traffic through substantial lower data cost Wi-Fi enabled networks;

4- We build mathematical energy models for different wireless network systems including IP-based network, conventional ICN design, and CAGIM. We then demonstrate substantial energy savings of CAGIM over other network systems. Both analytical model and evaluation results through extensive simulations based on energy models of different network systems with various practical network scenarios demonstrate that our Green ICN model highly outperforms current Internet designs, in terms of EE performance and hop-count reduction. The results reveal the interesting effects of a caching scheme on overall network system power consumption: An efficient caching scheme can make ICN "greener" through the reduced network traffic. Thus, by studying the network performance in a power-saving ICN system, we revisit EE research in ICN under a new outlook: Delivering content efficiently in terms of both network caching performance and power saving.

5- We study a related case study to verify the impact of the proposed Green ICN model by utilizing Game theory as an efficient tool for analyzing the interactions between the ISPs and power-aware network equipment companies (manufacturer) as well as assessing their business decisions to realize a game-based technology innovation across energy area.

6- Thus, to the best of our knowledge, the proposal is the first approach which integrates both green networking techniques and content priority-based caching schemes as a potential hybrid wireless network approach to raise EE and provide wireless content-based services efficiently in ICN. Particularly, for EE design, while an efficient caching scheme diminishes the traffic load and server hit rate, the proposed rate adaptation mechanism matches the reduced link rate to power savings. Besides, the server takes advantages of efficient cache utilization from caching scheme to further reduce the server operating power for power saving via reduced traffic load. In other words, from an EE perspective, an efficient caching scheme can decrease network load and consequently enhances the power saving ratio of the network system.

The research then realizes an effective power-awareness Information and Communication System (ICS) design by enabling considerable network infrastructure system’s power saving and efficient content delivery at the same time utilizing power-awareness network devices with suitable simple working strategies.

Overall, the research work in this dissertation contributes to the new research field of green networks and information-centric networking with a new concept of adapting power consumption of the nodes through dynamically adjusting the link-rate according to the content type, popularity and the traffic demands. This concept is supported by an implementation of the smart context-based caching strategy. Although some problems/challenges remain, we believe the proposed CAGIM with an emphasis on EE design will shed new light on this new challenging research field towards a feasible next-generation Internet transformation for FI.

1.4 Dissertation Organization

In this dissertation, we apply the ideas of Green networking into in-network caching feature in ICN to deepen the understanding of Green network design concept toward FI, given that most of the current ICN work in the wireless environment do not consider EE problem and mainly deal with the mobility of content provider or consumer.

The dissertation consists of seven chapter and each of the major points mentioned in Contribution Section (Section 1.3) corresponds to one or two chapters of the Ph.D. dissertation. Typically, while this opening chapter presents the problem statement, our motivation towards designing an efficient green scalable FI for feasible next-generation communication deployment and the proposal contribution, the remaining parts of this dissertation are organized as follows:

Chapter 2 investigates the research background and surveys literature review on the new field of Green networking for the future Internet. The chapter firstly explains the fundamental concept of Green networking with Dynamic Power Scaling methods on a variety of greening methodologies, including sleeping mode, Adaptive Link Rate (ALR) and data center management scheme. Then, the ICN concept, its working mechanism, and various ICN platforms are indicated. Subsequently, the major challenges and research trends in ICN are analyzed, with a focus on recent research efforts addressed the EE issue in ICN.

Chapter 3 to Chapter 6 are the heart of this Ph.D. dissertation in which we elaborate overview of the fundamental framework of the Green ICN model (Chapter 3), the integration of the proposed model and caching scheme for efficient context-based content services in the application domains of ITS (Chapter 4) and scalable future wireless communications (Chapter 5), then verify the economic incentives for CAGIM deployment through a game-theoretical case-study approach in Chapter 6 (Figure1.1).

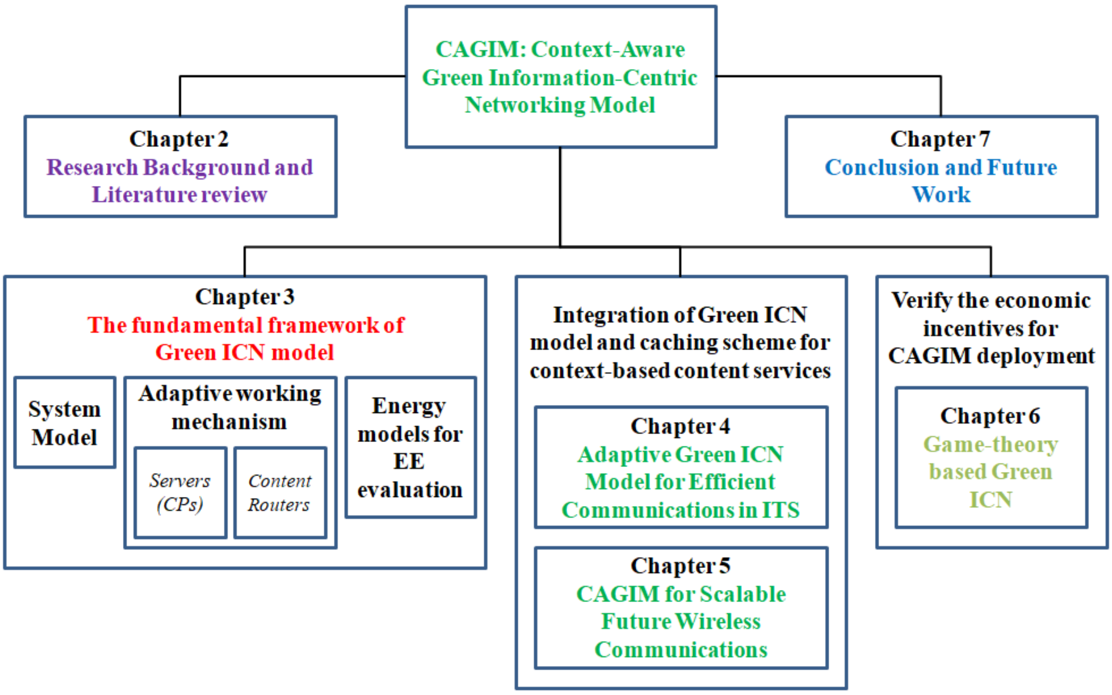

Figure1.1 Dissertation Organization

Chapter 3 gives an introduction to the general system concept and explains the working mechanism of the proposed Green ICN model. We define the system model and assumptions. Then, we use a cross-layer rate-adaptive scheme, and an optimized operating mode selection mechanism simultaneously for minimizing the power consumption from content routers (CRs), and content providers (CPs) in the ICN interconnections, respectively. By associating the power consumption of CRs and CPs with their operating mechanisms, we also build the analytical energy consumption models for EE evaluations of the proposed Green ICN model and other network designs (including conventional ICN design and existing IP-based architecture). This chapter is dedicated to lay down the foundation of optimizing the operating power consumed by both CPs and CRs so that the next chapters explain how this proposed Green ICN framework can be applied for efficient context-based content delivery in a wireless environment.

Chapter 4 extends the concept of the Green ICN model for the efficient communications in ITS. Typically, we apply the ALR-based operating for greening the communication in ITS. Also, we propose a new proactive-caching based communication protocol via the smart scheduler for seamless communications in ITS. The corresponding evaluation results based on the established energy model prove the efficiency of the proposed Green ICN system for ITS, in terms of both handover and EE performance (via analytical EE models).

Chapter 5 shows a scalable context-aware optimized Green ICN model (CAGIM) for feasible future wireless communications. We study the related ICN researches in a wireless environment and Wi-Fi technology with Wi-Fi Direct for Device to Device (D2D) Communications as the theoretical review to take the full advantages of the Green ICN model stated in Chapter 3. Specifically, besides the enhanced rate-adaptive operating scheme for CRs and the dynamic scheduling operating policy of CPs, we propose a smart popularity-based caching strategy (DCS) to improve the content diversity of the cache storage based on the content type and popularity level. DCS thus can further decrease the network system power consumption, thanks to its improved cache hit that reduces network traffic load. Toward the goal of realizing a context-aware green wireless network system with efficient content delivery, we also design a Wi-Fi Direct based scheme as an alternative approach to minimize power consumption and latency by sharing essential/important content objects via direct communications with a simplified priority-based caching scheme and power-saving mechanisms when wireless local area network (WLAN) connections are not available. The evaluation results corresponding to the enhanced mathematical energy models show that CAGIM can achieve high network efficiency by reducing both hop-count and power consumption considerably, compared to existing wireless network systems with different well-known caching schemes.

As a whole, **Chapter 6** discusses the need for an efficient Green ICN model for FI. We also develop a game-theoretical case-study on the proposed Green ICN model to study the interactions between an ISP and a network equipment company, then analyze the economic incentives of players for deploying the proposal in the context of green networking. Moreover, we discuss ICN deployment and standardization challenges, then show that the established game-theoretical Green ICN approach is robust, easy to deploy, and practically relevant for the network players.

The final chapter (**Chapter 7**) summarizes all the content and major findings of the previous chapters. Though the findings of the research reported in this dissertation are critical in this new challenging networking field, this in-depth study still has its limitation and several questions that remain unanswered. The final chapter then also gives suggestions to the potential relevant future studies in the field of Green networking towards sustainable and scalable efficient future networks, not only limited to the author but also to all researches and scholars with similar areas of research interest. This dissertation acts as a practical effort to pave the way towards the realization of efficient and scalable green communications through promoting and shifting research and development (R&D) activities in ICN towards the sustainable real-world network infrastructure (deployment) for future networks.

Chapter 2

Research Background and Literature Review

Chapter 2 gives a concise theoretical review on remarkable work in the new field of Green networking for efficient next-generation communications. Firstly, the chapter provides a brief overview of fundamental green networking concepts and their methodologies. We then focus on the ICN concept, working mechanism and different available ICN-based platforms. Also, we explain why Named Data Networking (NDN) would be a promising platform for FI implementation, and discuss some of the challenges and research trends in NDN.

2.1 Green Networking and Dynamic Power Scaling

Dynamic Power Scaling is a power management method in Green networking, which adjusts the link rate or network node operation to match traffic load for maximizing power saving. One of the most notable approaches to Dynamic Power Scaling is Adaptive Link Rate (ALR) technique [7]. ALR mechanism follows the energy-proportional computing paradigm [8] to save the network devices power via link rate scaling. In particular, ALR dynamically adapts the link-rate to network utilization to save energy consumption of the power-aware network devices. Under the reasonable assumption that network devices consume less power when operating at a lower rate, the ALR mechanism allows network device components to operate at a lower clock rate to save power consumption. This method is efficient because the network devices are provisioned and designed to operate at their maximum capability regardless of the network traffic load, i.e., the content nodes' average traffic is much less than their actual power capacity. In fact, in a conventional network system without ALR feature, network nodes still work with high and almost constant power consumption which is typically far larger than the necessary operating power for network utilization on average. Hence, ALR is one of the research themes which draws most of the attention in greening network to reduce the energy consumption of network devices. Nedevschi et al. [9] utilized two power management approaches (rate-adaptivity and sleeping) to save network power consumption by considering power profile of network devices and network traffic. A real-time hardware-prototype ALR system is implemented and analyzed in [10] as a practical way to evaluate the real-time performance of ALR, instead of simulation. Also, a detailed survey of various Green communication applying ALR mechanism was presented in [11]. Even though currently, the primary application of ALR is in the IP-based network, we find such an innovative mechanism beneficial for FI architecture to reduce the energy consumption of network nodes by matching their link loads to the actual network utilization for our Green ICN model. Particularly, since the power consumption of network system can be taken as a function of network link load, adapting network links to a rate which is proportional to the content interest traffic can save a considerable amount of energy from network devices.

Low Power Idle (LPI) is another Dynamic Power scaling strategy which allows the network devices (nodes and storage servers) to enter low-power states when not transmitting or transmitting less than a specified threshold number of packets. The network devices in LPI mode then can quickly switch to the high-power mode or full power mode to transmit data when (sufficient) packets arrive at the node for EE purpose. For example, a simple model of multi-core server system was stated for power consumption estimation [12]. Additionally, Intel Corporation showed that the threshold value (upper bound) of a server power consumption could be set [13]. However, power management for the server is a feature which is usually disabled because it may cause inconvenience for the network administrators. Also, regarding the network power consumption approaches, a number of works proposed power consumption model of storage server system then discuss some mechanisms that can be applied for enhancing network energy efficiency [14][15].

Note that LPI mode is different from Sleep mode, which is another greening method [16-18]. The reason is that Sleep state can be maintained with very low power but the system needs to provide considerable power to "wake" the node up for data transmission (i.e., resume to the active state). The authors in [19] stated a combination of two greening approaches (rate-adaptivity and power-aware routing) to save network power consumption by giving a simple model of power used based on two kinds of link state (on and off). A survey of various optimizing link reconfigurations was presented in [20]. Nedevschi et al., [9] presented both of rate-adaptation (ALR) and sleeping as an approach for reducing the energy consumption. They compared the performance of these two forms with different values of network utilization and showed that both are efficient schemes to deal with energy consumption issue. In addition, various popular methods of green networking for FI are introduced and stated in [21].

As ALR and LPI state are not exclusive and can be jointly adopted, in this study, we consider these two main approaches in Green networking for our Green ICN model with the hybrid concept of ALR and operating mode control function utilizing LPI mechanism. In this way, we aim to design the adaptive solutions for both server (content provider) and content routers as an efficient solution to optimize the energy consumption of ICN utilizing the suitable network devices and components: ICN content routers support ALR technique and servers allow network managers to set the threshold value (upper limit) of power consumption. However, in our proposal, we do not consider the sleep mode because it is difficult to estimate the energy efficiency of the sleeping mode during the transition time and "wake-up" periods. Worse still, the sleep mode endures undesired high latency, which does not match the requirement for increasing demands of real-time services in next-generation communications.

2.2 Introduction to Information-Centric Networking (ICN)

2.2.1 Introduction to ICN and its key features

Nowadays, as Internet use has evolved substantially since the IP-based network was designed, the Internet is shifting from host-centric to content-centric model to match the huge content-oriented demand from network users. In this context, Information-Centric Networking (ICN) concept [1][2] has introduced a new promising Internet architecture built on named data instead of named host to solve the current host-centric Internet's severe problems of security and inefficiencies in content delivery. In detail, ICN focuses on name-based routing and in-network caching for content delivery efficiency to reduces response time, traffic load, and network resource usage, compared to the current host-centric Internet because requested content data can be accessed from a replica instead of the only content source as in current IP-based Internet architecture. The innovative working mechanisms and ICN's merits then make it become a pioneer for the Future Internet (FI) architecture in the era of the Internet of Things (IoT) where the Internet is mostly used to access content. Thus, ICN has become a "hot" research topic with lots of proposals recently.

ICN with its full features and architectural design towards data-oriented communications, where content as the first-class entity in the network, was firstly proposed by V. Jacobson [1][22]. In ICN interconnections, each content object has its unique location-independent name. In addition, content can have a flat or hierarchical naming structure. The hierarchical naming structure is similar to Uniform Resource Locators (URLs) or Domain Name System (DNS) namespace while a flat name is represented by a human-unreadable string. The benefit of using a hierarchical naming scheme is that content name is readable. Also, content can be segmented and updated easily by content producers with the segment and optional update version of content.

On the other hand, flat name systems enable self-certifying content objects. Routing in ICN is also based on content name with two main approaches: through name resolution system (NRS) with signaling messages from a content producer with the information of content availability, or directly via name-based routing (longest prefix match LPM) without the need of resolving content names to their locators. The data delivery in ICN is conducted at a chunk-by-chunk level where a content is split into multiple same sized chunks and a chunk is the data transmission unit. ICN then has an hourglass design with content chunk layer as its "narrow waist" (Figure 2.1) in which ICN aims to create and validate the content chunks in the protocol stack. This design aims to exploit multiple simultaneous connectivities for data delivery (e.g., LTE, Wi-Fi, Ethernet) due to ICN simpler interaction with layer two, compared to the current IP-based Internet.

Moreover, ICN realizes in-network caching mechanism so that a content can be stored in different content nodes in the network. Note that in-network caching in ICN is different from that of Web caching or CDN deployments as any node in ICN interconnection can be a cache. Therefore, ICN realizes a ubiquitous and transparent cache implementation. However, each ICN node only has limited cache storage, then once a content cache memory gets full, a replacement/eviction policy is performed to store the new item in place of the old item. The default replacement policy in ICN is the well-known Least Recently Used (LRU) strategy. Regarding mobility, when a content user (consumer) moves, he/she only needs to re-issue the content request from the new location so that the packets will be redirected hop-by-hop corresponding to the routing information of ICN nodes. Better still, as a content in ICN is location-independent, even when the content producer moves to a new location, it is still reachable. As a result, ICN supports producer mobility.

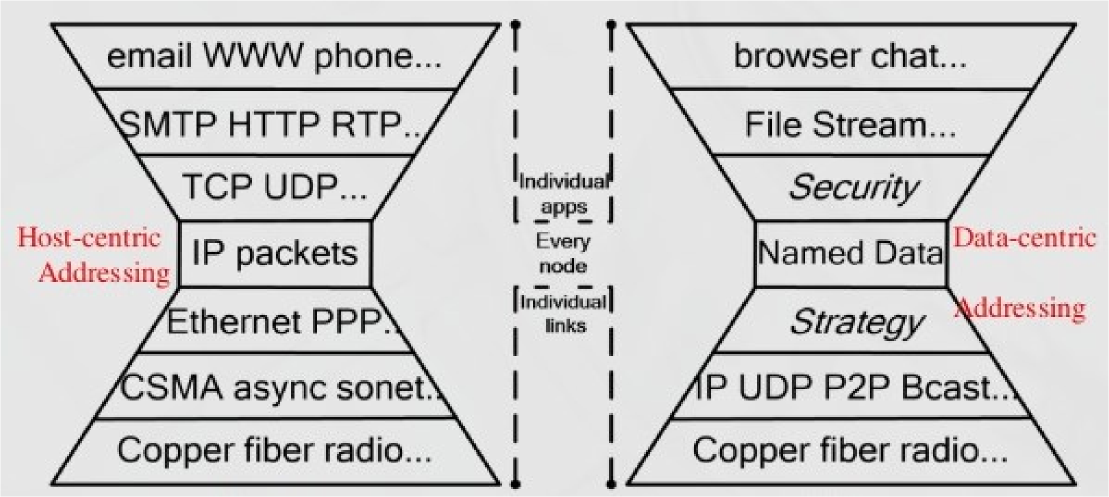

Figure 2.1 ICN Hourglass Architecture with Content Chunks acted as "narrow waist" (evolved from current host-centric Internet) [1]

Currently, name-based routing scheme, forwarding, and especially caching strategies are driving the ICN research direction as they are the key to diminish the backbone bandwidth and improve network performance for high content delivery efficiency. In fact, the default cache placement policy of ICN, Leave Copy Everywhere (LCE), is highly inefficient because it caches whole data of all content items in all the (intermediate) CNs along the delivery path. To solve the high cache redundancy issue in LCE, Psaras et al., proposed ProbCache [23], which caches content probabilistically corresponding to distance to server and cache availability of CNs along the retrieval path. WAVE [24], a popularity-based chunk-level caching strategy, populates the chunks exponentially from the edge node to downstream nodes along the path. However, as the foremost part of the content is stored at the edge side, WAVE causes a higher latency for the user, even there is a cache hit in ICN. The authors in [25] proposed Fine-Grained Popularity-based Caching Design for Content-Centric Networking (FGPC), which keeps the most popular content in the cache storage and Dynamic-FGPC (D-FGPC) with content popularity threshold for higher stability in hit rate performance.

2.2.2 Various ICN platforms and the selection of NDN for implementing the proposal

Since ICN has been getting growing attention in the recent years, there are various ICN-based platforms and projects towards Future Internet (FI) design have been proposed since 2007. All of them utilize the concept of ICN to realize its innovative working mechanism for FI, and we summarize the most notable work in this Section.

Data-Oriented Network Architecture (DONA) [26] is one of the earliest ICN-based network design (introduced in 2007) with name resolution for persistent content access and on-path caching. A content object in DONA is published by the source (publisher). Each content has a flat and self-certifying name built by concatenating a hash value of a registered content publisher and a label selected by the publisher. Thus, the consumers receive the Data packet with the public key of the publisher and signature of the data that match the requested content.

Pursuing a Publish Subscribe Internet Technology (PURSUIT) [27] architecture, a notable FP7 EU project, is a publish-subscribe communication model which inherits from the former project Publish-Subscribe Internet Routing Paradigm (PSIRP) project [28]. PURSUIT utilizes the Publish-Subscribe Internet (PSI) model with forwarding identifier for routing. This architecture aims to provide layered content access control using the rendezvous nodes (RNs): The publisher sends a Publish message to its RNs to inform content with flat-name. PURSUIT supports security via self-certifying names and mobility through the exchanged messages between publishers and subscribers, even when they change their current locations.

Network of Information (NetInf) [29] is a notable proposal from Scalable and Adaptive Internet Solutions (SAIL) project. NetInf is also based on the PSI model and implements flat-name content with self-certified names as of PURSUIT. NetInf supports both of subscribers and producers mobility. However, the routing process can be performed based on either name-based routing or name resolution approach. To maintain host-independent communications and reduce undesired traffic, the content delivery in NetInf is only performed via the involved content routers.

NDN, stands for Named Data Networking [30][31], is a major project under the US NSF Future Internet Architecture program, which continues from Content-Centric Networking (CCN) [3] architectural design proposed at PARC by V. Jacobson. NDN deals with un-fulfillable high volume traffic usage in current host-to-host Internet architecture by focusing on name-based routing for content retrieval without caring where content is located. NDN is a pioneering ICN platform with forwarding engine which motivates hop-by-hop routing based on hierarchical and human-readable content name.

Mobility First [32] is another ICN-based notable work introduced by NSF Future Internet Architecture program, which aims to deal with the mobility problem. Mobility First addresses content and entire network mobility through the Global Name Resolution Service (GNRS). Each content object is identified by a Global Unique Identifier (GUID), which is a flat and self-certifying name. GNRS uses GUID to update content address and handle mobility by updating its entries when an object changes current location (PoA). The data packets are also transmitted along the reverse path to content requester as of NDN.

Though there are various ICN-based projects as mentioned, our Green ICN model is mainly based on NDN since NDN is an ICN prototype which provides a scalable solution to high volume network traffic for the content demand of future communications. The reason is that NDN is the only design which offers the backward-compatible capability with existing IP-based network infrastructures [3][31], instead of proposing a clean-slate FI architecture. As it is difficult to substitute the whole Global IP address in the existing Internet architecture, clean-slate ICN-based approaches are undesirable and hardly deployable for FI in reality, and we consider an overlay NDN-based network design is a well-suited extensible network framework for a practical incremental implementation over IP. For flow control, NDN also only returns at most one Data packet for an Interest packet to control flow and reduce congestion rate. Also, a hierarchical naming structure in NDN enables packet aggregation and network scalability. However, note that the proposal is not limited to NDN and can be applied to any ICN platforms for the large-scale network system.

2.2.3 NDN working mechanism

NDN has two types of packets: A consumer broadcasts *Interest* packet for requesting a desired content to its nearby content nodes (i.e., in the consumer's proximity range for communications), and an appropriate node with the requested content data will respond by sending back the *Data* packets to the consumer in the reversed direction (as of corresponding Interest packet, via corresponding network interfaces) to the original requester for content retrieval. Interest packet includes a content name as a unique identifier for requesting the desired data and is defined by the hierarchical naming structure to enable high aggregation and scalability. Interest then can be considered as HTTP get packet (the content request packet) while Data packet is similar to HTTP response which brings requested data back to the user in existing Internet design. Each content is split into chunks identified by content name and its sequence number, and a chunk is also the data transmission unit in ICN. The packets in NDN is routed based on content name longest-prefix match and the Data packet shares the same content name as of Interest packet and includes the corresponding requested chunk of that content. Hence, one Interest packet is satisfied by one Data packet with the same content name as a response to the user's desired content request. The structure of Interest packet and Data packet are shown in Figure 2.2 [3].

