Energy Efficient and Enhanced-type Data-centric Network Using Network Virtualization Technology

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Summary

The Internet originated from an experimental network of research and development which supported information transmission among just a few computers in the 1960s. With the tremendous growth of the Internet, the Internet as a social infrastructure has impacted various fields and is playing a more and more important role in people's life. The focus of Internet usage has also gradually shifted from explicit information transfer to information dissemination. However, the architecture of the current Internet still uses the original host-centric networking communication model developed in several decades ago and focuses on conversation between exactly two hosts for information transmission. Unfortunately, in recent years, the increasing variety in communication terminals and Internet services has exposed several critical weaknesses with the current Internet architecture, such as inadequate mobility, security and scalable content distribution. In this context, to meet future needs, building the future Internet on the new generation network (NWGN) created from scratch has been advocated.

The information-centric networking (ICN) communication model is being assessed for NWGN as the most attractive alternative networking paradigm. ICN focuses on what the requested information is, and so differs from the host-centric networking communication model of the current Internet, which focuses on where the requested information is. ICN fully promotes information dissemination. ICN allows the user to directly use data name to access network and obtain the desired data from the network. The network is able to discover and transfer the requested data according to the data name. In order to implement

an efficient ICN, several open issues need to be addressed, including mobility, security, scalability, quality of service (QoS) and energy efficiency.

This dissertation focuses on the scalability, QoS and energy efficiency issues of ICN. This dissertation proposes an Energy Efficient and Enhanced-type Data-centric Network (E^3-DCN) for ICN. E^3-DCN realizes a ICN network that can not only provide the original data service and but also combine the desired data resources and in-network services/processing functions to generate the requested data automatically. It will radically helps to improve service flexibility and utilization and robustness with regard to the number of network services. Using network virtualization technology, E^3-DCN guarantees dedicated network resources and achieves network control plane and data plane separation and network awareness to allow QoS guarantees. In addition, E^3-DCN achieves energy efficient data transmission to reduce data switching energy consumption through its optimal energy efficient data discovery and delivery method and dynamic energy efficient network resources allocation method.

This dissertation is organized as follows: Chapter 1 introduces the network architecture and problems of the current Internet, and the requirements of the future Internet. The target and outline of this dissertation are also introduced in Chapter 1. Chapter 2 describes related works on ICN for the future Internet. The position of this dissertation is also clarified. Chapter 3 describes the network architecture of the proposed E^3-DCN. The design details and relevant experiments of E^3-DCN are also described. Chapter 4 proposes an energy efficient data discovery and delivery method for E^3-DCN. Numerical results show that data transmission energy can be reduced 40% on average. Chapter 5 proposes a dynamic energy efficient network resources allocation method for E^3-DCN to reduce data transmission energy consumption. Numerical results show that data transmission energy can be reduced by 15% on average and 30% at maximum. Chapter 6 concludes this dissertation.

Chapter 1

Introduction

Chapter 1 introduces the background of this dissertation, including the current Internet architecture with key problems and the main requirements for the future Internet. The target and outline of this dissertation are also clarified.

1.1 Current Internet

1.1.1 Architecture

The Internet originated from the first packet switching network, Advanced Research Projects Agency Network (ARPANET), which was an experiment network for research and development activities funded by the Advanced Research Projects Agency of the United States Department of Defense in 1969 [1-1]. With the tremendous growth of the Internet, the current Internet has become a social infrastructure that influences various fields