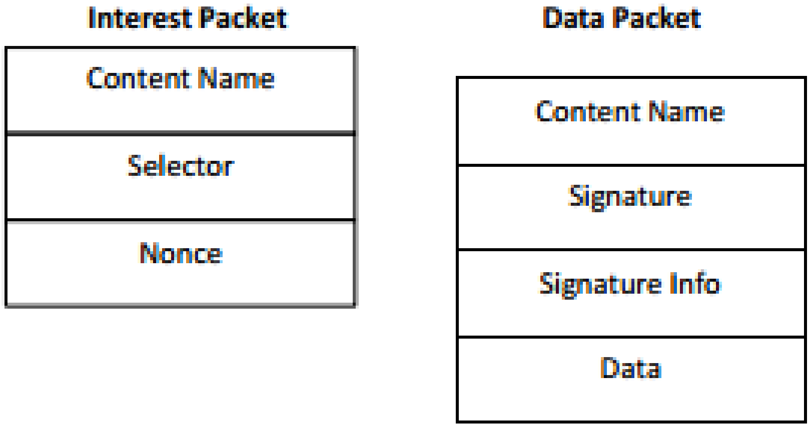

Figure 2. 2 Structure of Interest packet and Data packet in NDN [3]

There are three types of data structures defined in NDN, namely Content Store (CS), Pending Interest Table (PIT), and Forwarding Information Base (FIB) for packet forwarding [3]. CS, PIT, and FIB have different dedicated functions as their names' implication and they are responsible for the basic operations in NDN. CS is a buffer for caching content items (in the form of Data packets) to improve the content delivery performance via cache storages in ICN interconnections. PIT maintains the information of the requested Interest by recording Face (network interface) of the packet. Then, entries in the PIT are used by Data packet to trace the return path (reverse direction as of Interest packet) with the Face it should be sent through for the content retrieval process. FIB works as a routing table which allows multiple output faces to keep the name prefix along with next hop information.

The detailed operation of the NDN packet forwarding procedure includes the following steps:

1 - A content user sends an Interest packet for requesting a specific content.

2- A Content Router (CR) receives an Interest packet and checks whether its CS contains data matched the requested content name or not. If a cache hit happens, i.e., the requested content is found in CS, the router consumes the Interest and returns the requested Data packet. Otherwise, the CRs checks it PIT entries.

3- If a matched entry (incoming face with matching content name) is found in the PIT, the Interest is discarded and the packet is forwarded to the incoming face listed in PIT entry. If the incoming face is not found in the PIT, the incoming face is added to the PIT entry (Requesting face list) and moved towards FIB.

4- The Interest is then forwarded based on information in FIB: If CR finds a matching prefix in its FIB, the Interest is forwarded to next hop using the face in the matching entry of FIB.

5- If matching data is responded from a content node in ICN, Data packets are delivered via the corresponding interfaces according to the entry in the PIT and they are also cached in CS to serve the same requests in the future. Data packets then can be delivered via the same path of Interest packet in the reversed direction based on PIT's registered entry information. Note that the duplicate and unsolicited Data packets are discarded and there is no routing or control traffic associated with the replicas.

NDN realizes multi-cast feature in which if the same content chunks are requested (from different clients) as PIT can identify and aggregate multiple requests of the same content then forward them as a single Interest packet. In detail, only one Interest will be forwarded upstream with only one entry is added into the PIT which records all the faces (network interfaces) along the path that the chunk data need to be gone through to respond user requests. By combining multiple Interests for the same content, NDN can limit the forwarding of unsuccessful Interests. NDN mechanism then targets to minimized bandwidth usage and average latency.

Also, NDN redirects the content request to the best interface with the longest match prefix (LPM). Typically, the hierarchical structure is used to perform the longest-match lookups and each node has sufficient 'knowledge' to select the best faces for forwarding Interests corresponding to the matching prefix. Also, Within a CS of a CR, content chunks are cached and replaced by Least Recently Used (LRU), by default. The hierarchical and human-readable naming scheme in NDN and its binary encoding format are illustrated in Figure 2.3 [3].

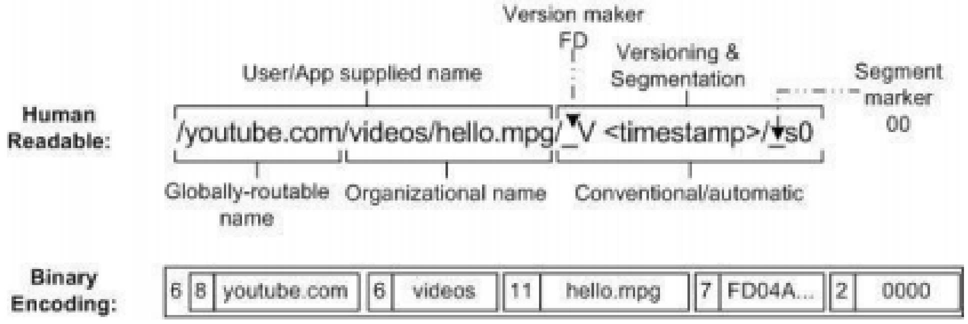

Figure 2. 3 The Hierarchical and Human-Readable Naming Scheme with Binary Encoding Format in NDN [3]

Different from data transmission process in IP-based networks, when a user accesses a content, its data packets are cached in CS of all CRs in NDN along the transmission path for fast content dissemination. In this way, if the same content is requested by other users later, data can be served from the nearest cache with the corresponding content data (either original content producer or content nodes with a replicated copy in CS). Thus, the content delivery gets faster than accessing from original content source as of IP-based model because a content is not limited to a specific location, thanks to the in-network caching capability of ICN nodes. This also makes content would be active through dynamic content generation, rather than static as of CDN cache or Web caching because content can be selected for caching based on context. The basic function of NDN content delivery in NDN and typical corresponding data structures of these three components (CS, PIT and FIB) are depicted in Figure 2.4 and Figure 2.5, respectively (referred to [3]).

For security measure, Data packets in NDN have a signature field to and the publisher public key as metadata to verify the content integrity (built-in Data packet security). Particularly, NDN authenticates the name-content mapping by signing the name and content in each Data packet, i.e., Data packet is authenticated with a digital signature [3]. As only one Data packet is forwarded for each Interest, DoS attacks are also extremely difficult to be done. NDN supports consumer mobility by sending Interest packets from current consumer location but for producer mobility, all FIBs of content nodes should be updated to ensure the seamless connectivity but this process can be alleviated by in-network caching feature of ICN.

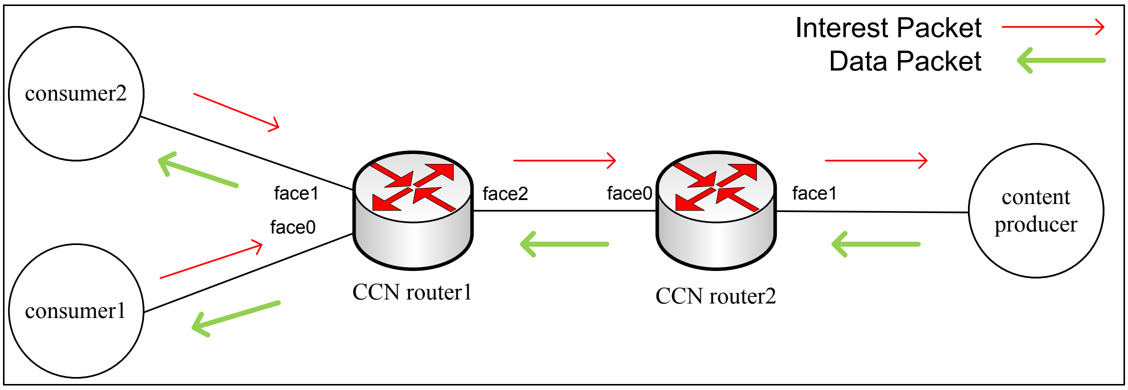

Figure 2.4 Content Delivery Function in NDN

2.2.4 Major challenges and research trends in NDN

Although NDN enables a simple, robust, and flexible network architecture which matches today’s communication problems and application demand patterns, many interesting challenges in NDN remain to be tackled, including:

a) Naming: Since NDN uses name as the identifier of a content for routing and forwarding decision, the naming scheme is considered as one of the most critical keys in NDN. In fact, the research related to the naming scheme is still under active in NDN and the major concerns include how to make naming structure consisting of multiple components comply with existing standards and how to build an efficient hierarchical naming structure in NDN. The reason is that the hierarchical content names have a flexible format with no universal naming rules, in terms of both syntax and semantics

Content Store of Router 1

Content Name	Data
/waseda.jp/fse/csce/SATO_lab/GreenICN.ppt/_ver3/_s1	...

Pending Interest Table of NDN Router1

Content Name	Incoming Faces
/waseda.jp/fse/csce/SATO_lab/GreenICN.ppt/_ver3/_s1	0,1

FIB of NDN Router1

Prefix	Face list
/waseda.jp	2

Figure 2.5 Data Structures of the three Fundamental Components in an NDN router

b) Caching: In-network caching is the key to high network performance in NDN. Thus, caching management and replacement strategies, incorporated by the in-network caching deployment in CS of CRs, are significant to improve the NDN scalability, especially in case of real-time and interactive content demand traffic.

c) Routing: NDN implements name-based routing in which each content is divided into chunks and each chunk is given a name in the form of content name concatenated with the chunk sequence number of the content. Currently, there is no limitation for content namespace length, therefore, maintaining the routing table size and updating the routing information for huge data traffic in the Big Data era are challenging problems to enable efficient global-scale content-centric networks for FI.

d) Security: NDN has built-in content-based security and Data packet has digital signature assigned by Public Key Infrastructure (PKI) with the association of content namespace using the public key for security in NDN as shown in Figure 2.6 [3]. Hence, the effective security key management validation of user authentication are key challenges to guarantee the content confidentiality and security measure in NDN.

e) Mobility support: NDN has better mobility support especially for consumer mobility, compared to host-to-host based network because the content can be found en-route even after the hand-off. Particularly, NDN handles mobility more efficiently as the mobile node can change its PoA and still maintain the consistent name. However, achieving seamless content retrieval with the smooth connection, and handling producer mobility with quick handover are still big challenges for research of NDN mobility.

f) Energy-efficiency (EE): In general, ICN consumes a higher amount of power consumption compared to the IP-based network due to extra power for CR's caching capability. Thus, EE is also a crucial factor for the feasibility of ICN in general and NDN in particular for the FI.

In this study, we take a comprehensive study of both EE and caching mechanism in ICN (NDN platform) to bridge ICN and Green networking (particularly dynamic power scaling scheme) for the objective of deployable and highly efficient ICN design. This approach is reasonable since in-network caching is a power consuming technique due to additional power consumption for caching. A survey of preliminary EE caching scheme in ICN is presented in [33].

Figure 2.6 Signature field of Data Packet in NDN [3]

2.3 Summary

This chapter summarizes the core concepts and major related work of green networking, ICN and preliminary research work in greening ICN for future internet. We present a brief survey of green networking. Next, we introduce ICN and its key features. We then discuss why ICN is among the most promising approaches for FI through its functionalities and review some notable work in ICN. We also demonstrate that NDN would be the most suitable ICN platform which efficiently tackles current network limitation for data dissemination.

Chapter 3

The Proposed Cross-Layer Green ICN Model

In this chapter, we first discuss the network topology and system model used in our Green ICN model. Next, we design the cross-layer rate adaptation which adjusts the CR (Content Router) link rate to the optimized provisioning values corresponding to the network traffic and popularity levels of content demand. We also propose different customized operating modes for a server/CP (Content Provider) and dynamically select its optimal operating mode according to the Interest traffic. These two dynamic operating strategies are conducted since we realized that CR power corresponding to link rate and CP operating power are two feasible power elements which we can utilize to optimize the overall ICN system power consumption. Then we build the probabilistic energy models of the proposal and other existing Internet designs to evaluate their EE performance. This chapter serves as the introduction to the proposed Green ICN model principle for the dynamic operating mechanism of both CRs and CPs in the ICN system. Also, this chapter introduces the fundamental notations used in this study and concept of power saving ratio of CRs as this concept lays down the fundamental of the proposed Green ICN model which will be further improved to achieve substantial power savings corresponding to the context in the next chapters.

This chapter is based on our previous research paper: **Quang N. Nguyen**, Arifuzzaman. M, T. Miyamoto, and Sato Takuro, "An optimal Information Centric Networking model for the future green network," IEEE 12th International Symposium on Autonomous Decentralized System ISADS 2015, Taichung, Taiwan, March 2015 [34].

3.1 Network Topology, System Model and Assumptions

As hierarchical cache system is a commonly-used system model in ICN studies [35][36] to make the popular content objects/services/applications scalable, we propose a generic multi-layers network topology including of a cluster of M servers and N distinct routers. Each server is a CP which stores a part of available content objects.

In more detail, the network has (L+1) levels with the cluster of servers (CPs) which acts as the root node (level L+1), and all other Content Routers (CRs) are allocated into other levels of the topology as intermediate nodes. Specifically, the nodes at level L are (highest-level) CRs with maximum hop count from users whereas the level-1 CRs are directly connected to the content users as shown in Figure 3.1 (referred to [34]). The level of CN is then set based on the number of hops from the consumer. This network model realizes various dynamic hierarchical network topologies where the core CRs attached to the CP whereas each user is associated with a specified leaf node at level one (edge CR). This network model is flexible for operator and service provider by allowing them to investigate and manage data traffic at different levels of network topology (cache hierarchies). The hierarchical cache system with multiple layer caches also decreases the traffic consumed by original content providers, transportation cost and latency/response time by serving content as close to the user as possible via an appropriate cache within the hierarchy.

The user can send content requests (Interest packets) from the connected first-level CR to the closest CR at a higher level. In this ICN system, all the routers involved in the transmission process of a content (i.e., content nodes along the delivery path) will cache the content so that subsequently, if the same content is requested, it will be served by the closest ICN CRs with the requested data. Hence, a content object which is the original content (from content producer/provider) or a replica of desired content can be found at numerous levels (by in-network caching policy) via the wired connection. A request which cannot be served by a cache hit from CS (Cache storage) of CR is forwarded to next higher level of network topology, and in the worst case, the content request reaches the content source as in IP-based network. Thus, the more popular content objects are expected to be at the edge CRs (close to users) whereas the less/non-popular content objects are cached on CRs near to the CP.

We assume that the ICN system consists of different content c and all the requests are independent and identically distributed (i.i.d) within the set of all available content objects C (i.e., $c \in C$). Each CR has additional cache storage (CS) for caching content items and let S be the cache size of each CN, and all CNs share the same caching capacity. We suppose that each user wants to access to data via only one CN at a time and the communication delay between end-user and respective CR is negligible.

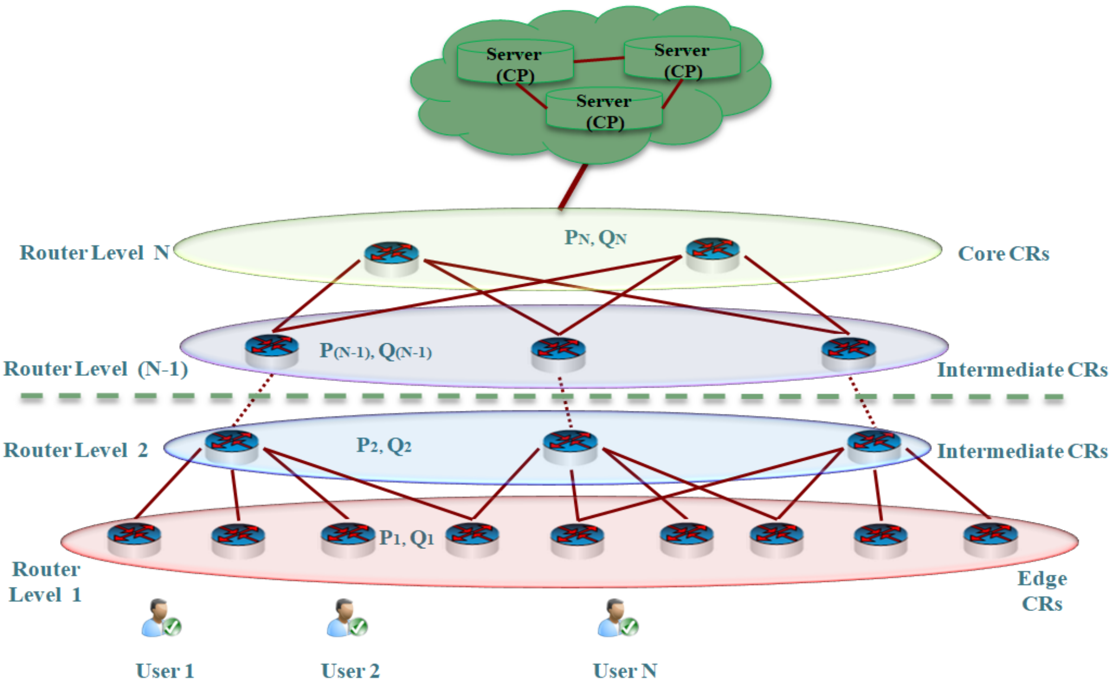

Figure 3.1 Network Topology for the Proposed Green ICN System

Although we present a simplified multi-tier model, this model can be applied to any realistic general/mixed topology in which a content node level can be identified and the access nodes locate at the first level of the network. Various scenarios with different topologies are discussed and evaluated in Chapter 4 and Chapter 5, suppose that the lower level nodes refer to CRs closer to the user along the delivery path for multi − hop content delivery.

This section describes the network topology and assumptions to provide the necessary background for the adaptive working mechanism and energy models of the proposed Green ICN system which are clarified later in this chapter. Also, for convenience, we use the terms node and router (CN and CR), server and CP interchangeably in this dissertation.

3.2 Cross-Layer Rate-Adaptive Scheme for Content Routers (CRs)

We assume that all ICN CRs in the proposal are equipped with ALR technique, i.e., the system utilizes power-aware network devices which can adjust the operating rate of the associated link according to the optimized utilization. This assumption follows the idea of power-proportional networking in which power consumption of a network node is proportional to the utilization of network interface links. Then we determine dynamic CRs working scheme to make content nodes' operating link rates sensitive to the network traffic based on content popularity for the goal of enabling power savings.

For this goal, we define p_l as the probability that one content user can find a specific content c (c $\in$ C) at a CR level l, under assumption that every CR at the same level of the tree network topology share the same value of p_l (given that the content requests generated by all users are homogeneous). Note that the popularity level of a content is identified according to the number of requests from the users for the content during a (fixed) period (i.e., based on the content popularity distribution model).

In the proposed ICN tree topology, the more popular content is, the higher chance a user can find it in CR at low levels because it is replicated more frequently compared to non-popular one. In other words, the popular contents would have a higher value of

p_1 than the unpopular contents. This tendency reflects the ICN feature which spreads the popular content objects and pushes the most important ones to the network edge. Since p_1 can be considered as an indicator of content popularity level, we denote T_p as the threshold value of p_1 to abstract two distinguished types of content as follows: If a single content has $p_1 \geq T_p$ then it is popular content. Otherwise, it is identified as an un-popular content. Note that similar to p_1, all CRs share the same value of T_p for the corresponding contents. Then, in ICN, for a content c $\in$ C, we have:

$$\sum_{k=1}^{N+1} p_k = 1. \tag{3.1}$$

In contrast, in the case of current IP-based Internet architecture, we can infer that $p_k = 0 \; \forall k$ in the range of [0, L] and $p_{L+1} = 1$ because different from ICN design, the only way to get a content data is sending the request to the server via the routers.

Next, let Q_l be the probability that a content user traverses l-hops (or 'climb up' l levels, where l ≥ 1) of the tree topology to find an interested content c $\in$ C, then Q_l can be defined as:

$$Q_l \; = \; p_{l+1} \; \prod_{k=1}^{l} (1 - \; p_k). \tag{3.2}$$

Hence, each time the Interest packet is forwarded to the next hop at the higher level, the user has a higher chance to find the interested data of CNs in ICN interconnections because of the cumulative probability increment. Similar to p_k, the number of levels (hops) that content user traverse is expected to be lower with more popular content.

We then adapt the operating power of an ICN CR to its optimized utilization by adjusting the CR's correspondent link rate according to the popularity of the contents that the CR serves. Let R_l be the incoming link rate to level-l CR for a content c $\in$ C and R_{ICN} be the link rate of a CR in Conventional ICN model. Since a popular content has a higher chance to be found at the first levels, we set the maximum link rate for the level 1 CRs as in the case of Conventional ICN. Then R_l, where l > 1 will adapt to the operating link utilization of ICN node based on the value of R_l and popularity level of all interests for different content c ∈ C come to the CR, i.e.,:

$$\begin{cases} R_1 = R_{ICN} \\ R_1 > R_l \ \ (1 < l \ \leq L) \end{cases} . \tag{3.3}$$

In ICN, the number of hops that a user needs to traverse to reach a CR with requested content would decrease as the content gets higher popularity. Hence, for efficient dynamic rate adaptation in ICN, the accumulative required link rate for serving a popular content should be higher than that of the unpopular ones so that a higher number of Interest packets can be satisfied locally. In fact, a popular content is requested much more compared to non-popular content items and most popular ones can produce a large amount of network traffic. Also, the edge routers and lower-level CRs should work with higher rates than the CRs at higher since in-network caching mechanism is pushing popular content objects closer to the user at the edge side.

Let β be the energy-efficiency index of network equipment (CRs). Specifically, $0 \leq \beta \leq 1$ and $\beta = 1$ implies the ideal case when the network devices are fully supported ALR function. Considering the case when a single or multiple interests come to a router level l but only ask for a single popular content c ∈ C, then the new optimized value for R_l (with ALR-support CR) is:

$$New\ R_l \ = \ (1 - \ \beta)R_{ICN} + \ \beta \, \{ \, R_{ICN} \ \ [1 - (p_1 + \textstyle\sum_{k=1}^{l-2} Q_k)]\} \, , \tag{3.4}$$

and

$$New\ R_l \ = \ (1 - \ \beta)R_{ICN} + \ \beta \, \left\{ R_{ICN} \ \frac{p_1}{T_P} \left[1 - (p_1 + \textstyle\sum_{k=1}^{l-2} Q_k)\right]\right\}, \tag{3.5}$$

in the case that CR at level l only receives request(s) for a single non-popular content. The first term in (3.4) and (3.5) returns the ratio of CNs which does not support the ALR function. Also, the expression $[1 - (p_1 + \sum_{k=1}^{l-2} Q_k)]$ indicates the scale-down link rate ratio of a CN at level k for transmitting a single content c with the proposed ALR function.

Let S_l be the set of contents come to a level l CR. As distinct content objects may have different popularity levels, without loss of generality, the optimized value of R_l for a level l-ICN router, namely *Optimized* R_l, when there is at least one popular content is asked:

$$Optimized\ R_l = (1-\beta)R_{ICN} + \beta\,\{\, R_{ICN}\ \ [1-\ \min(P_{1c} + \textstyle\sum_{k=1}^{l-2} Q_{kc})]\},\tag{3.6}$$

$$\forall Content\ c \in S_l\ and\ |S_l|\ \le S$$

and

$$Optimized\ R_l = (1-\beta)R_{ICN} + \beta\,\{\, R_{ICN}\frac{\max P_{1c}}{T_P}[1-\ \min(P_{1c} + \textstyle\sum_{k=1}^{l-2} Q_{kc})]\},\tag{3.7}$$

$$\forall Content\ c \in S_l\ and\ |S_l|\ \le S$$

otherwise, i.e., only non-popular content request(s) are sent to the CR. Additionally, c in (3.6) and (3.7) refers to all content(s) arrived at the CR level l. The constraint $|S_l| \le S$ means that the total size of content chunks stored in a CR should not exceed its cache size (boundary condition). The min and max functions are used in (3.6) and (3.7) because the ICN system should assure that a CR can satisfy all the interests for different contents (with different popularity levels) sent to it by adapting link rate to its (optimized) sufficient utilization. In other words, (3.6) and (3.7) can be deduced from (3.4) and (3.5) respectively to assure sufficient link utilization for Interests of the content with highest required link rate come to a CR. This policy, therefore, ensures that CRs operate with provisioning link rate which is sufficient to serve traffic demand according to generated Interest traffic and content popularity levels.

Let P_O be the operating power of a CR in conventional ICN design. Since all the CRs are equipped with ALR function, the optimized value of operating power consumption of Content Node at level l in proposed ICN system ($Optimized\ P_{O,l}$) can be identified from the value of $Optimized\ R_l$ as:

$$Optimized\ P_{O,l} = \frac{Optimized\ R_l}{R_l}\ P_O \tag{3.8}$$

Using (3.8), we can identify the power scaling down ratio of the proposed system compared to conventional ICN corresponding to both content popularity level and traffic load (as defined from (3.6) and (3.7)). This power reduction ratio reflects the impact of link rate on network device (CR) power consumption. Note that even if a CR does not get any Interest packet, it still consumes a fixed operating power corresponding to the minimum (baseline) link utilization level. This mechanism ensures that each CN minimizes its utilization for maximizing power savings. Particularly, the proposal realizes the instantaneous link rate adaptation in response to various content popularity as well as changes in content demand and network traffic.

For this Green ICN model, the network devices are provisioned with sufficient link rates for generated traffic and different popularity levels of all content objects flowing to them. This is a practical and feasible approach for real-world network deployment since existing Ethernet links can operate at a lower data rate than their capacity in a conventional networking model (allow multi-interoperable data rates of actual/realistic Ethernet standard deployment, i.e., at 10/100/1000 Mbps mode of Ethernet links). Particularly, in the case of the deployable Green ICN using Ethernet, the link operates at a lower data rate (10 or 100 Mbps) can save considerable power compared to the high data rate (1 Gbps) [37].

Overall, thanks to ICN's in-network caching feature, the chance that a content with high popularity is cached at a low-level CR becomes higher. This reduces the distance that users need to traverse to get the desired content because the probability of data delivery through the upper CRs is lower, especially in the case of popular content objects. By analyzing the correlation of content popularity and various multi-tier network topology then rapidly adapting the operating link rate to the optimized value, the proposed ALR-based mechanism can reduce CNs' power consumption significantly via diminished network load. This Green ICN model does not produce additional overhead for control messages because the strategy can simply operate at each CR via its network link by downclocking/unloading the interfaces to save power.

3.3 Optimized Operating Mode for Content Providers (CPs)

Since a server consumes much more power compared to a router, there is a high potential for optimizing the overall power consumption of the network system effectively by finding a suitable mechanism to decrease the server operating power. Towards this goal, in this section, we adopt the various adaptive operating modes for a CP which match data traffic to it. Motivated by the observation that the data servers' operations should be varied with the workloads and interest arrival pattern, we aim to gain considerable power saving from CPs during their ideal periods. We apply the idea of the Mealy machine to treat a CP as a finite-state machine and identify its optimal operating mode based on both of CP's current state (operating mode) as well as current traffic load and Interest to the server. By switching each CP to the optimized operating mode according to network traffic through it, instead of operating with full power capacity, the proposal can maximize the power saving of CPs. The optimal mode is activated with the assumption that the operating mode/state of each server can be changed after a specified interval of *T*.

To this end, the system uses traffic provisioning to put the CP into its optimal mode which is a low power state mode (LPI state) to achieve considerable power savings. Particularly, we design four distinct practical operating modes for a CP: I (Idle), SM (Save Mode), F (Full Mode), or A (Adaptive mode). Supposed that the proposed ICN system uses servers whose maximum power consumption can be set [13], each operating mode can work with different upper limit values of power consumption and a server can be in either one of the customized power modes as follows:

- Full-mode (F), denotes that the server is working with the full power-capacity as threshold power consumption.
- Adaptive mode (A), denotes that the server is working with the adaptive saving mechanism based on interest traffic to the server.
- Save mode (SM), denotes that the server in this mode will work with maximal power consumption equal to a portion of its power capacity.
- Idle mode (I), denotes that the server in this mode will be put in the idle state to maximize the energy saving.

In more detail, the power value of F mode is 100% server power capacity (i.e., operate with full capacity without activating any power management feature) whereas this value decreases to a fraction of that for other remaining modes. Besides, the maximum values of I mode and SM mode is predetermined, but in case of A mode, the maximum power consumption is identified dynamically based on interest traffic to a specific server. Note that in this proposal, we do not consider sleep mode since this may need additional power for "wake-up" and undesired higher latency, which is not fitted to increasing demand for real-time content-centric services in future networks. Therefore, I mode is different from Sleep mode because the server in Idle mode is still in an active state to maintain its low operating mode but not transmitting any packet, instead of sleep which enables higher power saving with the cost of undesired delay and disconnection. This mechanism then maintains the high-performance while keeping power consumption within the threshold power of the target server.

We then schedule a CP of the server cluster with its optimized working mode dynamically based on the current state (operating mode) of the server and interest traffic send to server for a fixed period T for power saving. Firstly, we define inter-packet arrival-time Δt as the arrival-time difference between two consecutive content requests sent to a server. The system then compares Δt value to period T to check whether to activate the I mode for the server: If the server does not get a new content request (Interest packet) during period T (i.e., $\Delta t \geq T$), I mode will be selected as the next optimal operating mode of CP for maximum power saving. Otherwise, the proposed algorithm chooses one out of three remaining traffic-based power profiles as the upcoming optimal power mode for the server by considering the Interest traffic to the server during a period T.

The traffic is identified by two input variables: the number of content requests (Interests) and the number of distinct content users sent requests to a specific server during a period T. Combining these two variables' values gives us four possible different cases of interest traffic sent to a specific CP and the optimal operating mode scheduling algorithm for a particular CP of the server cluster is shown in Figure 3.2 (referred to [34]). The following notions and parameters are used:

(a) T_1 and N_{1i} are the threshold value and the number of the content requests (Interests) sent to server s_i for a period T, respectively. Assume that all the CPs of server cluster share the same value of threshold T_1.

(b) Similarly, T_2 *and* N_{2i} are the respective values for the second input variable, which is the number of different content users of server s_i during period T. For the sake of Denial of Service (DoS) prevention, we adapt the value of T_2 corresponding to value of T_1: A content user should only send up to a specified number of content requests (Interests) to a server s_i for a period T to enhance the cache robustness. This policy helps to prevent CR from cache pollution attack in which an attacker keeps requesting an unpopular content to populate cache maliciously.

(c) The Save Mode (or Adaptive/Full mode) is selected unless the case that the server does not get a new content request during period T (i.e., I mode is selected). SM is the mode which allows the server to save power the most when the dynamic algorithm does not activate I mode as both of the two input variables are lower than the threshold values. In contrast, F mode operates maximum power capacity when both of two input variables are high enough. The optimal power mode decision scheme is summarized in Table 3.1.

Regarding A mode, it is activated when either one of two parameters is less than the threshold value. Let P_A be the upper limit of the power consumption for A mode of a specific server s_i, and its value can be dynamically calculated by the following formula:

$$P_A = P_F \text{ x} \left[1 - \left(w_1 \text{ x} \frac{T_1 - N_{1i}}{T_1} + w_2 \text{ x} \frac{T_2 - N_{2i}}{T_2}\right)\right] , \tag{3.9}$$

where w_1 and w_2 are two weighted values of two input variables, and $w_1 + w_2 = 1$. P_F denotes the power consumption in case of F mode. In (12), if $T_1 < N_{1i}$ then let $(T_1 - N_{1i}) = 0$ whereas if $T_2 < N_{2i}$ then let $(T_2 - N_{2i}) = 0$.

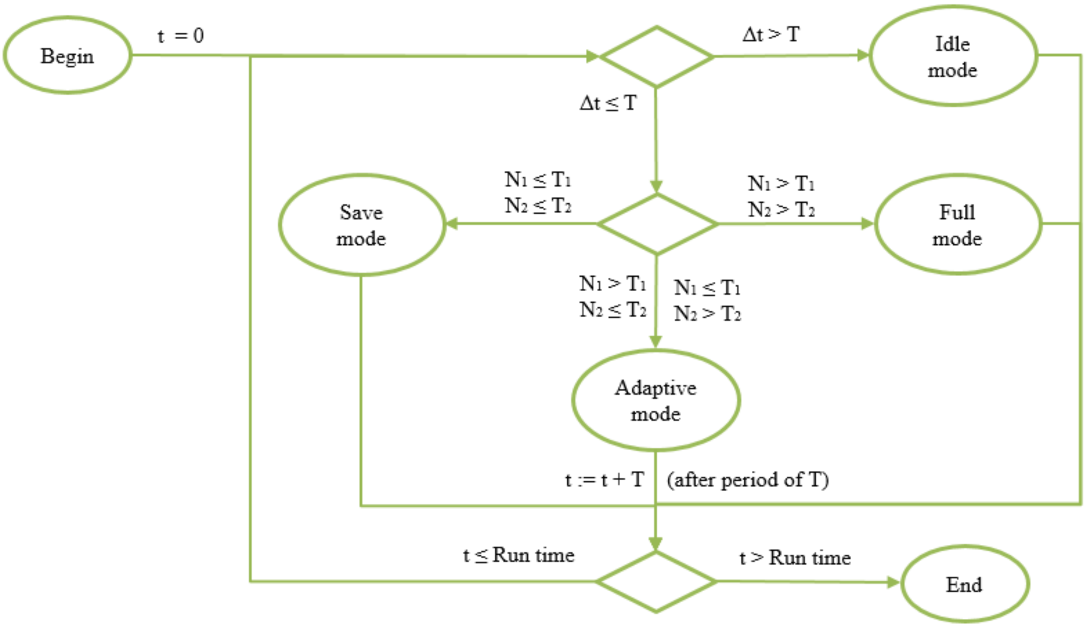

Figure 3.2 Algorithm of Optimal Operating Mode Selection for a Single Server

Table 3.1 Optimal Power Mode Decision Mechanism for a Specific Server [34]

Input Variables		**Output Variable**
Number of content request (interest)	***Number of different content user***	***Optimal Power mode***
L_1	L_2	SM/I
L_1	H_2	A/I
H_1	L_2	
H_1	H_2	F/I

The objective of this scheduling algorithm is to decide the optimal power mode of server cluster's CPs by applying the dynamic power control rules, then minimizes the overall power consumption of each server. Let m_1, m_2, m_3, and m_4 be the number of servers in the proposed ICN system operating in F mode, SM mode, I mode, and A mode, respectively. Therefore, the optimized value of all servers' operating power consumption at a specific time is:

min (server cluster power consumption at a specific time)

$$= m_1 \text{x} P_F + m_2 \text{x} P_{SM} + m_3 \text{ x} P_I + \sum_{k=1}^{m_4} m_k \text{ x} P_{A_k} \ , \tag{3.10}$$

where P_F, P_{SM}, P_I, and P_A are the operating power consumption of a server working in F mode, SM mode, I mode, and A mode, respectively.

This working mechanism much improves the power-consumption efficiency of the server, compared to the conventional ICN system or the current IP-based network system, which can be considered as the servers only work in F mode (i.e., m_1 = M and $m_2 = m_3 = m_4 = 0$).

Thus, together with in-network caching function in ICN, optimal operating mode of CP can contribute to power saving via lower server hit rate as well as CPs' operating power time and power. This observation along with the proposed ALR-based mechanism in Section 3.2 motivate us to work towards improving CS utilization efficiency for efficient wireless communications in different contexts, which will be clarified in Chapter 4 and Chapter 5.

3.4 Analytical Energy Consumption Models for Green Networking Evaluations

To evaluate power consumption and EE performance of different network system approaches, in this section, we develop energy models to analyze how the network elements affect the whole network system power. We consider the total energy of a network system is calculated by summing up the energy consumed by all network components and devices that make up the network, as well as taking into account the factors of network topology, content popularity, network device energy efficiency index and CP operating mode switch. For the scope of this study, we do not consider the overhead power consumption of a network system, e.g., cooling and lighting power. We assume that a network system includes two major network components: N CRs and M servers/CPs (clusters of servers). In this way, we present the respective mathematical models for energy consumption of current IP-based legacy network and conventional ICN design (without any proposed Greening method), referred to [38]. Then we build our proposed Green ICN system model with supporting network infrastructure using power-aware devices for saving power dynamically through proposed adaptive green mechanisms declared in this chapter. For each case, the correspondent energy model of the network system for analysis is built from network devices' energy elements.

Regarding power consumption evaluation, there are three main elements for server power consumptions: embodied power, power for server storage, and operating power of the server. A normal IP router power consumption is the combination of embodied power and working power of router, whereas there is an additional element (power for cache memory) in ICN CRs and each CR also consumes more for embodied and working power, compared to IP router.

3.4.1 Energy Consumption in an Ordinary IP-based Network System

The energy consumption of an IP-based network system is identified as:

$$E_{IP} = N \text{ x } E_{R-IP} + M \text{ x } E_S$$
$$= N \text{ x } T_w \text{ x } (P_{E-IP} + P_{O-IP}) + M \text{ x } T_w \text{ x } (P_{S1} + P_{S2} + P_{S3}), \quad (3.11)$$

where $E_{R\text{-}IP}$ and E_S are the energy consumed by an IP router and energy consumed by the server; $P_{\text{E-IP}}$ and $P_{\text{O-IP}}$ are the embodied power and working power of an IP router; and P_{S1}, P_{S2}, and P_{S3} are the embodied power, power for server storage, and operating power of a server, respectively. T_w is the working time of the whole network system.

3.4.2 Energy Consumption in a Conventional ICN System

The energy consumption of a conventional ICN design can be calculated as:

$$E_{ICN} = N \text{ x } E_{R-ICN} + M \text{ x } E_S$$
$$= N \text{ x } T_w \text{ x } (P_{E-ICN} + P_{C-ICN} + P_{O-ICN}) + M \text{ x } E_S, \quad (3.12)$$

where $P_{E\text{-}ICN}$, $P_{O\text{-}ICN}$, and $P_{C\text{-}ICN}$ are the embodied power, working power, and power to cache memory of an ICN CR, respectively. Regarding power consumption evaluation, both the current IP-based network system and ICN system share the same power consumption for servers, whereas an ICN router incurs slightly higher power compared to a normal IP router due to extra energy consumed for caching capability.

Note that for both IP and ICN systems, all network elements work with their max capacity as no green mechanism is applied to the network devices.

3.4.3 Energy Consumption in the Proposed Green ICN Model

The proposed Green ICN energy consumption is a combination of two optimized values defined in previous sections:

$$E_{Proposed\ GreenICN} = \sum_{k=1}^{N} Optimized\ \ E_{R-ICN,r_k} + \sum_{i=1}^{M} Optimized\ \ E_{S-ICN,s_i}, \tag{3.13}$$

where optimized energy consumption of all CRs is:

$$\sum_{k=1}^{N} Optimized\ \ E_{R-ICN,r_k} =$$

$$N \text{ x } T_w \text{ x } (P_{E-ICN} + P_{C-ICN}) + \sum_{k=1}^{N} Optimized\ \ P_{O-ICN,r_k} \text{ x } T_{Or_k}, \tag{3.14}$$

And the optimized value of the cluster of CPs:

$$\sum_{i=1}^{M} Optimized\ \ E_{S-ICN,s_i} = M \text{ x } T_w \text{ x } (P_{S1} + P_{S2}) +$$

$$\sum_{i=1}^{M} Optimized\ \ P_{S3,s_i} \text{ x } T_{O_{s_i}} \tag{3.15}$$

where T_{Or_k} is the operating time of router r_k with proposed ALR design, and $T_{O_{s_i}}$ is the operating time of the server *i* with optimal power mode.

As shown in (3.13), the EE objective function (achieve the minimum power value) can be achieved by switching all network nodes and links to their optimized values according to the traffic load and utilization dynamically.

3.5 Summary

In this chapter, we propose a novel Future Green ICN Model with adaptive power consumption ability based on the Interest traffic to the server to optimize the working power of servers/content providers to deal with over-provisioning network system (for the worst case). Particularly, we design four different power consumption modes (Idle, Save Mode, Adaptive and Full Mode) and select the optimal server operating mode to maximize the power saving from CP. We also adapt the power consumption of the content router according to the tuned link rate through the minimized network links by considering the content popularity and utilizing ALR technique.

The objective of this chapter is to design a dynamic energy efficient ICN model for the Future Internet by adapting router link-utilization with the popularity of contents and server with its optimal operating mode to optimize the network energy consumption value. This chapter lays the foundation for the practical applications of the proposed system which will be described in detail in the next chapters, in which the proposed Green ICN model is integrated into novel caching schemes to diminish CR operating power and the chance that a CP needs to work in F mode as an efficient way to achieve substantial overall system power savings for different context-based content services in wireless ICN.

Chapter 4

The Adaptive Green ICN Model for efficient Communications in ITS

In this chapter, we design an adaptive ICN-based architecture for efficient communications in Transport Systems by integrating a novel proactive-caching based mechanism into the proposed Green ICN model defined in Chapter 3.

This chapter is based on our previous research publications: **Quang N. Nguyen**, M. Arifuzzaman, D. Zhang, K. Yu, and T. Sato, "Proposal for Standardization of Green Information Centric Networking based Communication utilizing Proactive Caching Intelligent Transport System," Journal of ICT Standardization, Vol.4, Iss.1, pp35-64, July 2016 [39]; and **Quang N. Nguyen**, Arifuzzaman. M and Sato Takuro, "Proactive-Caching based Information Centric Networking Architecture for reliable Green Communication in Intelligent Transport System," The 7th International Telecommunication Union ITU Kaleidoscope academic conference "Trust in the Information Society," Barcelona, Spain, 9-11 December, 2015 [40].

4.1 Introduction

In essence, ICN architecture [2][3] can handle mobility more efficiently since the content can be found en-route even after the handoff and especially better support for the scope of location transparency, i.e. the mobile node can change its Point of Attachment (PoA) and still maintain the consistent name for the user mobile. However, supporting smooth connection for seamless content retrieval is still a major issue and ICN mobility concern has not been received adequate exploration despite the fact that wireless technologies are becoming a popular means for Internet users to get information/data. This issue becomes more critical for the mobile user in the case of wireless communication in transportation system because the period a transportation vehicle stops at a station is relatively short, then the Point of Attachment (PoA) may be changed before the content user gets satisfied content data. Moreover, a wireless access scheme has limited bandwidth and it is a challenge to access content in real-time for interactive services.

Therefore, in order to address the ICN architecture's mobility problem and enhance the performance, effectiveness along with energy efficiency of ICN in case of transportation systems' wireless access, the aim of this work is building a proactive-cache based flexible ICN architecture to support the seamless wireless communication with energy saving for the Intelligent Transport System (ITS). By considering the different practical scenarios (e.g. the case that mobile users can leave the public transport vehicle earlier than expected) to prevent possible unnecessary content traffic, reduce congestion and energy consumption as well as considering low-cost feature of Wi-Fi technology, we do believe our proposal will become a feasible and efficient pioneer solution to on-going ICN standardization procedure for utilizing in the transportation industry. The simulation results in ndnSIM corroborate our proposal efficiency by diminishing the delay time substantially for supporting seamless wireless communications and save about 20% energy consumption compared to conventional ICN model (NDN design).

Hence, the transportation industry (transportation companies) can offer customers a smooth, robust and secured connection transparently during periods when they stay on a transport vehicle with lower energy cost.

4.2 Related Work

Pre-caching/proactive caching is recognized as one of the major schemes to reduce the response time, latency and enhance the user experience, given that mobility content access in real time has become a challenging issue due to bandwidth limitation and exponential Internet growth. Thus, a number of works have been conducted on proactive caching schemes and pre-fetching technique for the current client-server

Internet architecture to make the desired data objects immediately available to a mobile user when the mobile moves to a new network attachment point. Regarding the proactive caching approaches for mobility, in [41], all neighboring proxies caching content items are initiated to match the mobile's subscriptions after the occurrence of disconnection. Then, when the mobile node connects to one of these proxies, it can immediately get contents which were already transmitted to that proxy at the time of its disconnection. A selective neighbor caching (SNC) scheme is stated in [42] to reduce signaling overhead and handover delay in WLAN. The authors introduced a predefined threshold value of handoff probability considering handoff frequencies between APs (Access Points) to select neighbor APs for their SNC model. Another selective neighbor caching scheme is exploited for enhancing seamless mobility in ICN as defined in [43]. In the proposal, an optimized subset of neighbor proxies are selected as a pre-fetching destination of the content and the mobility behavior of users is considered to select the prospective neighbors. However, the proactive caching solutions in existing mobile network infrastructure are different from respective approaches in ICN. Since in general, the mobile host's context is proactively utilized in the current system, whereas the goal of the ICN system is only offering the mobile nodes content that matches their interests.

In addition, some previous researches also deal with mobility issues of mobile nodes in the transportation system. For example, the authors of [44] proposed a commuter router infrastructure for the public transportation system, but their scheme is mainly equipping additional routers with store-and-forward rather than maintaining an uninterrupted connection via the Internet. The "PUll and SHare (PUSH)" model is presented in [45] for the case of collaboration between users for a peer-to-peer (P2P) based content sharing scheme to deliver video content. Its objective is to improve user's Quality of Experience (QoE) under expected periods of disruption, in the case of commuter trains. In [46], Worldwide interoperability for microwave access (WiMAX) is considered for communication in railway scenario because of its QoS and mobility support at high speed. However, WiMAX technology has its drawbacks and is insufficient for long-term deployment. Researchers in [47] built architecture deploying multiple cooperatively operating access routers on the train. This approach improves network performance but it requires additional coordination mechanism and endures higher overhead. Recently, a few researches also deal with this scope in ICN. A vehicle-to-vehicle communication in ICN is stated in [48] by extending the Content-Centric Networking (CCN) framework to support content delivery for vehicular communication efficiently. In [40], a prototype of energy-efficient and reliable ICN based wireless communication technology within the context of ITS is proposed for ICN standardization process. The solution combines both green networking and innovated proactive-caching based scheme in ICN mobility together to raise energy efficiency and effectiveness for the goal of green and seamless mobility in ICN.

4.3 Research Motivation

In order to meet commuter's demand for broadband service, it is inevitable to establish a common wireless access platform for public transportation systems, especially in case passengers' desired interests are now mainly information-centric services (e.g. HD movies, multimedia services) whereas the current network infrastructure of public transportation system still relies on traditional TCP/IP model. Towards this end, the aim of our study in this chapter is building a proactive-cache based flexible ICN-based architecture to support the seamless wireless communication with energy saving for the Intelligent Transport System (ITS).

In this study, we select the public transportation system, e.g. train, bus for the case of ITS because thanks to positive characteristics including punctuality and convenience, public transportation vehicles are commonly used and getting more and more popular, especially in urban areas and big cities. The public transportation's commuters also have a high tendency to use their mobile devices for different kinds of interested information/content via the Internet during the period when they spend on the public transportation system. Better still, the motion of a commuter can be predicted from the path of a train/bus line. In particular, the moving direction, stopping time at a specific station along with the moving time between two different stations can be pre-determined in normal cases (relatively fixed time-schedule). This means that connection time and disconnected time of a mobile node to a conventional wireless network in train system can be identified as the time when the train stops at a station and when it moves to another station, respectively. This feature is a great benefit to exploit proactive-caching scheme for transportation communication since the route is static and moving process can be predicted.

As motivated from mentioned transportation system feature, we propose to integrate proactive-caching based scheme utilizing ICN caching and naming functions for standardization process in ITS, to provide smooth access connection to valid content segment via 'smart scheduler', then enhance user experience. In this way, we address the ICN architecture's mobility problem and enhance the reliability along with the efficiency of ICN for practical application in the case of transportation systems' wireless access.

Our proposal is mainly based on NDN prototype because NDN is considered as the only architecture among them that possesses the backward-compatible capability [3][31]. NDN also provides data integrity and authentication verification. Besides, NDN has an hourglass architecture with Content chunk layer as a "narrow waist" and top layers focus on streaming services rather than HTTP as in IP-based architecture. This matches the mobile users' growing content demand tendency of interactive services via their mobile devices, in case of the transportation system.

The simulation results in ndnSIM corroborate our proposal efficiency by substantial diminishing the delay time, average number of hop together with improving data rate to support seamless wireless communications (thanks to our proactive caching strategy). In addition, the proposal can save about 20% energy consumption compared to conventional ICN model (NDN design). By considering the different practical scenarios to prevent possible unnecessary content traffic and reduce congestion as well as a low-cost feature of Wi-Fi technology, we believe our proposal can become a feasible and pioneer solution to integrate the merits of ICN for efficient communications in the transportation industry. The proposed ICN model also acts as a solution for network scalability because it can help to relieve the network burden of cellular network (mobile network) by providing all commuters (wireless content users) fast access to large contents and high QoS content via their mobile devices (in essence, cellular network communication via Base Station has high cost and higher latency due to no caching capability and pre-caching scheme for moving content users).

4.4 Communication Topology for Transmission System and Assumptions

We take the railway as a scenario of public transportation for ITS communication because nowadays, the railway is a dominated public transportation system in the big metropolitan areas e.g. Tokyo, London and Moscow. Our ICN system topology design for railway/train transportation communication system is built on top of NDN [3] as shown in Figure 4.1. We propose a 5-level tree-based network topology comprising of a server as a root node and distinguished Content Routers (CRs) accompanying IEEE 802.11 Wireless Access Point (Wireless APs) allocated into remaining 4 levels of the tree (the central content router is at level 4). We assume that the ICN system consists of various contents and every content is stored on the server which acts as a Content Provider (CP). Furthermore, all contents have the same size and each ICN CR can cache a same maximum number of contents. It can be seen from Figure 4.1 that we design the ICN system topology of a prefecture with the idea that each prefecture has a central CR connected to the content server (CP) for ITS.

In this model, we assume one wireless AP, as a first-level CR, is equipped at each part (railroad car or wagon) of a train, to build a train-level Wireless Local Area Network (WLAN). A wireless AP can be connected to CRs at different stations, which act as level 2 routers. Considering wireless AP and other routers as NDN content routers, when an AP receives an Interest, it first looks for the information object (content) in its content store (CS). If the content is found in CS, it sends back data to the content requester. If the content is not found in the CS, two tables i.e. Pending Interest Table (PIT) and forwarding information base (FIB) are used to handle the Interest packet. PIT collects incoming interfaces of the Interest packets so that the data packet can be delivered back on the same path (of incoming interest) towards the content requester whereas FIB directs Interest packet toward one or more content sources/repositories.

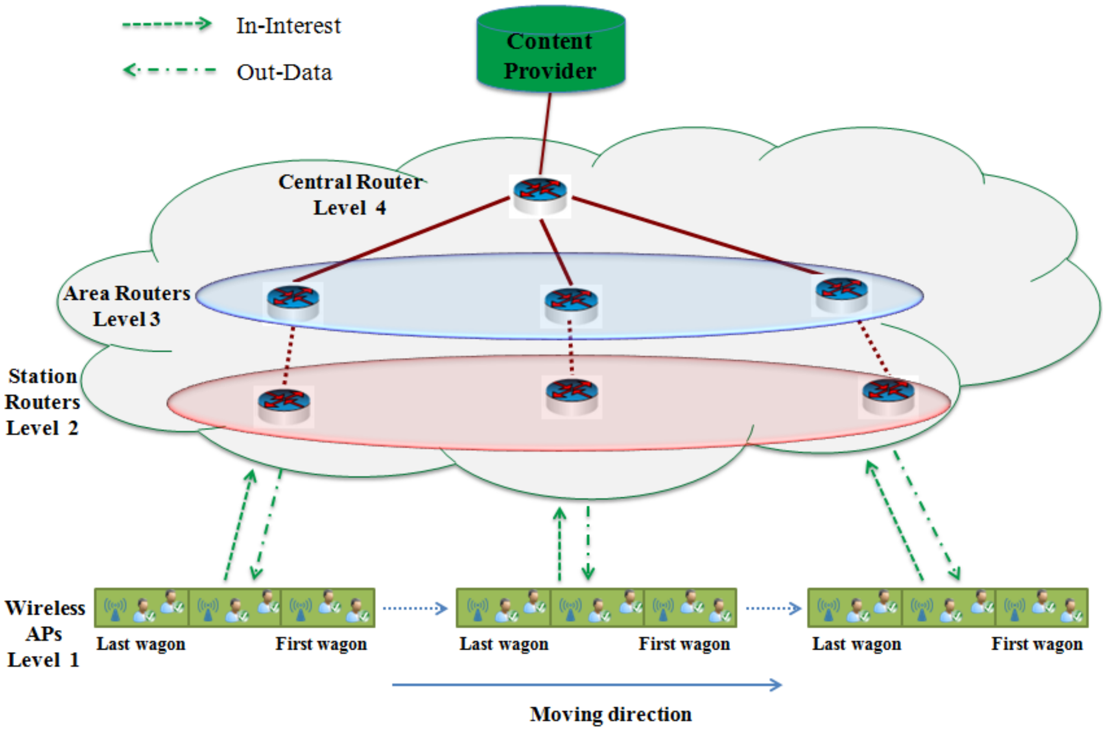

Figure 4. 1 Proposed Network Topology for ICN-based ITS [39]

Hence, a commuter (mobile user) can connect to correspondent wireless AP of his/her current railroad car (Wi-Fi) via a connection between this AP and CR at a station when the train stop at a station. However, the connection is not available during the moving periods of time. Due to the fact that the moving time is longer than the stopping time, the commuter is expected to endure the intermittent connection when connecting to a wireless network of the transportation system in current Internet architecture. CRs at stations (router level 2) are connected to higher level CRs including: Area (or city)

CRs act as level 3 routers and prefecture (central) CRs act as level 4 routers via a high-speed wired transmission.

When the train arrives and stops at a station, a wireless AP will get the pre-cached content segments from CR of the station via high-speed wireless access based on proactive caching scheme. Consequently, the ratio of packet loss and latency in case of our proposal can be reduced compared to the existing network system. Further detail of this proactive caching scheme and the way to divide a content into segments are clarified in the next part of this section.

Benefits of this network topology are easy deployment and practical design for the hierarchical structure of network and service provider in case of the transportation industry. As a result, it is suitable for the migration process from current network infrastructure (with widely available and low-cost Wi-Fi APs). Besides, in this tree-topology, the more popular content is expected to be located closer to the end-user then offering lower latency and higher QoS for interactive mobile services.

4.5 The Application of ALR Operating Strategy for Greening ICN-based ITS

In this Section, we state our proposed adaptive strategy of Content Nodes (CNs, including all CRs and Wireless APs) equipped with aforementioned ALR technique (Note that some of which were introduced in Chapter 3).

Firstly, we define p_k as the probability that one content user can find a specific content $c \in C$ at a CN level k, under the assumption that all CNs located at the same level k of the tree network topology share the same value of p_k because we assume network is symmetric and the requests generated by all users are homogeneous.

In the case of current IP-based Internet architecture, we can infer that $p_1 = p_2 = p_3 = p_4 = 0$ and $p_5 = 1$ since as mentioned, different from ICN design, the only way to get a content/data is sending the request to the server via the routers. Moreover, more popular content is expected to be closer to the users because it is replicated more frequently compared to non-popular one. This means that the more popular a content is, the higher possible a user can find it at lower levea l, i.e. the popular contents have a tendency to possess a higher value of p_1 than the un-popular contents. Hence, we define two kinds of content:

$$\begin{cases} popular\ content: & p_1 \geq T_p \\ non-popular\ content: & p_1 < T_p \end{cases},$$

where T_P as the threshold value of p_1 for all Content c ∈ C (assume that all contents have the same value of T_P).

Similar to p_k, the number of levels (hops) that content user traverse is expected to be lower with more popular content. Hence, the expected number of hops (levels) that the user has to travel would be decreased. Let Q_k is the probability that a content user traverses k-level (or k hops, where k ≥ 1) of the proposed tree topology to find an interested content c ∈ C, then Q_k can be defined as follows:

$$Q_k = p_{k+1} \prod_{l=1}^{k}(1 - p_l) \ . \tag{4.1}$$

Then, we determine the dynamic operating power of ICN CRs to match their optimized utilization by adjusting the correspondent link rate of CRs based on the popularity of the contents that the ICN nodes serve.

Let R_k is the incoming link rate to a level-k CR for a content c ∈ C. Since a popular content has higher chance to be found at the first levels, the maximum link rate is set for the level 1 CRs (Wireless APs) as in case of Conventional ICN:

$$R_1 = R_{ICN} \ , \tag{4.2}$$

where R_{ICN} is the link rate enter a CR in Conventional ICN model. Let S_k is the set of content interests come to a level k content router. Then R_k (with k > 1) will adapt to the operating link utilization of ICN node based on popularity level of content c and the value of R_1 (for every interest for content c ∈ S_k):

$$R_1 > R_k \ (k > 1) \ . \tag{4.3}$$

Since in general, one content node may receive various interests to ask for different contents, we consider two cases: One is Interest(s) come to a content node but only ask for unpopular content(s) and the other is there is at least one Interest sent to that node to ask for popular content. Then the optimized value of R_k for a level k-ICN router, namely *Optimized* $R_{k,ICN}$ ($1 < k \leq 4$), in case that there is at least one popular content is asked:

$$Optimized\ R_{k,ICN} \ = \ \alpha \{ R_{ICN} \ \ [1 - \ \min(P_{1c} + \textstyle\sum_{l=1}^{k-2} Q_{lc})]\} \ , \tag{4.4}$$

$$\forall Content\ c \in S_k\ and\ |S_k| \ \leq S$$

where α is the proportional coefficient of link rate and power consumption of Content Nodes (APs and CRs). $\alpha \geq 1$ and $\alpha = 1$ means the link rate is directly proportional to the power consumption of network devices. In addition, c in the equation refers to all content(s) arrive to the CR level k.

and

$$Optimized\ R_{k,ICN} \ = \ \alpha \{ R_{ICN} \ \frac{\max P_{1c}}{T_P} \ [1 - \ \min(P_{1c} + \textstyle\sum_{l=1}^{k-2} Q_{lc})]\} \ , \tag{4.5}$$

$$\forall Content\ c \in S_k\ and\ |S_k| \ \leq S$$

otherwise, i.e. user only expresses interest for unpopular content(s). The min function in Equation (5.4) and (5.5) returns the minimum value of argument for various values of c, i.e., it guarantees that the adapted link provides adequate utilization for the content with highest utilization request in Equation (5.4). Similarly, the max function in Equations (5.5) returns the maximum value of all arriving content c to enable enough link utilization for most popular content from all (unpopular) contents at that level. This mechanism assures that a CN can adapt its link rate to optimized utilization in order to satisfy all the interests for different contents (with different popularities) which were sent to it.

Since α may get value > 1 then in case device is not fully support ALR function and value of *Optimized* $R_{k,ICN}$ identified from Equation (4.4) or (4.5) is higher than R_{ICN} (i.e. *Optimized* $R_{k,ICN} \geq R_{ICN}$) then let: *Optimized* $R_{k,ICN} = R_{ICN}$.

We then define the Power Adjustment Factor P_A:

$$P_A = \frac{Optimized\ R_{k,ICN}}{R_{k,ICN}}\ (0 < P_A \leq 1)\ . \tag{4.6}$$

Let $P_{R2\text{-}ICN}$ be the operating power consumed by a content router in conventional ICN design (more detail in Section 4.6). Since we assume that all CRs are equipped with ALR function, the optimized value of operating power consumption of Content Node at level k in ICN (*Optimized* $P_{R2\text{-}ICN,k}$) can be identified as:

$$Optimized\ P_{R2\text{-}ICN,k} = P_A \quad P_{R2\text{-}ICN}\ . \tag{4.7}$$

Therefore, for this ICN proposal, when a content gets more popular then the load of the network decreases and diminishes the transport energy notably.

4.6 The Proposed Proactive-Caching based Protocol for Seamless Communications in ITS

In this part, we describe the proposed strategy of proactive caching to support seamless communication for mobile users in ICN based transportation system scenario. We select Aggregation points as the location of proactive caching to enhance the scope of sharing the content. For that reason, as can be seen from Figure 4.2, station routers act as Aggregation nodes (under the assumption that all the routers and wireless APs are CRs as defined in [3]). Let C be the set of all content. When a mobile device first expresses its interest for a specific content c ($c \in C$) to its current railroad car's wireless AP, the interest goes to the CP through wireless AP, then Aggregation node (current CR station) and respective higher level content routers (CRs at level 3 and level 4). Our goal is to populate the different segments of content on the en-route of the interest path

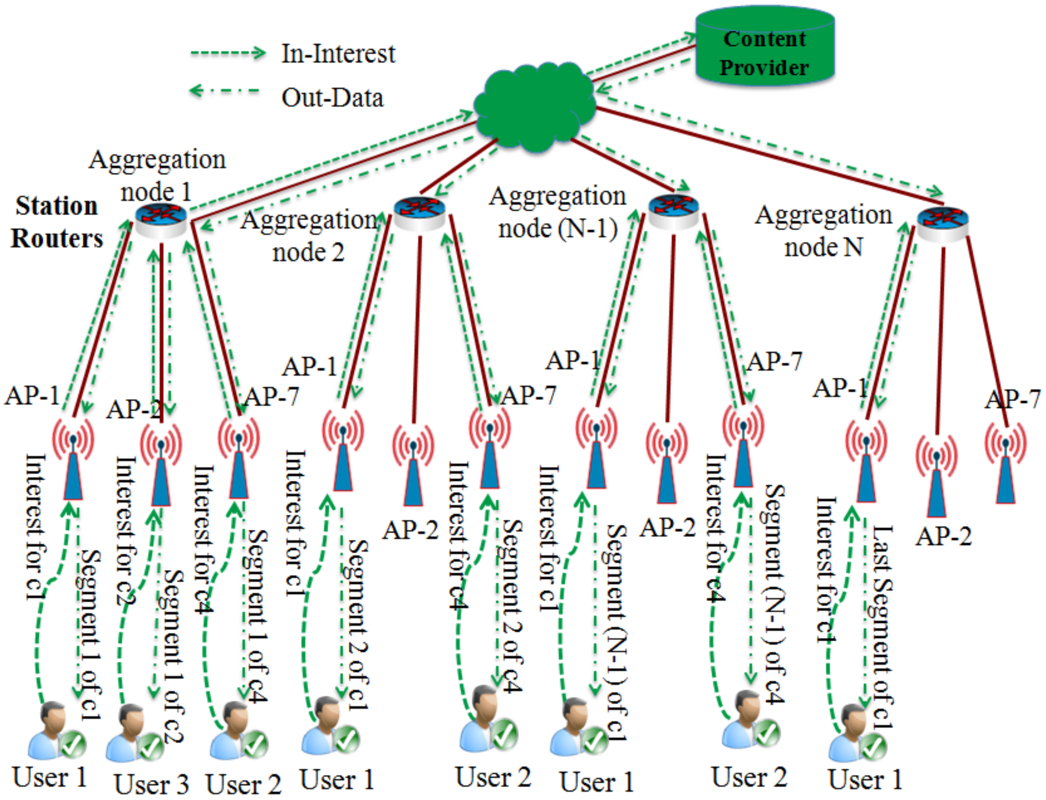

Figure 4. 2 Flow of Interest and Content Delivery Path with Proposed Proactive-Caching in Station Router Node for ICN-based ITS [39]

as well as the disjoin-neighbor path. When the CP receives an interest asked for a content, that content data is divided into several segments and then these segments are pre-cached to a number of appropriate Aggregation nodes (station CRs at level 2). Size of segments of a specific content can be calculated considering a fact that a content is composed of a set of chunks (a chunk is a unit for caching and transmitting data).

Let N be the expected number of stations that one commuter stays on the train, then proposed system pre-caches content's segments to a total of (N-1) stations' CRs away from the first station location where the content request is sent to CP, according to the moving direction of the train line. With this mechanism, a commuter is expected to get his/her full content within a total of N stations. The value of N is also used to identify the size of different segments of content will be pre-cached to different stations' CRs. A delivery scheduler, namely "smart scheduler", define the way how a content is pre-cached to stations. This "smart scheduler" decides the appropriate location (station) for pre-caching by applying our proposed proactive caching strategy and can calculate the amount of content segment should be cached to maximize gain and user performance. Moreover, to prevent redundant content traffic, the pre-caching process for a suitable segment of a specific content $c \in C$ to station N's CR only happens in the case that station (N-1) still gets the interest for that content from the same user at the time train stops at a station. Otherwise, the next segment is dropped, i.e. the time that commuter expresses his/her interest for a content at the station (N-1) is the time the next segment of content is pre-cached to station N's CR (upcoming station of the station (N-1) in train line). This is because the next segment of the content is likely to be requested there in the next phase. In other words, if a commuter does not generate any interest for a content at a station (his/her expected station at one time) then a segment of that content will not be pre-cached to the next station's CR to prevent possible congestion. This mechanism deals with the situation that a commuter leaves the train earlier than expected.

In order to do that, the system generates 'fake' interest (for the same content) from the neighbor aggregation node (next/nearby station's CR). Thus, both aggregation points (en-route and out of route) fetch the content and cache the content. The cached segments in APs can be accessed by all matched subsequent mobile content users, then diminishes the network bandwidth consumption. Hence, when the train moves to the nearby station and user shows his/her interest for a content c_i (content they already asked) again, the interest will be served via current railroad car's wireless AP from station CR because a valid segment of content is already cached in this CR. Figure 4.2 demonstrates the operating procedure of our proactive-caching based scheme in ICN for ITS through an example: At first, there are three users who send three interests for three different contents from three APs (i.e. three wagons of the train) at a specified station (aggregation node 1) on train line: user 1 sends interest for content c_1 to wireless AP1, user 2 sends interest for content c_4 to wireless AP7 and user 3 expresses interest for content c_2 to wireless AP2. At that time, segment number 2 of these contents (c_1, c_2 and c_4) will be calculated, determined and pre-cached to the aggregation 2 (nearby station). Then when the train moves to aggregation node 2 (nearby station), user 1 and user 2 continue asking for their interested contents so segment number 2 of these contents will be served to them. Whereas user 3 stops sending his interest for content c_2 (he leaves the train at this station), hence the segment 3 of c_2 will not be pre-cached to aggregation node 3 (next station). User 1 and user 2 continue sending their interests for content c_1 and c_4 to aggregation node (N-1), i.e. (N-2) station away from the first station (aggregation node 1). However, only user 1 gets the full data of his interested content c_1 by sending interest for his desired content at aggregation node N, and receiving the last segment of c_1 from aggregation node N (user 2 and user 3 do not get the whole data they get interest because they leave the train earlier than expected). Thus, this proactive caching strategy provides higher efficiency, better congestion control and reliability for the network system and mobile users. In addition, because we design the wireless AP for each railroad car of the train so during period that train moves between different stations, users also can get their interested data from the suitable wireless AP which acts as an ICN CR (after this AP gets the appropriate data segment of interested Data from the station CR), then better support for the seamless connection.

Specifically, in our ICN system, a commuter (mobile content user) only sends interest for a specific content to the CP at first station by reason of our proposed proactive caching strategy whereas in conventional ICN design, a content request from a commuter needs to come to a server in the case that no content node contains that content. Worse still, getting data from the server is the only way to retrieve a content/data in the current IP-based network system. Hence, the delay will be diminished substantially since the interest does not need to go to CP. Thanks to this working mechanism, we show that the proposed pre-fetching protocol is relevant for the standardization process of ICN in context of ITS. This scheme also offers a reliable communication since information is firstly served by authorized and authenticated CP of the service provider. Then suitable segments of contents can be transmitted to lower level nodes. Therefore, mobile users can get continuous content segments from appropriate AP via smart scheduler during the period when they stay on the train with expected lower latency and shorter retrieval time. As a result, the proposed scheme provides a higher Quality of Experience (QoE) and better mobility performance for the passenger as well.

4.7 Analytical Energy Models for EE Evaluations

The total energy of the network system can be considered as sum of the energy consumed by all network components and devices that make up the network system. We assume that each network system comprises two major elements: N content nodes (CRs and APs) and one server (CP). This section states our energy evaluation models as an extensive analysis from the Energy models in Chapter 3.

4.7.1 IP-based network system energy consumption

The energy consumed by an IP-based system (traditional TCP/IP model) can be expressed as:

$$E_{IP} = N\ E_{R-IP} + E_S = N\,P_{R1-IP}\,T_w + N_1\,P_{R2-IP}\,T_w + N_2\,P_{R2,AP-IP}\,T_w + (P_{S1}\,T_w + P_{S2}\,T_w + P_{S3}\,T_w), \tag{4.8}$$

where $E_{R\text{-}IP}$, E_S are the energy consumed by an IP router and energy consumed by the server; $P_{R1\text{-}IP}$, $P_{R2\text{-}IP}$, $P_{R2,AP\text{-}IP}$ are the embodied power of a network node (router/AP), working power of an IP router, and working power of an AP, respectively; N_1, N_2 and N are the number of routers, number of APs, and number of CNs respectively ($N_1 + N_2 = N$) and P_{S1}, P_{S2}, P_{S3} are the embodied power, power for server storage and operating power of a server (same value for both ICN and IP based network system), respectively. Besides, T_w is the working time of the whole network system.

4.7.2 Conventional ICN system energy consumption

The conventional ICN system energy consumption can be calculated as:

$$E_{ICN} = N\,E_{R-ICN} + E_S = N\,(P_{R1-ICN}\,T_w + P_{R3-ICN}\,T_w) + N_1\,P_{R2-ICN}\,T_w + N_2\,P_{R2-ICN,AP}\,T_w + (P_{S1}\,T_w + P_{S2}\,T_w + P_{S3}\,T_w)\ , \quad (4.9)$$

where $P_{R1\text{-}ICN}$, $P_{R2\text{-}ICN}$, $P_{R3\text{-}ICN}$ are the embodied power, working power and power to the cache memory of an ICN CN (CR/AP), respectively. For power consumption evaluation, both the current IP-based network system and conventional ICN system share the same power consumption for servers, whereas an ICN node consumes slightly higher power compared to a normal IP node because of the CN's caching function (additional cache memory energy for CR in case of ICN).

4.7.3 Proposed Green ICN Model for ITS energy consumption

The optimized value of total energy consumed by our proposed Green ICN system is a combination of two optimized values:

$$Proposal\ E_{ICN} = \sum_{k=1}^{N} Optimized\ \ E_{R-ICN,r_k} + Optimized\ \ E_{S-ICN}\,, \quad (4.10)$$

where optimized energy consumption of all CNs:

$$\sum_{k=1}^{N} Optimized\ \ E_{R-ICN,r_k} = N\,(P_{R1-ICN}\,T_w + P_{R3-ICN}\,T_w) + \sum_{k=1}^{N} Optimized\ \ P_{R2-ICN,r_k}\,T_{Or_k}\,, \quad (4.11)$$

and the optimized value of server (CP):

$$Optimized\ \ E_{S-ICN} = (P_{S1}\,T_w + P_{S2}\,T_w) + [P_F\,T_{O_s} + P_1\,(T_w - T_{O_s})], \quad (4.12)$$

where T_{Or_k} is the operating time of CN r_k with proposed ALR design, and T_{O_S} is the operating time of server S. Besides, assume that systems uses server (CP) with two specific states: Idle mode when no content interest send to the server and Full mode otherwise (there is at least one interest come to CP during a period time T). Then let $P_F \; and \; P_I$ are working power of Full mode and Idle mode and assume that $P_I = 0.3 \, P_F$.

4.8 Performance Evaluations and Discussion

In this Section, we verify benefits of proposed greening mechanism together with proactive caching strategy in ICN architecture to enhance the user experience of the mobile users in case of commuter train's passengers.

We simulate our proposed ICN based system in ITS with ndnSIM, which is a scalable emulator of Named Data Networking (NDN) [49] under the ns-3 framework, to evaluate efficiency of proposed wireless access ICN based scheme for public transportation in contrast with traditional TCP/IP and Conventional ICN model (NDN design). The network topology used in the simulation is tree topology as aforementioned: There are four ICN CRs level 3 (area/city CRs), four CRs act as ICN station CRS (CRs level 2) and the prefecture/central CR at level 4 is connected to the repository (server/content provider) to form a 5-level tree network topology.

We assume that a train has seven distinguished railroad cars, and each car has its own dedicated wireless AP. There are two commuters (mobile content users) at each railroad car and a mobile content user/client (passenger on the train) is connected to respective wireless AP level 1. He/she first demands a specific content via mobile devices, i.e. sends Interest packet for that content and an ICN content server acts as a content provider for providing content. The content is then proactively cached at every train station according to the "smart scheduler", which decides the appropriate amount of content segment should be proactively cached (pre-cached) in ICN routers of train stations and the delivery schedule including location and timing delivery as described in Section 4.6.

The period for staying at each station and moving between two stations are 18s and 90s, respectively. The stoppage time at each station is 18 seconds, which can be determined as an average value for a train line in practice. For simplicity, we take N (expected number of stations that a user stays on a train line) equal to four. Wireless APs are connected via IEEE 802.11g standard. Assume all the ICN nodes have the functionalities of the PIT (Pending Interest Table), FIB (Forwarding Information Base) and CS (Content Store) as described in [3]. The total number of objects/different contents is 20,000 and assume that a content user does not generate any interest for the objects/contents which are not stored in the repository. The Zipf distribution, which is similar to the Zipf-like distribution as defined in [50] is used for the content popularity distribution. Content request rate is equivalent to 25% of network utilization. Cache object eviction policy is LRU (Least Recently Used). We also assume that every content has the same size of 1000 MB (with a payload size of 1KB). The link capacity/bandwidth we use for simulation is 1 Gbps. The network elements and their respective power consumptions for evaluation are referred to data presented in [38][51]. Under the assumption that we have two similar network systems with same characteristics: one follows conventional ICN (NDN design) and the other has traditional IP-based architecture. We then make simulation and demonstrate our proposal performance and efficiency compared with these two existing network system designs, in terms of hop count, network delay, Interest Data rate (for network and handover performance) and energy consumption (for EE evaluation) with the above parameters.

4.8.1. EE Performance

- Impact of ICN CN caching size on average power consumption: From our simulation result as shown in Figure 4.3, the average power consumption of both Conventional ICN and our proposed ICN model increase when we increase the size of the content cache of each CN (five different ICN CN cache sizes: 64 GB, 96 GB, 128 GB, 192 GB and 256 GB with $\alpha = 1$). This is because the ICN system needs to endure additional caching energy for the CN as stated (the respective values of CNs' power consumptions can be found in [21]). Moreover, the proposed model can save significantly power consumption compared to other current network designs.

- Impact of Alpha value (α) on average power: As can be seen in Figure 4.4, the value of α and average power consumption of the network system have a linear relationship. Therefore, when we increase the value of α, as expected, the energy consumption of the proposed ICN system is also increased. Typically, we take the value of α ranges from 1 to 1.3 for the evaluation. Though Conventional ICN consumes slightly higher energy consumption compared to our current IP-based architecture due to additional energy for caching capability, from Figure 7.5, our proposed Green ITS model can substantially decrease energy consumption. In more detail with $\alpha = 1$ (the ideal case with ALR-fully support CN), the proposed system can save about 21.16 % energy compared to conventional ICN in the same scenario, whereas these ratios are decreased to 18.57 % with $\alpha = 1.3$.

4.8.2. Network Performance and Handover Evaluation for Seamless Communications in ITS

- Average Packet Hop count of proposed ITS system: the Average Packet Hop count is almost stable with the simulation time as shown in Figure 4.5 except the cases that the Mobile Node (MN) is involved in the Hand-offs period when it moves to change the PoA to another Station node (when train stops at a station). The higher value for this metric represents the case of hand-

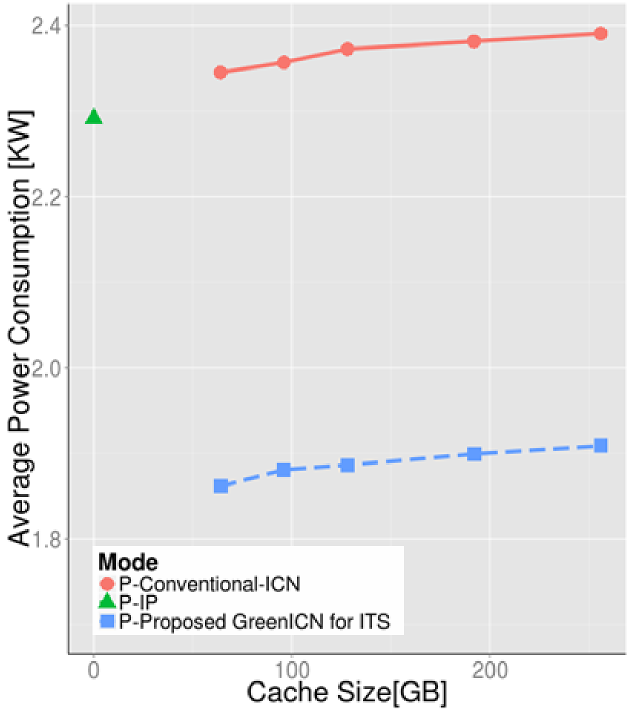

Figure 4. 3 Average Power Consumption of Different Network Systems versus the Different Caching Size of ICN Content Router [39]

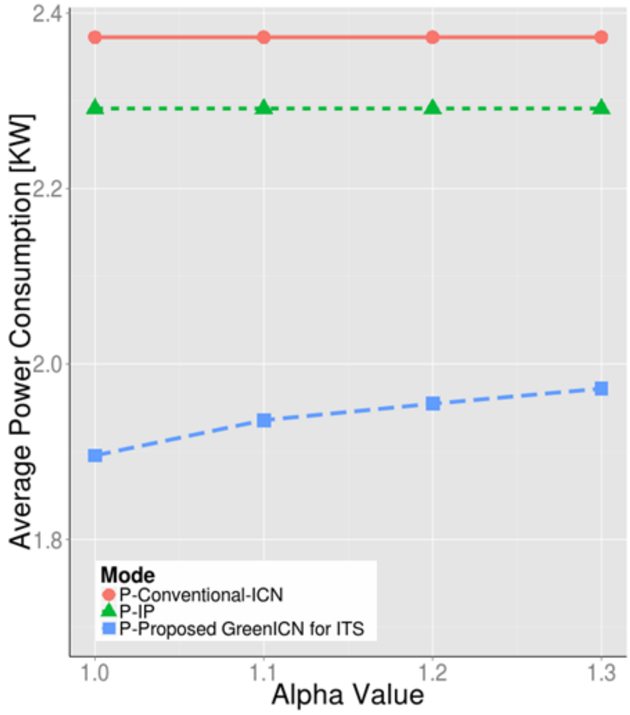

Figure 4. 4 Average Power Consumption of Network System versus *α* Value [39]

off. And as we can see from the figure that the period taken to hand-off is very short, thanks to our "smart scheduler" and innovated proactive caching strategy.

- Average Network Delay of proposed ITS system: For the objective of seamless mobile communication, network delay is a key metric. From our simulation result as shown in Figure 4.6, similar to the Average Packet Hop, the average delay is kept at less than 6 milliseconds which is considered very low. Even in the hand-offs period when the mobile content user moves to change the PoA from one station to another station (Wireless AP node), the delay is less than 10 millisecond. It can be seen that a mobile user can get a smooth connection with almost no disruption during the time he/she is on the train.

- Interest Data Rate of proposed ITS system: For this metric, we evaluate the rate of both Data packet and Interest packet, in case that the train moves at different speeds and proposed ICN model for ITS utilizing our proactive-caching strategy or not. It can be seen from the Figure 4.7 that the Interest rate is not directly affected by speed. Instead of that, it maintains a stable rate with or without the proposed proactive-caching scheme. On the other hand, though as expected, when the train starts moving faster, the data rate is lowered in both case, the proposed proactive caching with "smart scheduler" offers data rates about double compared to the case of proactive caching absence. This is because using the proposed proactive-caching scheme, passengers can get valid segments of interested contents that are previously requested in the Content Store of neighbor Station Routers during the time they stay on the train. Hence, we show that the proposal provides better performance for a commuter to gain seamless content access while moving by significant reducing retrieval time.

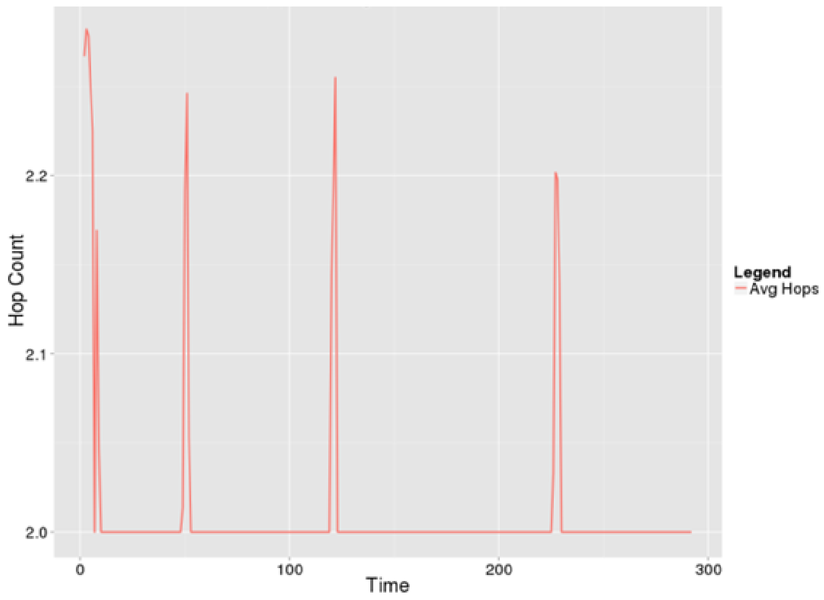

Figure 4. 5 Average Hop Count in Proposed ITS Network System [39]

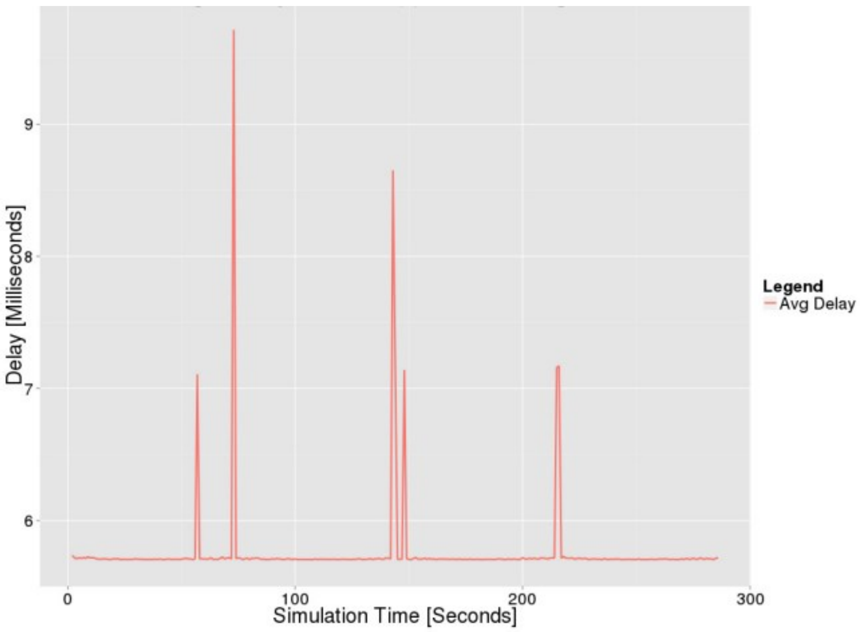

Figure 4. 6 Average Network Delay of Proposed ITS Network System [39]

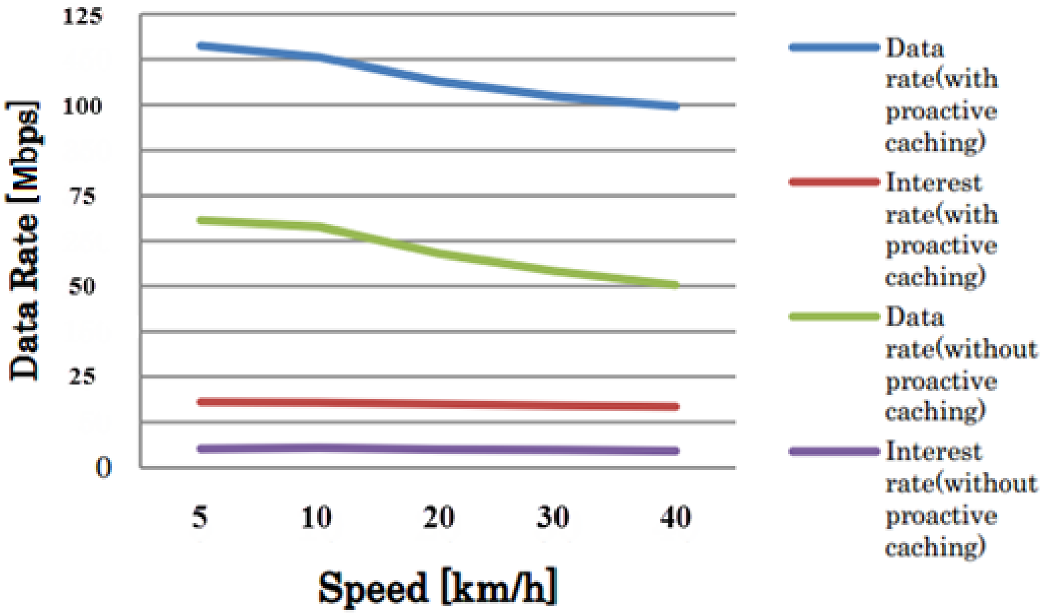

Figure 4. 7 Interest Data Rate versus Train Speed of Proposed ITS Network System [39]

In general, for all of the discussed metrics, simulation with topology for ITS proves the efficiency of our proposal proactive caching ICN model compared to current IP-based model and Conventional ICN design, in terms of energy efficiency and effectiveness (by utilizing flexible and efficient integrated solution of combining ALR and proactive caching based schemes). The evaluation results reveal that our proposed ICN model would be a potential FI solution for cost-effective and EE communications for ITS scenarios.

4.9 Conclusion

In this chapter, we have designed an ICN communication model utilizing innovated dynamic pre-fetching and ALR based strategy together as a practical ITS solution to offer reliable and effective wireless content access for the commuters in the transportation system (particularly public transportation systems). Our proposed system also supports seamless communication to raise content robustness and reliability, then secure the mobile content user's security and can be used in a wide range of transportation system in the future to realize advanced mobile communication. Particularly, thanks to the "smart scheduler", appropriate content segments are pushed in advance, then the proposed ICN-based Internet access scheme can significant diminish negative impacts, e.g. high latency, low data rate and support seamless communication by improving reliability, QoE and network performance. The simulation results corroborate our theoretical idea and reveal the efficiency of our proposed scheme, in terms of effectiveness (low latency) and energy efficiency (up to 20% energy saving), compared to both of current IP-based Internet architecture and conventional ICN (NDN design).

Chapter 5

The Scalable Context-Aware Optimized Green ICN Model (CAGIM) for Future Wireless Communications

5.1 Introduction

The Green ICN model with proactive-caching and ALR (Adaptive Link Rate) based schemes in Chapter 4 performed well for the specific case of content delivery in Transportation System. However, the evaluations were limited to a small scale, and we did not consider the general communication means of WLAN, a much more popular and among the most widely-used wireless network access schemes. Then, to realize a practical scalable ICN-based system for future wireless communications, we consider two approaches in CAGIM: WLAN and Wi-Fi Direct based D2D communications as an alternative network solution when the WLAN is under network failure circumstances. Also, we introduce Distinguished Caching Scheme (DCS), which caches content items according to content type and popularity instead of placing content objects evenly in the cache storage as defined in existing ICN researches to improve the efficiency of cache space utilization. We then revisit the EE topic in ICN from a new perspective by investigating and analyzing the impact of an efficient caching scheme in the context of EE performance. Besides, CAGIM adapts the link-rate of Content Nodes (CNs) from the edge side (Wireless APs) to further optimize the network system energy consumption. This chapter also evaluates the average energy saving ratio of CNs at different levels of proposed topology and demonstrates considerable improvement of CAGIM over conventional ICN design and our original Green ICN model as defined in Chapter 3.

This chapter is based on our previous research publication: **Quang N. Nguyen**, M. Arifuzzaman, Y. Keping and T. Sato, "A Context-Aware Green Information-Centric

Networking Model for Future Wireless Communications," IEEE Access Vol.6, 2018 [52].

5.2 Related Work

5.2.1 ICN Researches in Wireless Environment

Although there is a large body of research tackling challenges in ICN wireless environment, most of the research efforts have focused on mobility scenarios. For instance, CarSpeak [53] realized communications between cars in a content-centric networking model as an interesting ICN based approach for vehicular networks. Another notable work is GreenDelivery [54], in which the authors utilized proactive caching and push-model as an energy efficient solution for the typical case of a small cell system.

In addition, caching scheme and green networking are usually conducted separately in existing ICN studies. In the light of this, besides taking ALR as a measure for EE performance in ICN as we defined in Chapter 3, we introduce a smart priority-based content caching scheme as a potential hybrid approach for greening the wireless ICN system.

Regarding the ICN concept, though currently there are numerous ICN-based models, the proposal is based on NDN (Named Data Networking) prototype [31]. Also note that though we propose CAGIM for incremental NDN deployment, the proposal is not limited to NDN and can be applied to any other ICN frameworks.

5.2.2 Wi-Fi Technology and Wi-Fi Direct for Device to Device (D2D) Content Sharing

Nowadays, Wi-Fi is a predominant mean for daily broadband wireless access as Wi-Fi traffic will account for almost half of the total IP traffic by 2020, up from 42% in 2015

[55]: A majority of wireless devices today is communicating via Wi-Fi APs, thanks to the simplified management and inexpensive data cost.

Wi-Fi Direct is a technological evolution which supports peer-to-peer Wi-Fi connections between devices in various indoor and outdoor scenarios. Wi-Fi Direct was recently standardized by Wi-Fi Alliance as a protocol for supporting direct communications (D2D) with higher data rate and longer ranges support compared to ZigBee or Bluetooth [56]. In particular, Wi-Fi Direct sets up wireless communications among a group of in-proximity wireless devices and helps to off-load data from cellular infrastructure to UE (User Equipment). D2D communication among peers in Wi-Fi Direct is within a group where only one device in the group acts as Group Owner (GO), and others are clients of the group. D2D connections between devices also improve network throughput and EE as analyzed in a recent study on D2D smart-phone networks [57].

In this research, we apply the concept of Wi-Fi Direct and Wi-Fi technologies which realizes both WLAN and Wi-Fi Direct D2D transmission schemes with simple and self-scalable domains for wireless/mobile devices in ICN. Thus, the combined solution acts as an efficient context-aware communication model, instead of considering ALR, ICN caching, and Wi-Fi Direct individually as of existing research work in ICN, especially in the context of EE networking.

5.3 The Wireless Network Topology and Assumptions

We consider the (L+1) level tree-based network topology including a cluster of M servers which acts as CPs (Content Providers) and a total of N CNs (Content Nodes), as depicted in Figure 5.1. We select the tree topology to closely reflect how the CN link rate varies at different levels of network topology. This type of topology also represents typical content delivery scenarios and has been widely used in ICN studies [38] [58]. A CN can be either a CR (Content Router) or a Wireless AP, under the assumption that each AP also has the caching function and a CN can work as an NDN node [3]. In more detail, the cluster of CPs is the root node at level (L+1), and all CNs are allocated in other lower levels of the tree topology. We assume that the ICN system delivers different content c. C is the set of all available content items (i.e., $c \in C$) and all content objects are stored at the CPs (servers).

In this model, a wireless user connects to the wireless access network via a Wi-Fi AP at his/her current location at the first level of the ICN based topology to get interested content items. The user then can get the desired data by receiving original content from a CP or a replica of desired content from an appropriate *CN* with caching capability via a wired connection. These Data packets are in turn transmitted to the wireless user via the device's wireless interface. Content delivery is conducted at the level of data chunks (segments), i.e., chunk-by-chunk transmission from the first to the last segment.

This research focuses on wireless communications with limited mobility (WLAN scenario). Hence, under the assumption that all APs have the same transmission radius, we assume that a wireless/mobile device only moves within a specified area managed by a Wireless AP at the edge network as a PoA (Point of Attachment). Also note that though the network nodes and APs are interconnected in a tree topology, we can apply the proposal to various dynamic multi-tier network models where the APs connect directly to the users located at the first level of the network, then level two CNs link to these APs, and so on.

The following sections (Section 5.4 and Section 5.5) state the proposed model to yield energy savings with respective network topology in WLAN for ICN based wireless communications.

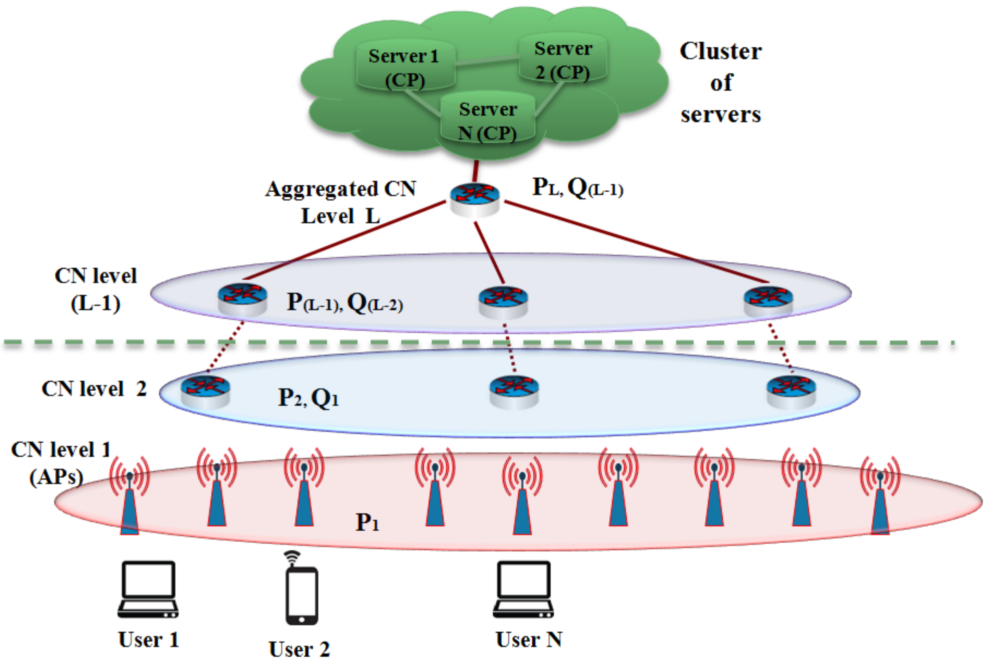

Figure 5. 1 Network Topology for the Proposed Wireless ICN System [52]

5.4 The Enhanced Rate Adaptive Operating Scheme for Content Routers

In this part, we assume that all CNs (CRs and Wireless APs) are equipped with ALR technique [7] so that they enable scaling of network device's operating link rate to real traffic needs for saving network system power consumption. Through the observation that content objects would be found in the caches of ICN nodes, we adopt the ALR-based scheme which can adjust the associated link rate of a CN to its optimized utilization according to the popularity levels of content items that the network node serves (as defined in Chapter 3). The notations in Table 5.1 are used for the Green ICN proposal. Note that this section is an extended design of the adaptation scheme defined in Section 3.2 for the case of scalable wireless accesses using widely-available Wi-Fi technologies.

We first define p_k as the probability that the users can find interested content at a CN with a distance of k hops away from them (a level-k CN). Every CN located at the same level k of the network topology shares the same value of p_k because we assume that the Interest packets, i.e., requests for content objects from all users, are i.i.d. (independent and identically distributed). Note that the content popularity level of a content is identified according to the number of requests from users for the content (i.e., indicated by the frequency of a certain item being requested by consumers). For content popularity model, we use Zipf distribution to abstract content popularity into various content classes: distinct content items with same popularity level have the same value of p_k and belong to the same content class. A content gets more popular if it has a higher number of Interest packets from the users. A more popular content is then expected to be closer to the users, and it tends to be found at lower levels. This tendency is opposite to current IP-based design in which the only way for a user to get an interested content is to send the request to the server via routers, i.e., $p_k = 0 \ \forall k \in (1, 2, \dots, L)$ and $p_{L+1} = 1$. Then, we define Q_k as the probability that a user has to traverse a total of k hops from edge node (Wireless AP), and Q_k can be determined by following formula:

$$Q_k = p_{k+1} \prod_{l=1}^{k}(1 - p_l). \tag{5.1}$$

Let R_k be the incoming link-rate to a level-k CN in proposed ICN system. Since a popular content has a higher tendency to be found at the lower levels, we determine that the maximum link rate is for the level one CNs, which are APs, i.e., $R_1 > R_k$ where $1 < k \leq L$. This operating method efficiently diminishes power consumed by CN at high levels, especially in the case of large-scale networks with a large number of access nodes.

We introduce T_P as a threshold variable to identify whether a content is popular. Specifically, if a single content c has $p_1 \geq T_p$, it is determined as a popular content. Otherwise, it is a non-popular content. The adapting rate policy then dynamically adjusts the individual link rate of a Wi-Fi AP operating interface as follows: This link rate is equal to link rate as of the conventional ICN design in case of popular content and is lower than that value otherwise. The reason is that the popular/important content objects should be transmitted with a higher link rate than the unpopular ones so that a higher number of Interest packets can be satisfied locally within a shorter distance.

As operating rate of first level CRs can be scaled down to gain higher energy savings according to the content demand, we adapt the link rate to the actual value of optimized network utilization from the first level, rather than from higher level as we did in Chapter 3. Particularly, considering the case when a single or multiple Interest packets come to an AP at level one but only ask for a single non-popular content c ∈ C, the new optimized value for R_1, i.e., the adjusted link rate for CR at level one is:

$$New\ R_{1,ICN} = (1-\beta)R_{ICN} + \beta\ (R_{ICN}\ \frac{p_1}{T_P})\ , \tag{5.2}$$

where β represents the ratio of CNs with ALR function, and R_{ICN} is the link rate capacity in conventional ICN without ALR-based method.

Hence, without loss of generality, the new optimized value for R_1 (*Optimized* $\text{R}_{1,\text{ICN}}$) when the users only have interests for non-popular content(s) can be calculated as:

$$Optimized\ R_{1,ICN} = (1-\beta)R_{ICN} + \beta\ (R_{ICN}\ \frac{\max\ p_{1c}}{T_P})$$

$$\forall Content\ c \in S_1\ and\ |S_1|\ \leq S. \tag{5.3}$$

And the optimized value for R_1 in case at least one request for a popular content is sent to first level AP is:

$$Optimized\ R_{1,ICN} = R_{ICN}\ , \tag{5.4}$$

where S defines the maximum number of content objects that each CN can cache, and S_k is the set of all distinct content items that users send Interest packets to a CN at level k.

In (5.3), the max functions denotes that a first-level CN needs to get adequate required link rate to serve the demand of the most popular content (highest p_1) among the set of all unpopular content items c ∈ S_1.

Table 5. 1 Notation Used for Proposed CAGIM [52]

Notation	Meaning
p_k	The probability that one user can find a specific content c ϵ C at a level-k CN (Figure 5.1)
Q_k	The probability that a user has to traverse a total of k level of topology ($1 \leq k \leq L$) to find an interested content c (Figure 5.2)
R_k	The incoming link rate to a level-k CN
S	Maximum number of content objects that each CN can cache
T_p	The threshold value of p_1 for all content c ∈ C to classify popular and unpopular content
R_{ICN}	The link rate capacity in the conventional ICN design
β	The ratio of CNs which support ALR function (when β =1, CN operating power is ideally proportional to the link utilization)
S_k	The set of all distinguished content items that users send Interest packets to a level-k CN
Optimized $R_{k,\mathrm{ICN}}$	The adjusted value of R_k in proposed ICN model to minimize CN operating power
$P_{R2\text{-}ICN}$	Operating power consumed by a CR in conventional ICN
$P_{R2\text{-}ICN,k}$	The value of operating power consumption of a CN at level k in proposed ICN model
$P_{\mathrm{R2\text{-}AP,\ base}}$	The base power consumption of AP (fixed value)

Next, R_k ($1 < k \leq L$) is adapted to the optimized operating link utilization of an ICN router according to the value of R_1 and popularity levels of all requests for distinguished content objects c sent to it (c ∈ S_k). This method reduces network resource consumption for energy savings. Hence, the optimized operating link rate for minimizing the operating power of a level-k ICN CR (*Optimized* $R_{k,\mathrm{ICN}}$) can be identified by (5.5) for popular content(s):

$$Optimized\ R_{k,ICN} = (1-\beta)R_{ICN} + \beta\,\{\,R_{ICN}\ [1-\min(p_{1c}+\textstyle\sum_{l=1}^{k-2} Q_{lc})]\}\,, \quad (5.5)$$

and (5.6) for the case of only non-popular content(s):

$$Optimized\ R_{k,ICN} = Optimized\ R_{1,ICN}\ [1-\min(p_{1c}+\textstyle\sum_{l=1}^{k-2} Q_{lc})]\} \quad (5.6)$$

$$\forall Content\ c \in S_k\ and\ |S_k| \leq S. \quad (5.7)$$

Since distinct content items may have different content popularities, the min function in (5.5) and (5.6) returns the highest value of link rate among all required by users in a specified CR level k. Specifically, the expression $[1-(p_1+\sum_{l=1}^{k-2} Q_l)]$in (5.5) and (5.6) indicates the scale-down power saving ratio of a CN at level *l* for transmitting a single content c with ALR function. Equation (5.5) and (5.6) then share the same constraint (5.7) to ensure that the ALR-based policy matches different popularity levels of all content items that the level-k CN needs to serve. Thanks for this working mechanism, for the less popular content items, the operating link rates of CRs at higher levels for transmitting content are decreased according to the rate values of edge CR and lower CRs.

Let $P_{R2\text{-}ICN}$ be the operating power consumed by a CR in conventional ICN. Suppose that all CRs are equipped with ALR function, the optimized value of $P_{R2\text{-}ICN,k}$ can be identified as:

$$Optimized\ P_{R2\text{-}ICN,k} = \frac{Optimized\ R_{k,ICN}}{R_{ICN}}\, P_{R2\text{-}ICN}. \quad (5.8)$$

Hence, for this proposed ICN model, when a content gets more popular, the load of the network decreases, which leads to lower operating power at higher topology levels. This mechanism then can save substantial power, especially in case of serving popular contents or when users mainly ask for popular content items.

Regarding the Wireless APs at level one of the tree topology, different from CR, an AP still consumes a fixed amount of power even if it is in the idle state [59]. The consumed power is the AP's base-power consumption ($P_{R2\text{-AP,base}}$). Therefore, in the case of non-popular content(s), if *Optimized* $P_{R2\text{-}ICN,1} < P_{R2\text{-AP,base}}$ then (5.3) is replaced by the following formula:

$$\text{Optimized } P_{R2\text{-ICN},1} = P_{R2\text{-AP,base}}. \tag{5.9}$$

As a result, the proposed ALR adapts the link rate based on both traffic load and content popularity level to minimize the power consumption of CRs (as defined from (5.3) to (5.6)).

5.5 The Proposed Context-Aware Hybrid Caching Policy for efficient Communications

This section discusses a smart caching scheme with customized caching policies for different types of content and popularity levels. The context-aware caching scheme further increases the power saving achieved by the ALR based-technique defined in the previous section (Section 5.4).

5.5.1 Types of Content

For the proposed ICN system's caching policy, to indicate the importance and priority of a content for transmission, we define two types of content: emergency content and non-emergency content. Emergency content objects are 'first-class' content items like content with urgent information (planned maintenance, system upgrade or even disaster warning) or important content items in case of network infrastructure failures (broken physical links, corrupted connection) and then have the highest priority to be kept in ICN caches. Non-emergency content items are remaining content objects which are either popular or unpopular content items with higher priority to be cached for more popular content (based on the value of p_1).

To achieve this goal, we propose a modification to the hierarchical naming structure of ICN (typically NDN design [31]) by appending a new binary bit at the beginning of content name prefix field in the Data packets as the foremost component. Since this approach still follows the ICN (NDN) forwarding mechanism with content name longest-prefix match for FIB to serve the Interest packets, the emergency ID bit identifies the content type and is an important attribute attached to content name for the retrieval process. In detail, if the first bit of a content name prefix has a value of one, the content is an emergency content. Otherwise, a normal content (non-emergency content) is identified. This method with appended header binary value is feasible as there are reserved fields for customized status code and extra information indication when the Interest packet is responded in NDN [3]. This naming method hence improves the proposal feasibility with light additional overhead as well as allows content-aware routing and can be simply depicted as shown in Figure 5.2.

Note that the Emergency ID bit field can only be set by the valid content producers (the default value is 0, i.e., non-emergency one). Then in the case of emergency content, the content is pushed from the producers to other nodes within the domain. Also, the emergency content has the timer value then after that value, the content will be treated as a normal content based on its Interest arrival rate.

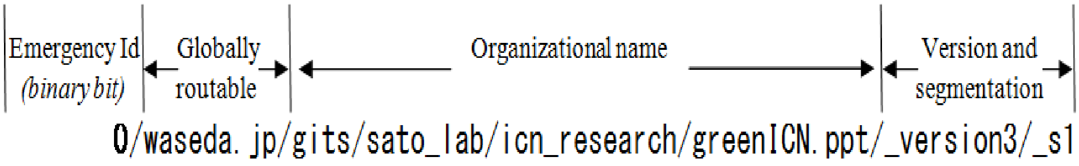

Figure 5.2 Content Name Prefix with New Emergency Identifier Bit [52]

5.5.2 The Hybrid Caching Policy

As CNs are assumed to have ALR function which can adapt the link rate to match traffic load and in turn save power, we propose DCS as a hybrid green caching policy to maximize the power savings. The idea is to cache a content object either entirely or partially on the CS according to its content type and popularity to increase the total number of content objects that can be stored in a CN and to increase the diversity of cached content. By doing so, content requests can be served locally from CNs memory cache as much as possible to reduce hop count and server load. As a result of the reduced traffic load, server and CN power consumption are minimized, which in turn enhance the quality of service (QoS).

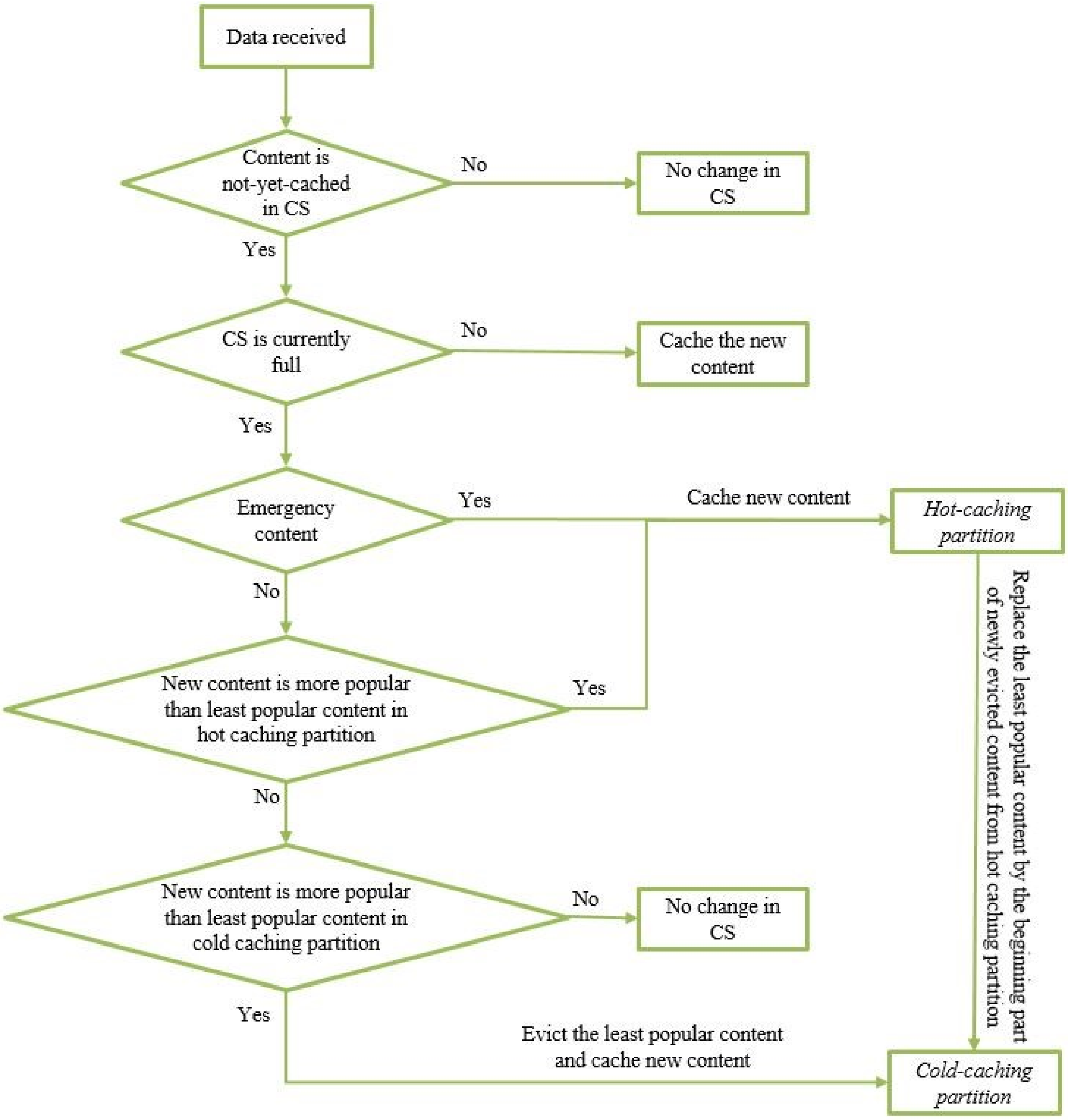

Figure 5.3 Hybrid Caching and Eviction Schemes [52]

We design the hybrid caching policy to deal with both emergency and non-emergency content items by dividing the caching memory capacity of a CN (CS) into two caching partitions, namely *hot-caching partition* which stores popular and emergency content items, and *cold-caching partition*, which is smaller and dedicated to partial data of non-popular content objects. This cache partitioning caching strategy's goal is to prevent interfered traffic from happening in ICN.

As CNs have the function of ALR to save power, we propose DCS as a green chunk-level caching scheme which further diminishes the overall network system power consumption by minimizing traffic load via the enhanced cache efficiency. Specifically, we employ the chunk-level caching mechanism in which a content includes a series of fixed-sized chunks which are cached on CS (Content Store) of CNs along the content delivery path. We use LCE (Leave Copy Everywhere), the default cache admission policy of ICN, which caches content items in all the (intermediate) CNs along the delivery path, as the caching scheme for all emergency content items in the hot-caching partition. This method allows urgent information sharing services in emergency cases to be broadcasted to all CNs in the same domain.

For all other non-emergency content objects, we define a new caching strategy in accordance with content popularity and name it as DCS (Distinguished Caching Scheme) to deal with the inefficiency problem of LCE. DCS adapts its caching strategy to content priority based on content type and content popularity level as follows:

(a) Hot-caching partition of a CN caching memory caches whole data of emergency and/or popular content items (which have $p_I \geq T_p$) that the CN serves. Emergency content objects are given the highest priority to be cached here.

(b) Different from the hot-caching partition, the cold-caching partition of a CN caching memory only caches the beginning part of the non-popular content. This partly caching strategy matches users' demand tendency for content items in the future, which are big-size content objects. Also, video content items, e.g., streaming content or VoD (Video on Demand) will take the major ratio of Internet traffic in the Big Data era, and it is observed that users tend to stop watching video after the beginning part. In other words, foremost chunks of a content would have higher popularity level than remaining (other) chunks within a file. We define that cold-caching partition has smaller size compared to the hot partition. This is because the cold-caching partition needs to store only sufficient initial chunks of unpopular content items at CN cache for the goal of diminishing the latency and matching user access pattern.

To realize a complete caching scheme for efficiently allocating content data among ICN caches, we now propose a new replacement eviction (replacement) policy for CAGIM, instead of simply applying LRU (Least Recently Used) policy as of default ICN. Particularly, when a CN needs to serve an Interest packet, it first checks whether the requested content is stored in the caching memory (CS). If a not-yet-cached content needs to be served by a CN and the cache storage of the CN is full, then a cache replacement may occur. At that time, the cached content with lowest p_l value, which refers to the lowest popular content in the cache, will only be replaced in case that its p_l value is smaller than that of the new one (except the case of emergency contents). If multiple cached content items in CS have the same popularity level, then LRU is utilized to determine which cached content is the candidate for eviction. Thus, for efficient cache resource allocation, DCS dynamically adjusts the caching ratio (i.e., number of chunks for content caching) corresponding to content popularity and the variation of content objects stored in CS of each CN, instead of always caching whole content items as of ongoing researches on ICN caching.

The detailed hybrid caching and eviction schemes are presented in Figure 5.3, where a specific content c is more popular than another content item if c has higher p_l value. Furthermore, one interesting point is that for the eviction policy, DCS can move content from hot to cold-caching partition when needed by deleting the last parts of the cached content. Particularly, the beginning data part of the newly evicted content from the hot partition, which is the same ratio as of non-popular content objects held in the cache storage, will be moved to the cold partition (Figure 5.3). As a popular content still can be demoted to cold caching partition when CS is full, a popular content then has a higher chance to be cached for serving the potential future content requests. This strategy reflects the observed fact that a relatively small number of popular content items is requested with very high frequency whereas the remaining huge number of content objects is seldom requested. The proposed strategy also efficiently utilizes the cache capacity because it reduces the number of duplicated content chunks by realizing higher cache diversity compared to standard ICN.

Overall, DCS makes the full use of limited cache storage of CR (CS) to solve suboptimal cache utilization problem by jointly considering content popularity and user behaviors to minimize bandwidth and traffic load. From the diminished number of packets transmitted to higher levels and CPs, the ALR-based mechanism (as defined in Section 5.4) dynamically adjusts link rate to match both popularity of requested content and reduced traffic load for maximum gain in power savings. As a result, thanks to the improved CS utilization efficiency, DCS also further reduces power consumption from CNs (with optimized link rate mechanism) via the minimum traffic load.

5.6 The Wi-Fi Direct based D2D Communications for Important Content Sharing

The Wi-Fi Direct based D2D communication scheme is only triggered when the ICN based WLAN links are not available (i.e., link failures occur) or when the whole network system is not accessible. This method minimizes the negative impact to the users due to the limited battery and storage capacity as well as due to the selfish nature of wireless users. Otherwise, the users still connect to the Internet and get interested data through ICN based WLAN as defined in Section 5.5.

5.6.1 The Wi-Fi Direct-based Communications and Data Transmission Scheme

Wi-Fi Direct imitates WLAN infrastructure, in which other group members consider the GO (Group Owner) as working AP in WLAN [56] [60]. The GO must be a Wi-Fi Direct-enabled node whereas clients can be either Wi-Fi Direct supporting devices or conventional Wi-Fi nodes.

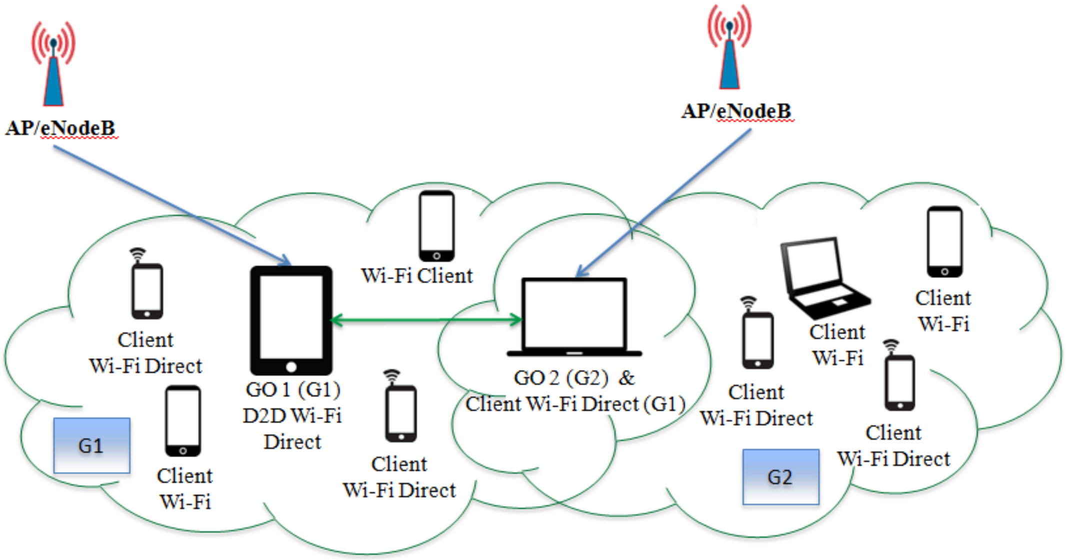

Figure 5. 4 Communication Model in Wi-Fi Direct-based Scheme [52]

We assume that GOs are connected to WLAN via APs (at the lowest level of the hierarchical network model). For the sake of simplicity, the connected Wi-Fi Direct CN at network edge operates as a controller, which manages and coordinates the group formation and content transmission processes. In this proposal, due to the limited cache size of the GO, a content object is just taken from a single GO in case of network failure (i.e., WLAN is not available). At that time, the GO acts as a local gateway by sharing the locally cached content chunks to all of its registered peers via the Wi-Fi Direct D2D links.

Regarding data transmission within a group, by rebroadcasting content chunks to other clients, the GO enables multicast transmission of same content to its multiple attached clients and promotes proactive caching of important content objects with low latency for emergency contexts, instead of allowing only a single transmission at a low rate. The D2D transmission within a group is a single-hop content delivery because all clients consider the GO as the only choice for next-hop. If the desired data are not available in the Wi-Fi Direct group (i.e., a cache miss), the GO will need to download from the closest network node which possesses the data (AP/eNodeB) or its preferred remote network toward data source.

For inter-domain communications between groups, a peer can be a bridge between different groups by acting as a GO of one group and as a client in other groups at the same time as a scenario depicted in Figure 5.4. This kind of GO or a suitable group client in the range of other groups then can work as a relay node to neighboring groups. Hence, the wireless users can get updated important information with considerably lower latency from the nearest authoritative content source such as a local repository or a specific node, in the case of emergency/disaster. The detailed mechanism of multi-group communications with relay node selection method will be presented in our separate work as an approach for supporting multi-hop D2D base communications in ICN.

5.6.2 Group Owner (GO) Selection and Power-Saving Methodologies

Regarding the GO selection, a wireless/mobile device initiates the discovery process by performing a regular Wi-Fi scan. After getting Probe response as confirmation from Wi-Fi AP on dedicated "social" channels (channel 1, 6 and 11), the device then may get into GO negotiation process if the group needs a new GO. The GO selection is based on the willingness of devices (identified by an integer Intent value from 1 to 15). Wi-Fi Direct equips two novel power saving mechanisms for the GO, namely NoA (Notice of Absence) and opportunistic power saving [60].

Also, since a GO has limited storage and energy capacity compared to a conventional CN, we propose that whether a node within a group is selected as a GO depending on additional criteria. For example, the GO selection process can be based on the residual energy level, the number of times that a node is used as a GO, and a GO will only serve for a specific period. Particularly, the GO should be selected from more powerful devices of the Wi-Fi Direct group, and a wireless node with an under-threshold value of residual energy is not considered for the GO selection process to prevent the node from ending up with energy drain. Also, for the goal of network sustainability, the GO needs to be rotated dynamically when it endures less than a predefined threshold energy value. This policy prolongs the lifetime of battery-powered wireless/mobile devices effectively, especially in case of disaster/emergency when a device is difficult to recharge.

This cooperative fair power consumption control scheme is critical for network sustainability because the GO can be considered as a point of failure in a Wi-Fi Direct network.

5.6.3 The simplified Priority-based Caching Scheme

In the situation when the Wi-Fi Direct communication is activated, we consider that only the most important data (high priority) are stored and forwarded to clients from GO due to the GO's limited cache capacity. Essential/important content items are emergency and the most popular small-size content objects because they are requested much more frequently since their births, compared to the remaining ones.

Suppose that the emergency content items have the highest priority to be stored to improve GO's cache memory efficiency. We then propose GO's caching mechanism as illustrated in Figure 5.5. This method is effective in the case that infrastructure like access network (WLAN) or cellular network is unavailable because people in same cluster/region (geographical location) may share the requests for similar content objects. In particular, emergency and most popular content objects are defined to reflect the spatial locality of the content dynamically. Also, essential emergency content objects like notices, safety confirmation or important information like breaking news are usually shaped in a relatively small size. In a research about the dependency between data size and energy consumption of transmission process using various wireless interfaces [61], the authors showed that Wi-Fi is the best medium for data transmission since it is more energy-efficient when transferring data, especially small-size data, compared to 3G and LTE.

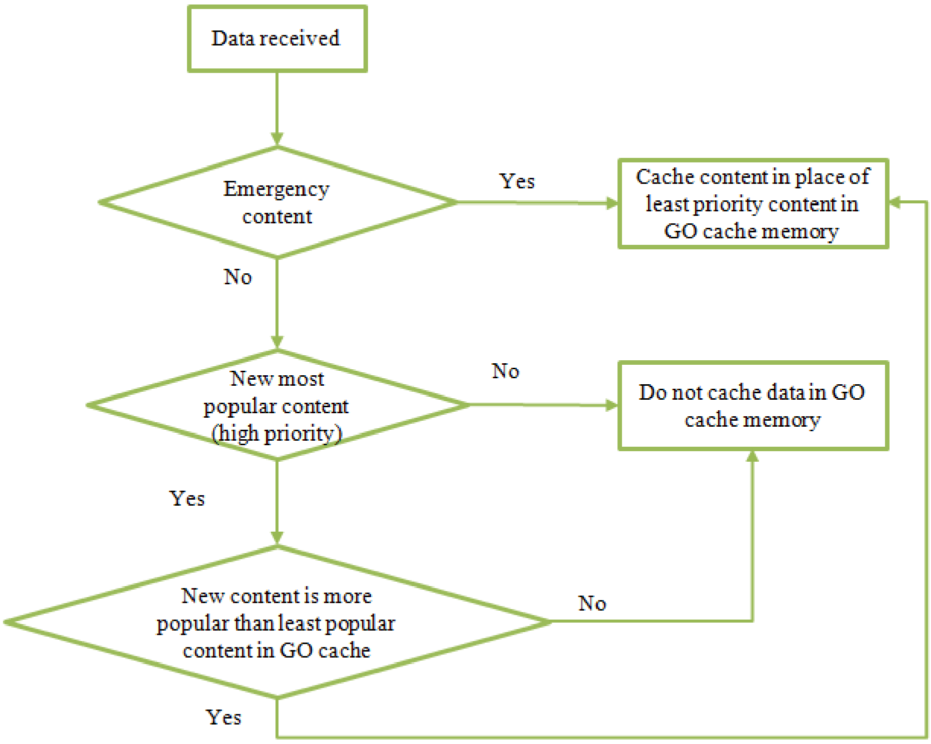

Figure 5. 5 GO's Caching Mechanism when Wi-Fi Direct is activated [52]

Besides, the important/necessary content items are expected to broadcast with low latency and transmit even to disconnected areas without ACK signal through direct communications. The important content caching mechanism at GO then enhances the probability that a user can get complete data of an interested content at once to improve QoE (Quality of Experience) in unwanted scenarios.

Overall, the introduction of mobile/wireless device cache for maintaining and storing the high-priority content objects can significantly improve QoE of the user by collecting and disseminating only the critical data. Particularly, this method improves the utilization of limited cache resources, even when just a small/limited storage is available for caching. This is a potential approach, given the fact that mobile devices are overgrowing and they are equipped with higher battery capacity, multiple heterogeneous wireless interfaces, and especially larger storage. The communication scheme also helps to alleviate the mobile operator burden by leveraging unlicensed "social" channels of Wi-Fi Direct to save expensive cellular resources because high-end mobile/wireless devices usually give high priority to Wi-Fi radio interface, rather than 3G or LTE (irrespective of signal strength).

5.7 The Enhanced Mathematical Energy Modeling Formulations for EE Evaluations

Before discussing energy consumption of our proposed system and other network system approaches, we formulate the rigorous energy model of each network system for EE analysis as an extension of the Energy model in Chapter 3. The total energy of a network system is calculated by summing up the energy consumed by all network components, and we assume each network comprises two primary elements: *N* CNs and *M* CPs. We do not consider the power consumption of mobile users here, but we will address this topic by conducting the detail evaluations of energy consumption and the saving ratio of mobile devices in another study.

5.7.1 Energy Consumption in an IP-based Network System

The energy consumption of an IP-based network system can be identified using the following formula:

$$\begin{aligned} E_{IP} &= N\ E_{R-IP} + M\ E_S \\ &= N\ P_{R1-IP}\ T_w + N_1\ P_{R2-IP}\ T_w + N_2\ P_{R2,AP-IP}\ T_w \\ &\quad + M\ \left(P_{S1}\ T_w + P_{S2}\ T_w + P_{S3}\ T_w\right)\ , \end{aligned} \tag{5.10}$$

where $E_{R\text{-}IP}$ and E_S are the energy consumed by an IP router and energy consumed by the server; $P_{R1\text{-}IP}$, $P_{R2\text{-}IP}$, and $P_{R2,AP\text{-}IP}$ are the embodied power of a network node (router/AP), the working power of an IP router, and working power of an AP, respectively; N_1 and N_2 are the numbers of routers and number of APs ($N_1 + N_2 = N$) and P_{S1}, P_{S2}, and P_{S3} are the embodied power, power for server storage, and operating power of a server (same value for both ICN and IP-based network system), respectively. Besides, T_w is the working time of the whole network system.

5.7.2 Energy Consumption in a Conventional ICN System

The conventional ICN represents the case when no green mechanism is associated with the ICN system, and its energy consumption is:

$$\begin{aligned} E_{ICN} &= N\ E_{R-ICN} + M\ E_S \\ &= N\ (P_{R1-ICN}\ T_w + P_{R3-ICN}\ T_w) + N_1\ P_{R2-ICN}\ T_w \\ &\quad + N_2\ P_{R2-ICN,AP}\ T_w + M\ E_S\ , \end{aligned} \tag{5.11}$$

where $P_{R1\text{-}ICN}$, $P_{R2\text{-}ICN}$, and $P_{R3\text{-}ICN}$ are the embodied power, working power, and power to cache memory of a CN (CR/AP), respectively. For power consumption evaluation, both the current IP-based network system and conventional ICN system share the same power consumption for servers, whereas an ICN node consumes slightly higher power compared to a normal IP node because of the CN's caching function.

5.7.3 Energy Consumption in the Proposed ICN System

Total energy consumed by the proposed Green ICN system is a combination of two optimized values to minimize network system energy. Specifically, we utilize CAGIM's adaptive optimization strategies including the proposed ALR-based mechanism for CNs, CPs' optimized operating mode with reduced traffic, and the reduced network load achieved by the proposed caching scheme as defined in previous sections:

$$E_{ICN-Proposal} = \sum_{k=1}^{N} Optimized\, E_{R-ICN,r_k} + \sum_{j=1}^{M} Optimized\;\; E_{S-ICN,S_j} \;, \qquad (5.12)$$

where optimized energy consumption of all CNs:

$$\sum_{k=1}^{N} Optimized\;\; E_{R-ICN,r_k} = N\,(P_{R1-ICN}\; T_w + P_{R3-ICN}\; T_w) + \sum_{k=1}^{N} Optimized\;\; P_{R2-ICN\,,r_k}\, T_{Or_k} + \sum_{k=2}^{N} Optimized\;\; P_{R2-ICN\,,r_{k-1}}\, T_{d_1} + \sum_{i=1}^{N_2} P_{R2-ICN\,,AP-base}\,(\,T_w - T_{Or_{1_i}}) \,, \quad (5.13)$$

and the optimized value of the cluster of M servers (CPs):

$$\sum_{j=1}^{M} Optimized\;\; E_{S-ICN,S_j} = M(P_{S1}\; T_w + P_{S2}\; T_w) + \sum_{j=1}^{M}\; Optimized\, P_{S3,S_j}\,(\,T_{O_{S_j}} + x_{S_j}\; T_{d_2}) \,,$$

(5.14)

where T_{Or_k} is the operating time of router r_k (router at level k of tree topology) with proposed ALR design, and $T_{O_{S_j}}$ is the operating time of the server S_j with optimized power mode. As CAGIM incurs extra delays for switching the operating mode of CP or link rate of CRs, we denote T_{d_1} and T_{d_2} are transition times between successive link rate changes and CP operating mode switches, respectively. In addition, x_{S_j} is a binary variable that indicates whether the next optimized operating mode of a server S_j is different from its current optimized mode: If the optimized mode does not change after period T then x_{S_j} takes the value of 0. Otherwise, its value is 1. Hence, there is an additional incurred energy consumption for switching between different network device operating modes or rate switches.

5.8 Performance Evaluations and Discussion

5.8.1 Network Scenario, Key Parameters, and Simulation Settings

In this section, we verify the benefits of the proposed CAGIM by simulation with ndnSIM [49], a common scalable ns3-based NDN simulator. For this research evaluation, the CNs are connected in a complete ternary six-level tree model (degree of three) through wired linked, whereas wireless content users access network via wireless links of WLAN as shown in Figure 5.1. As Wi-Fi Direct implementation is currently not available in the ns-3 framework, we adopt the 802.11n standard for the wireless AP connections. We installed NDN stack in each CN so that all ICN nodes have the three functional blocks of the PIT (Pending Interest Table), FIB (Forwarding Interest Base) and CS as of an NDN node [3] and suppose that network devices fully support ALR function ($\beta = 1$). Since the Wi-Fi Direct based protocol is a layer-two wireless communication and only deployed at the MAC layer whereas NDN functions are installed at the network device level, this does not affect the overall performance of the wireless access network as well as energy models of systems defined in Section 5.7. Note that the detailed EE performance of the Wi-Fi Direct-based protocol presented in this proposal will be evaluated in our later work by means of simulation and/or field trip experiment.

For simplicity, we assume that content objects have the same size of 800 MB with a chunk payload size of 1KB to prevent fragmentation. The link capacity/bandwidth used for simulation 100 Mb/s for wired and 65 Mb/s for wireless connections. The total number of distinct objects is 120,000 including 5% emergency content items (identified by the emergency Identifier bit), and top 10% most popular content objects act as important content items. T_p is defined as the p_1 value of the least popular content among top 30% most popular content class. We use one server with 100 TB as the CP at the root node for the evaluation. Specifically, we define the power consumptions of I mode and F modes are 40% and 100% of server power capacity, respectively. We simulate with 500 concurrent content users under the assumption that each AP serves five users and requests for a (whole) content object follows the Poisson distribution (five Interest packets per second). The typical value of T_{d_1} and T_{d_2} used for simulation are 0.1ms as suggested by [9]. The cold and hot caching memory partitions are set to be 30% and 70% of a CN's cache memory capacity. For cold partition, only 15% data at the beginning of non-popular content items are cached.

Table 5. 2 Network Element and Respective Power Consumptions [52]

Network element	Power consumption (W)
$P_{R1\text{-}IP}$, $P_{R2\text{-}IP}$,$P_{R2,AP\text{-}IP}$	13, 116, 10.2
$P_{R1\text{-}ICN}$ 64, 96, 128, 192, 256 GB	13.5, 14 , 15, 15.5, 16
$P_{R2\text{-}ICN}$ 64, 96, 128, 192, 256 GB	119.6, 120, 120.2, 120.4 ,120.6
$P_{R2\text{-}ICN,AP\text{-}base}$ 64, 96, 128, 192, 256 GB	12.4, 13, 13.4, 13.6, 13.8
$P_{R1\text{-}ICN,AP\text{-}max}$ 64, 96, 128, 192, 256 GB	13.3, 13.9, 14.3, 14.5, 14.7
P_{S1} , P_{S2} , P_{S3} (for each 10 TB), and $P_{R3\text{-}ICN}$	68, 20, 731, and 0.053

We adopt the Zipf distribution as defined by L. Breslau et al. [50] with $\alpha = 0.8$ for the content popularity distribution because it well represents the request frequency of content objects in the network. We refer to related studies to collect data of key network elements with their respective power consumptions [38][51] which is shown in Table 5.2. As mentioned, the scenarios we evaluated and considered is mainly stable, e.g., for users of a company, building or campus access who get data from the network, so we do not focus on mobility nodes.

Then we use same network environment and values of key parameters as aforementioned to make simulation and comparisons between various wireless network system approaches including two current network designs (IP-based system and NDN design [31] as Conventional ICN) and the proposed CAGIM model. We use the hybrid caching scheme of LCE and DCS strategy for the proposed ICN system, whereas LCE with LRU (Least Recently Used) eviction scheme, is used in other network systems if not otherwise specified.

Considering average power saving of network system is total system energy (defined from energy models in Section 5.7) over network runtime, we evaluate different network metrics in our simulation to assess efficiency of CAGIM over the IP-based system and conventional ICN, in terms of both EE and network performances (power consumption and network hop reduction ratio) as follows:

5.8.2 EE Performance Evaluations

(a) Impact of CN cache size on total network system power consumption: We consider seven different candidate CN cache sizes (up to 512 GB) to depict the network scale. From our simulation result in Figure 5.6, the ICN based system power consumption is affected by the CN cache size whereas IP-based network power is independent of cache size values because IP router has no cache size and caching function. In detail, both of conventional ICN and the proposed ICN power increase when we expand cache storage size of CNs due to additional power for CN caching capability. Moreover, the proposed model can save significantly power consumption compared to the other network designs. For example, with 128 GB cache size CNs, the proposed green model can save about 23.2% and 25.3% power compared to the IP based model and conventional ICN (NDN design) in the same scenario, respectively.

(b) Impact of the number of users on total power consumption: We simulate five different situations with 100, 250, 500, 750, and 1000 concurrent users together with

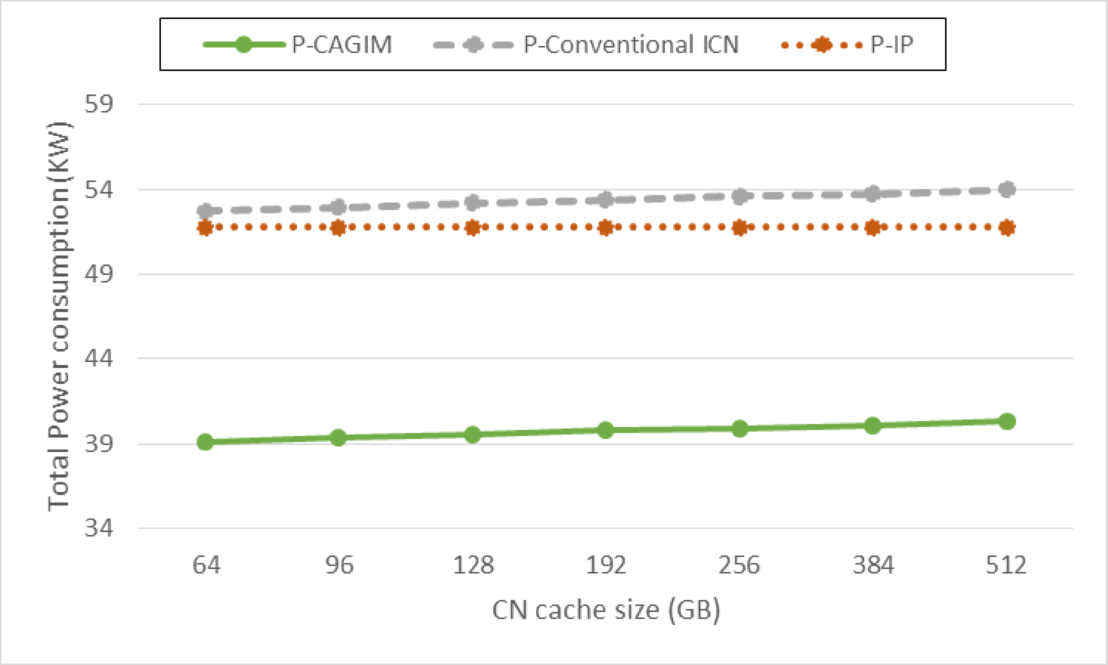

Figure 5. 6 Total Power Consumption of Network Systems with Different Cache Sizes [52]

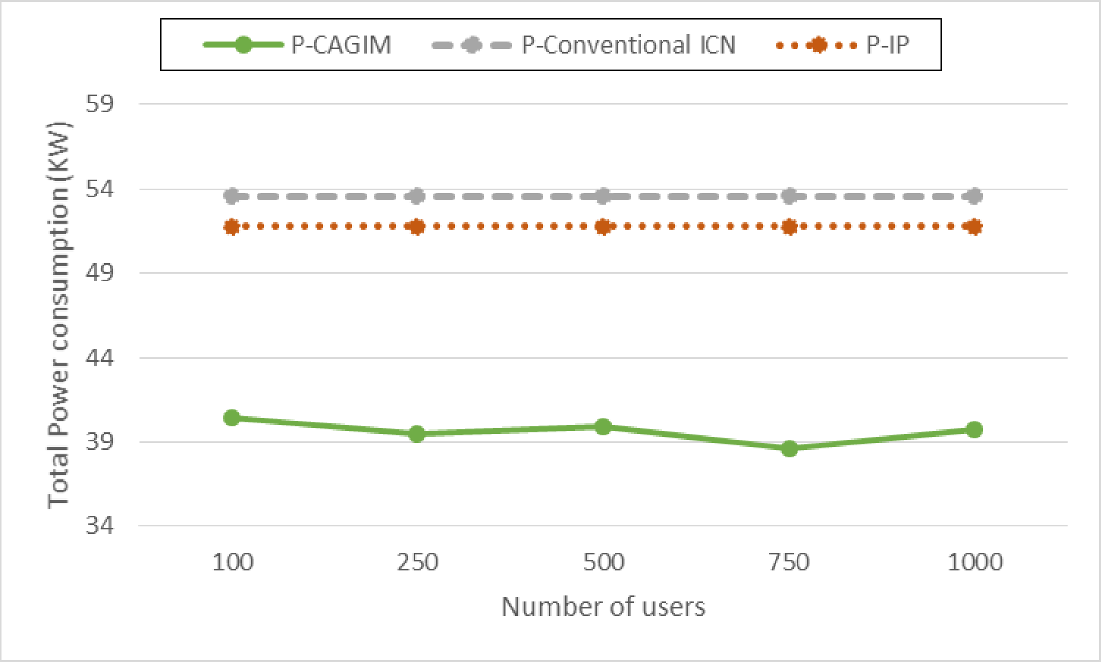

Figure 5. 7 Total Network System Power Consumptions under a Different number of Concurrent Wireless Content User [52]

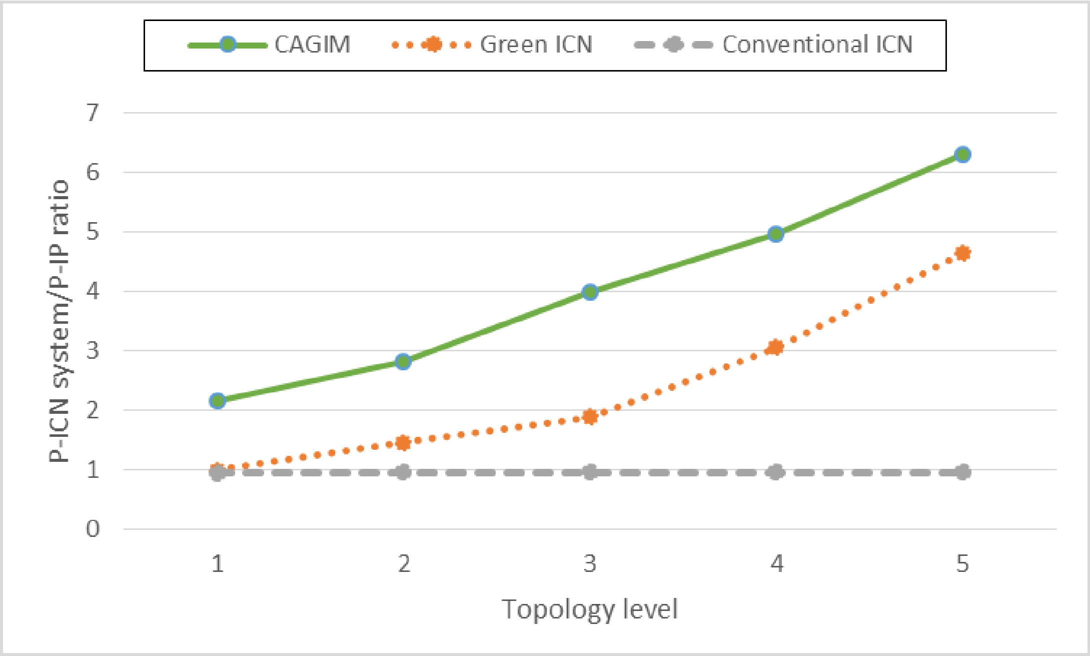

Figure 5. 8 Power Saving ratio Over IP of CNs in Different ICN Systems according to Network Topology Levels [52]

256 GB CNs. Figure 5.7 shows the relatively stable tendency of total system power consumed in CAGIM with a various number of content users. The reason for this stability is that when we increase the number of users, the content caching process only occurs faster (higher content request rate), rather than producing a big change in power consumption. This result is expected, given that the content popularity is fixed (alpha value is constant), and a user only generates a specified number of Interest packets at a time.

(c) Impact of power saving ratio of ICN CNs at different levels: To show the effect of power saving of CNs at different levels of proposed network topology, we investigate the power consumptions of 256 GB CNs with different ICN systems including CAGIM, our previous Green ICN Model defined in Chapter 3 and conventional ICN. We take the IP-based network as the baseline to compare the power saving ratio of these approaches as depicted in Figure 5.8. We then observe that the advantage of greening strategies becomes clearer at the higher level of network topology. In particular, though both CAGIM and our prior model improve the energy efficiency of network devices compared to NDN and IP network by utilizing ALR based scheme, CAGIM shows the higher performance. This is because CAGIM optimizes the link rate from the first level as well as uses a context-based naming and hybrid caching schemes, instead of using LCE with LRU as in our previous work. The result also shows that CAGIM is a scalable ICN approach and performs well when the network gets larger as it operates more efficient in terms of power savings at higher network layers.

5.8.3 Network Performance Evaluations

(d) Impact of hop reduction ratio under various caching schemes and CN cache sizes: To evaluate the proposed hybrid caching strategy, we compare CAGIM with the following four well-known caching strategies in ICN:

1- **Betweeness** [62] applies the concept of betweenness centrality to improve the network caching gain with a centrality-based caching algorithm via important CRs;

2- **ProbCache** [23] caches the received content items at CNs according to its hop reduction to CP and the cache capacity status of the remained CNs along the transmission path;

3- **ARC (Adaptive Replacement Cache)** uses multiple prioritized caches to realize better cache hit for network system with caches; and

4- **LCE** is the default cache placement policy of ICN.

Figure 5.9 shows that our model achieves the best performance of the distance save in terms of hop count for content retrieval whereas LCE performs worst due to its high cache redundancy. Betweeness also does not perform well as it focuses on some particular CNs then leaves other nodes underutilization. Besides, the high hop reduction ratios of CAGIM and ARC show that partitioning the cache space of CN achieves higher performance than sharing the cache (entire CS) among all the types of content items (without partitioning) as of the alternatives. The reason is that DCS distinguishes the caching policies based on context according to the popularity level, content traffic, and content type. Thanks to the cache diversity enhancement, CAGIM improves hop reduction ratio efficiently by serving data close to users, then consumes less resource and energy as well.

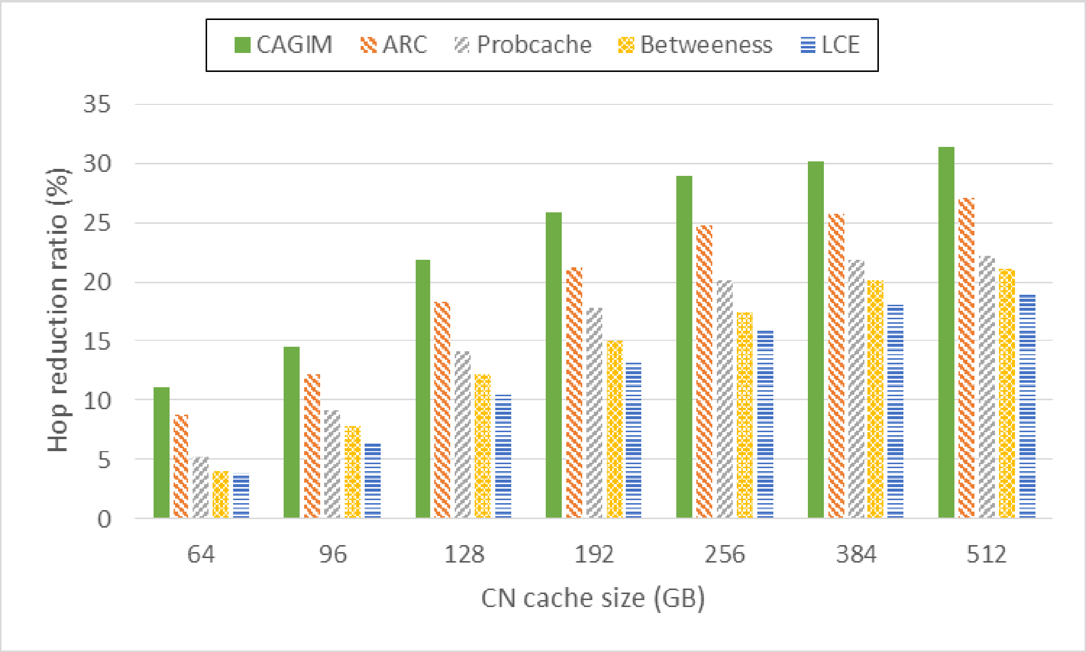

Figure 5.9 Hop Reduction Ratio of ICN Systems employing various Caching Policies versus CN Cache Size [52]

In general, the evaluation results confirm that proposed CAGIM with supporting energy-aware network devices can achieve the goal of efficient content delivery and high energy saving ratio in the network at the same time by consistently outperforms other existing network systems with different widely-used and relevant caching schemes.

5.8.4 Discussion

Overall, the Green ICN model dramatically improves both power consumption and network performance compared to current IP-based model and Conventional ICN design by efficiently utilizing network resource according to network traffic and content popularity levels. Additionally, by further exploring the correlation between power consumption and caching schemes, we show that not only CR link rate adjustments via CN interface (along the retrieval path) and controlling server mode, but also cache capacity and caching policies, can significantly improve network performance, especially for EE goal. Typically, as ICN CRs can store content, the power consumption of proposed ICN system can be considerably saved by caching at CRs, especially at higher levels where less popular content are stored (i.e., low link rate lead to high power gains). The evaluation results then show that the proposed model can be adopted/applied in practice for any hybrid and complex network topologies with identifiable levels on a large scale for efficient multi-hop content distribution. Notice that in contrast, IP-based architecture is not beneficial from the proposed rate adaptation mechanism due to the lack of caching feature for mapping the network nodes' operating rate to the content demand

5.9 Conclusion

In this study, we have designed an energy saving and efficient ICN model utilizing novel *ALR-based scheme* for content delivery in NDN framework, namely *CAGIM.* In addition, we propose a new caching mechanism, namely *DCS*, to solve the inefficient problems of energy consumptions as well as network resource utilization of LCE and current caching schemes. Particularly, DCS dynamically adjusts the number of chunks to be cached based on the content popularity and available CN’s cache space to improve the content diversity of cache storage. In this way, DCS pushes popular content items toward edge network caches while keeping the core network caches ‘cold’. The proposal then efficiently utilizes the limited (and valuable) cache resource for deserved-to-be-cached content objects to reduce the number of packets transmitted to higher level CRs and CPs. This results in the network system’s reduced bandwidth, traffic load, and in turn energy consumption, thanks to the proposed ALR method. Also, we introduce a *Wi-Fi Direct* based communication scheme as an *alternative network solution* for enabling important content sharing when WLAN is not available. Evaluation results verify the efficiency of the prototype Green ICN system by showing that CAGIM utilizing suitable network device achieves more than 20% power savings with high network performance, compared to the other existing wireless access schemes.

Chapter 6

The Need for a Green ICN Model and a Case-Study on the Game-Theory based Economic Incentive Analysis for the Proposed Green ICN System Implementation

In this chapter, we develop a game-theoretical Green ICN prototype incorporating all the proposed techniques as a case-study to analyze the economic incentive of the relevant stakeholders for implementing the proposal in the real-life. We then show that upgrading the IP routers to the Green CRs with a cache memory and adaptive operating mechanism as described in previous chapters is beneficial for network providers to provide user higher QoS and gain values by utilizing network resource more efficiently.

This chapter is based on our previous research publication: **Quang N. Nguyen**, M. Arifuzzaman, Y. Keping and T. Sato, "A game-theoretical green networking approach for information-centric networks," IEEE Conference on Standards for Communications and Networking CSCN, pp. 132-137, Helsinki, 2017 [63].

6.1 Introduction

As discussed, ICN consumes a higher amount of energy compared to the IP-based network due to additional caching energy of content nodes. Therefore, EE is a crucial issue for the feasibility of ICN deployment and analyzing the incentives for building the efficient ICN interconnection is the key to motivate the ICN implementation for FI.

To address this, the authors in [64] emphasized the importance of socio-economic issues when evaluating ICN for FI. However, whereas researchers have recently explored caching and forwarding incentive issues actively, economic implications of energy-efficient caching scheme and economic incentive analyses for widely-applicable ICN infrastructure deployment still have not received adequate considerations. For instance, N. Abani et al. proposed a popularity-based caching for ICN in which more content chunks were progressively cached as a file gets more popular [65]. Furthermore, even such studies on analyzing economic aspect mainly tackle with the evaluation of stakeholders' interactions for caching. Agyapong et al. [66] analyzed the impact of different factors on incentives of related players in ICN, including the ISPs and Content Providers (CPs). The authors built a simple model to address the economic incentive problem of different ICN network players in a hierarchical caching infrastructure. Researchers in [67] utilized a game based model to address the economic implications of caching in ICN by deploying ISP's caching system. This can provide better services, but the authors did not consider cost-savings for the retrieval process. Besides, K. Ohsugi et al. presented an interesting energy-efficient approximation for in-network caching by analyzing the consumption model of an ICN-based software router [68]. Then, the technical design and strategic policy incentives of players to deploy ICN infrastructure are still much less studied up to now and in need of detailed analyses.

Along this line, this chapter aims to assess the relevance of the proposed adaptive Green ICN model to enhance energy-efficiency and cost-effectiveness of access network for FI. We then present a simplified non-cooperative game between an ISP and a network equipment company (manufacturer) as a case-study on the proposed Green ICN model where the ISP is motivated to cache content and build network infrastructure for the goal of energy-efficiency. To address how the ICN network and devices can operate in a highly scalable and energy-efficient way for the real applications, we focus on energy efficiency of CNs (Content Nodes) in ICN. For this purpose, we evaluate total power gain from all CNs and average power saving ratio of CNs at different network topology levels on a bigger scale. We then show that the players can get benefits from caching investment for energy-efficient infrastructure and there is a certain point that they do not have incentives to change their strategic game, i.e., investment in Green ICN model is profitable. In addition, we discuss current ICN deployment challenges and show that the proposal is potential for implementation to enable an efficient socio-economic ICN deployment. This acts as a practical and potential contribution for ICN fast migration process, in the context that previous studies have largely ignored economic incentive assessments of ICN players for energy-efficiency infrastructure deployment.

To the best of our knowledge, we are the first who integrate the technical design of ICN with ICN players' benefits by applying a non-cooperative game theory model into appropriate network infrastructure as a relevant case-study for a practical and simple energy-efficient ICN deployment.

6.2 ICN Standardization Challenges and Research Motivation towards a Standard Green Networking Model in ICN

Thanks to novel ICN caching mechanism, users can get lower latency because requested content can be accessed via a replica instead of only from content source as in current IP-based Internet architecture. Recently, there have been many efforts and research projects related to ICN design recently. A survey in [69] stated various ICN approaches from clean-slate solutions to overlay models. In this research, we select NDN (Named Data Networking [3]) overlay model as a deployable and practical approach since it owns backward-compatible capability [3] [31].

However, most of the ongoing researches in ICN are currently focusing on enhancing ICN performances (by proposing new caching, routing, naming schemes, etc.), hence leaving out energy-efficient issues and respective economic incentives have not been received much attention. Moreover, in most of the current standardization documents of major standard-setting bodies, e.g. ITU, IETF and IRTF related to FI architecture and ICN, activities related to energy-efficiency and economic incentive analyses have not been considered.

Due to the critical importance of these topics and the potential of innovative technologies, we stress the worth of involving them in official ICN standardization process. Since at the same time, standards can encourage novel technology and enable wide adoption of new technology through a common platform.

Motivated by these key challenges and significant facts, this chapter then presents the concept of Green ICN model which offers suitable economic incentives for stakeholders in ICN interconnection and discusses possible low-power consumption deployment policies. Besides, we utilize Game theory as an efficient tool for analysis and assessment of the ISPs and network equipment companies' business decisions to realize a game-based technology innovation across energy area.

This study focuses on both cost-efficiency (low energy consumption) and effectiveness perspective of wireless communication, hence we aim to address and solve the key problem spaces of ICN, namely: scalable, cost-efficient content distribution, mobility and disruption tolerance as identified in ITU Recommendation Y.3033 [70] for Data Aware Networking (DAN), which is considered as ITU concept of ICN for Future Internet.

6.3 A Case-Study on Game-Theory based Model for the Proposed Green ICN Design and Implementation

6.3.1 Two-Players Dynamic Game Model for the Proposed Green ICN System

In this section, we present economic incentives analysis for a non-cooperative scenario by formulating the game between two selfish (independent) players in ICN as a relevant case-study for energy-efficient deployment. The first one is the network equipment company which is the manufacturer of new innovative technology (in this case it produces the ALR-support CNs) but currently only has a small market share and little acceptance. The second player is the ISP which owns good brand value and provides network and services to users with existing infrastructure. The network equipment company roles are producing new ALR-enable network devices for energy-efficiency deployment of ICN then earning a contract for the novel technology, whereas the roles of ISP are marketing new technology, receiving customer satisfaction and hence getting profit by serving subscribers with lower cost and higher energy-efficiency.

To prove the concept, we consider a simple two-sided market game model of an ISP and a network equipment company to analyze the competitive problem between them. The game is based on the proposed Green ICN model that we stated in previous chapters. We assume that there is no constraint on the agreement may affect players' decisions, i.e., both players are free to select their desired strategic plans. Table 6.1 shows the choices and corresponding payoffs of two players: ISP and the equipment company. For the sake of simplicity and presentation, all the payoffs are measured in the same units whereas it is not necessary to have the same components for the payoffs of different players in practice.

A nice offer of the game is that the manufacturer can extend its technical support, including post-sell service and maintenance based on each ISP's profile and requirement. Therefore, the network equipment company has two choices: it can offer a contract by providing network equipment together with post-sale support services for ISP or only provide the ISP network devices without any further technical support. In the latter case, the manufacturer will have a lower operating cost because it does not need to keep track of the profile of ISP and perform frequent technical support/maintenance for ISP. This service can be considered as an integrated part of the agreement/contract between players at which manufacturer supports ISP through unique trackable profiles and ISP in turn also can get higher profit from this post-sale service.

Table 6.1 Choices and corresponding Payoffs for the ISP (Player I) and Network Equipment Company (Player II) [63]

Player II **Player I**	**Contract with maintenance and support services**	**Contract without maintenance and support services**
Contract	(1 + b, 1 +b)	(b, b)
No contract	(-1, -2)	(-1, -1)
Once agreed then withdraw the contract	(-2, 0)	(-2, -1)

When an ISP signs a contract with network equipment company for network devices only (without further services), both of them will get a positive payoff of *b* unit, thanks to the benefits of energy-efficient deployment as described in Chapter 3. In detail, *b* is identified according to the value of optimized ALR ratio P_{I} (i.e., *b* value varies as β changes) as follows:

$$b = \left\lceil \frac{1}{P_I} - 1 \right\rceil \ , \tag{6.1}$$

where

$$P_I = \frac{Total\ Power\ consumption\ of\ ALR\ CNs\ in\ Green\ ICN}{Total\ Power\ consumption\ of\ CNs\ in\ Conventional\ ICN} \ . \tag{6.2}$$

Since *b* gets the upper bound unit value of $(\frac{1}{P_I} - 1)$, we can deduce that $b \geq 1 \ \forall \beta \neq 0$ (as discussed in previous chapters).

Next, if ISP and the network equipment company sign a contract including the post-sale support services then ISP will receive a higher payoff of (1+*b*). Since ISP can attract more user and earn higher revenue as a result of cost-effective caching strategy for lower cost and energy-efficient content access. At the same time, network equipment company also receives additional payoff because when ISPs get benefits, they would possibly renew the contract or the manufacturer also can get new contracts with other ISPs. Hence, considering the impact on the market share, the payoff of the network equipment company is also (1+*b*) in this case.

In the case that the ISP is not convinced of the potential of the new innovative energy-efficient ICN technology and does not go for the agreement, it will get a payoff of -1. The reason is that it may lose the future market if other ISPs become successful by using this novel energy-efficient network technology. In other words, the ISP would fall on the risk of running a business with the outdated technology which results in high power consumption then gives it a negative payoff of -1. On the other hand, the manufacturer will lose the significant partner with good brand value and hence also need to endure a negative payoff of -1. So, both player payoff is （-1, -1) as shown in Table 6.1. If the network equipment manufacturer offers post-sale support service to the ISP as well, it needs higher investment for additional operating cost as mentioned. Hence, after providing network devices and support services, if the ISP is not persuaded to do an agreement, the manufacturer will have an additional negative payoff of -1. Then the payoff value of two players (ISP, Manufacturer) in this case is (-1, -2).

One unique feature of this game is that an ISP can firstly agree to try the ALR-enable devices from equipment company and later even can withdraw and terminate the contract with the network equipment manufacturer if the ISP does not want to invest in new technology and agrees to pay the penalty for that (trial offer). Hence, another option is once agreed by the ISP to sign a preliminary contract for buying network devices but later refuses to go for the final contract. The trial offer of ISP works as follows: If an ISP signs a contract with the network equipment company and later chooses to withdraw then the ISP will have to pay a penalty of 1. Especially, in case that the manufacturer provides the post-sell support service as well, then this penalty will be transferred to the manufacturer as refund and compensation for investment and support services. Since in this case, the technology itself is good (with optional technical support) then ISP can save the operating cost and energy consumption, and customers also can enjoy advanced services with high quality. As a result, it is reasonable for ISP to pay the penalty if it chooses to cancel the preliminary contract with the network equipment company. Similarly, we then can formulate the payoff values (ISP, Manufacturer) for two remaining choices of the manufacturer, given that the ISP selects this strategy as (-2, 0) as the manufacturer provides the post-sale services and (-2, -1) when the manufacturer only supplies energy-efficient network devices for the preliminary contract.

6.3.2 Economic Incentive Analysis for the Game-theoretical Green ICN Approach

It is reasonable to analyze whether the proposed game reaches a stable situation, where none of the players is motivated to change their strategic decisions, given that remaining players do not change their strategies. This situation happens when all players can get their priority choices with preferable payoffs, i.e., they can gain optimized benefits, which are higher than what they could gain without coming to an agreement when playing the game. As we analyzed earlier in this section, the highest payoff for both players is ($1+b$, $1+b$) and this configuration can be achieved when equipment manufacturer signs a contract including the post-sale support service with ISP.

Then, we show the existence of a stable win-win model in a non-cooperative ICN context at which all players are satisfied with payoffs they get from their strategic decisions. Thus, both of the network players are motivated to set up an agreement for the optimized cost-effective and network deployment in ICN.

6.4 Summary

In this study, we formulate EE content distribution based on the proposed Green ICN model utilizing in-network caching and green ICN routers with the working mechanism as defined in previous chapters as a non-cooperative game-based case-study. We highlight strategic incentives for energy-efficient ICN adoption (Green ICN overlay model) to motivate fast, potential and feasible ICN migration path for FI. This work also realizes the first game-theoretic approach which integrates Green networking into ICN to deploy ICN sustainably and motivate ICN migration process in real life. Thus, we do believe that our proposal is a promising and feasible contribution as an early initiative for the ongoing ICN standardization process of major standardization bodies, which will lead to significant impact for the prevalent large-scale deployment of ICN toward the goal of making it become our next Internet architecture in the near future.

Chapter 7

Conclusion, Closing Remarks, and Future Work

7.1 Summary and Concluding Remarks

In this dissertation, we have proposed, developed, and evaluated a novel scalable Green ICN access model with a focus on next-generation EE design for FI. We study various innovative related methods using green network devices with simple and appropriate operating strategies to solve the EE problem of ICN in the wireless environment. Typically, we address the problem in several aspects using the rate adaptive network devices in which network utilization is attributed to the network system power consumption to deal with critical challenges in ICN.

First of all, we optimize the whole network system to save a substantial amount of unnecessary power by efficiently switching network node links and tune the CP optimal operating mode in a smart way, instead of consuming fixed power from suboptimal operating network elements' power as of traditional network system. Specifically, by conducting cross-layer optimization (with suitable supporting hardware), the adaptive operating mechanisms produce the optimized values for the operating power of CPs and CRs according to network utilization to achieve a considerable reduction in power consumption gained from lower network load.

Then, toward the goal of further diminishing the power of each network node via reduced traffic load, we take advantage of in-network caching feature in ICN to leverage the EE performance of the proposed Green ICN model. Particularly, we propose three caching schemes to deal with the different context of wireless content accesses in ICN. The first strategy utilizes innovative dynamic pre-fetching as a practical and effective ITS content access solution for the commuters in the transportation system. Thanks to the “smart scheduler”, appropriate content segments are pushed in advance, then the proposed ICN-based Internet access scheme can significantly diminish negative impacts, e.g. high latency, low data rate, and support seamless communication by improving reliability, QoE and network performance. However, its limitation is a relatively narrow application domain (particularly for public transportation systems). The other caching methods, on the other hand, use content type and priority as an effective measure to solve the inefficient problems of energy consumptions as well as network resource utilization of LCE and current caching schemes in a more scalable way corresponding to the context. Typically, we propose CAGIM with a new popularity-based caching scheme in WLAN, namely DCS. DCS improves the content diversity and cache utilization of CS by pushing popular content items toward edge network caches while keeping the core network caches ‘cold’. Also, we introduce a Wi-Fi Direct based communication scheme as an alternative network solution for enabling important content sharing when WLAN is not available. The advantage of this simplified caching mechanism is that it ensures good performance with low latency for high-priority content delivery via direct communications (D2D). CAGIM then realizes a viable wireless access approach in which network complexity is moved toward the edge side with the proper support from widely-available Wi-Fi technologies. Particularly, Interest packets are forwarded to either specific Wireless AP nodes or the dedicated GO according to different network conditions and content types. These caching schemes then efficiently utilize the limited and valuable cache resource for deserved-to-be cached content objects to reduce the number of packets transmitted to higher level CRs and CPs.

Together, we reveal that the proposed green networking methods and caching scheme considerably improve network performance, in terms of both hop count and power savings by achieving about one-fourth power-saving compared to the current IP-based network system and ICN conventional design while still gaining high network performance, with proper hardware support. The evaluation results demonstrate that a large amount of power is ineffective and can be saved, especially at the higher level nodes of the network topology. The reason lies in the ability to eliminate the worthless power consumption from unnecessary redundant data packet exchanges, thanks to the reduced traffic load through in-network caching capability in ICN, especially in the case of data transmission from the content nodes close to the core network. We then show that an efficient caching consumes less bandwidth with lower latency for the content delivery process. This results in the network system's reduced bandwidth, traffic load, and in turn energy consumption, thanks to the proposed ALR method. In other words, the higher number of content requests can be successfully served from ICN caches via a cache hit, the higher power saving that the network system can achieve in the Green ICN model. Note that IP-based network with regular IP routers is not beneficial from our rate adaptation strategies due to the absence of cache capability.

Moreover, we propose a relevant case-study to illustrate economic incentives of players, then evaluates their interactions and incentive compatibility in ICN overlay using a non-cooperative game-theoretical model. By formulating a game-theory based approach to realize Green networking in ICN, we show a stable win-win model for players of the proposed Green ICN model. We also analyze how the optimized policy strategy of network players varies according to the saving power ratio of CNs with proposed ALR scheme. Consequently, we have raised the energy issues in ICN and analyzed the potential benefits of an ISP from investing in caching and deploying energy-efficient network infrastructure in ICN. In practice, such a rigorous game theory-based approach suggests the high feasibility of the proposed Green ICN model and acts as an effective tool to deploy the proposal for the goal of scalable well-suited ICN system for wireless accesses.

Our study then provides a new insight of green networking into in-network caching under a new technical viewpoint using a game-theoretical economic model as a case-study to realize an efficient ICN system: which network element’s power can be optimized through dynamic operating strategy by mapping the network device utilization with its power consumption; where we can store/put popular/high priority content at network nodes in ICN interconnections; and how can caching scheme be leveraged to further diminish the content node power consumption via reduced network traffic. In this way, we answer the key research question of how to optimally enable an efficient Green ICN system from green networking via the CN’s operating strategies and caching scheme point of views in which caching is exploited to leverage traffic load and power savings at the same time.

Besides, the proposed Green ICN model can operate with different caching scheme (insertion and replacement strategies) to further diminish total system power consumption through the reduced network traffic efficiently. This mechanism is transparent to the user to increase content diversity in ICN and spread highly popular and important content items close to users through edge caches for eliminating redundant traffic and wasteful power consumption. The proposal then efficiently decreases backbone traffic, latency and potential operating power over hierarchical networks, especially for scalable network designs with many hops.

Additionally, the Wi-Fi Direct based approach is feasible and easy to adopt for a real network deployment since Wi-Fi Direct shares the same infrastructure as of Wi-Fi protocol and its implementation does not require big investments for CAPEX (CAPital EXpenditure). As Wi-Fi Alliance recently standardized the Wi-Fi Direct protocol, the proposed model then can be incrementally deployed over existing IP-based Internet infrastructure. This is critical for the design of future network by enabling interoperable standard while neither putting a burden on existing network infrastructure nor decreasing network performance as shown in our evaluation sections. Also, our findings are scalable, applicable to all practical hierarchical networks, and not constrained to a specific ICN framework. Instead of that, our proposal can be adopted for any information-centric systems and we only select NDN as one promising prospective representation/candidate for ICN design. We then show that the proposals can save considerable power with a simple and deployable implementation, while neither decreasing network performance nor putting an additional burden on the network by fully utilizing available network resources with in-network caching capability of ICN.

In short, our findings make ICN a green networking architecture for various practical applications and services towards future communications. The results of this dissertation therefore are readily applicable to other networks where in-network caching scheme is enabled for content delivery in similar types of ICN interconnections (e.g., mixed network model in which some CRs at each network levels are replaced by CDN cache server as a way to distribute sub-Datacenters closer to users according to the geographical locations) for real-world network deployment to effectively accelerate the adoption of ICN. Furthermore, by showing the significance of setting up the standardization of ICN wireless communication, we propose our work for official standardization process of major standardization bodies, e.g. ITU, IETF and IRTF. We believe that CAGIM with mixed optimization techniques can become the potential key technology as well as a feasible solution for *large-scale sustainable deployment* of the future green wireless communication system for a wide range of different scenarios, given that ICN is still in the initial stage of implementation for FI.

7.2 Future Work

This study is an in-depth work on energy-efficient and context-aware wireless content access using the architectural framework of ICN, however, it is inevitably not complete work at this moment. There are several improvements we want to carry out in the upcoming work to strengthen our proposal and its practical applications.

Firstly, the realization of the proposed Green ICN model with large scalability under field experiment (with real network devices) for practical use-cases by considering the case of cluster of distinguished servers with different types of content-oriented services and applications, e.g., VoIP (Voice over IP), HD multimedia services is needed to further estimate the proposal efficiency. The optimal caching storage for CR deployment which maximizes the EE performance in ICN is another critical point that we will address to ensure the scalable and sustainable ICN implementation. For deployable Green ICN in real-life, we also can verify the efficiency of the ALR-based mechanism by provisioning link rate value to guarantee enough link rate selected from switchable link-rates of Gigabit Ethernet 10/100/1000 Mbps.

In this work, we focus on the understanding the feature of caching scheme for greening ICN system in a static environment. Then, for upcoming work, we plan to evaluate our proposal in a dynamic environment in which UEs (content users) can join and leave the network system for content exchanges by utilizing Markov model for defining user arrival and service rate transition states. The proposal will have a higher impact when we verify its efficiency in such a dynamic environment since network scenario should reflect the change of wireless/mobile user number when new users enter whereas the current content users may leave the ICN system. Also, we will consider content user mobility patterns and mobile device energy consumption in Wi-Fi Direct and other alternative wireless access technologies e.g., Bluetooth, WiMAX, and LTE to further study the proposed model in the mobile environment.

Next, we intend to analyze a cooperative platform where ISPs and CPs form partnerships as coalitions to share resources and save investment cost under different caching policies. For future potential research directions, we also consider applying text mining to identify whether content objects are related (based on similarities of content attributes), rather than assume independent and unrelated ones to reflect more practical scenarios.

Finally, we want to discuss a potential direction to apply the study in this dissertation to the new active research topic of *network slicing* [71], a currently active research trend with promising result, given that network slicing, usually coupled with

SDN/NFV (Software Define Networking/Network Function Virtualization) technologies, is still in its early deployment stage and active research is on progress to improve dynamic network resource allocation. As network slicing deals with and aims to minimize network resource while matching user and application requirements corresponding to dynamic network services, we are eager to extend the study presented in this dissertation to see how network slicing would help to leverage the efficiency of the proposed green ICN model through dynamically minimizing network resource utilization and network traffic for FI. This approach could be a practical contribution towards standardization process of ITU to identify the framework for service function chaining in ICN (Y.ICN-FnChain [72]), and framework for the support of Multi Network Slicing (Y.IMT2020-MultiSL [73]).

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List of Academic Achievements

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種 類 別 (By Type)	題名、 発表・発行掲載誌名、 発表・発行年月、 連名者（申請者含む） (theme, journal name, date & year of publication, name of authors inc. yourself)
Articles in Refereed Journals	○ [1] **Quang. N. Nguyen**, M. Arifuzzaman, Y. Keping and T. Sato, “A Context-Aware Green Information-Centric Networking Model for Future Wireless Communications,” IEEE Access Vol.6, 2018. [2] Rungrot Sukjaimuk, **Quang Nguyen,** and Takuro Sato, “A Smart Congestion Control Mechanism for the Green IoT Sensor-Enabled Information-Centric Networking”. Sensors. 2018; 18(9):2889. [3] Cutifa Safitri, Yoshihide Yamada, Sabariah Baharun, Shidrokh Goudarzi, **Quang Ngoc Nguyen**, Keping Yu, and Takuro Sato, “An Intelligent Content Prefix Classification Approach for Quality of Service Optimization in Information-Centric Networking,” Future Internet, Vol. 10, Issue No.4, April 2018. [4] Mohammad Arifuzzaman, Naheed NazneenTuli, Yu Keping, **Quang N. Nguyen,** and Sato Takuro, “Integrated Caching and Routing Strategy for Information-Centric Networks,” European Journal of Advances in Engineering and Technology, Vol 5(2), pp.80-90, 2018. ○ [5] **Quang N. Nguyen**, M. Arifuzzaman, D. Zhang, K. Yu, and T. Sato, “Proposal for Standardization of Green Information Centric Networking based Communication utilizing Proactive Caching Intelligent Transport System,” Journal of ICT Standardization, Vol.4, Iss.1, pp35-64, July 2016. [6] Keping Yu, Battulga Davaasambuu, Nam Hoai Nguyen, **Quang Nguyen**, Arifuzzaman Mohammad, and Takuro Sato, “Cost-efficiency residential energy management scheme for Information Centric Networking based Home Network in Smart Grid,” International Journal of Computer Networks & Communications (IJCNC), Vol.8, No.2, March 2016.
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Presentations at Domestic Conferences/ Study Groups	[1] **Quang N. Nguyen**, Arifuzzaman. M and Sato Takuro, “Proactive-Caching based Information Centric Networking Architecture for supporting Green Communication in Intelligent Transport System,” IEICE Technical Committee on Information-Centric Networking, 03 July 2015, Osaka. [2] **Quang N. Nguyen** and Takuro Sato, “A novel green proactive-caching scheme for mobility in Information Centric Network,” IEICE General Conference, Advanced Technologies in the Design, Management and Control for the Future Innovative Communication Network Symposium, 10-13 March 2015, Kyoto, Japan.
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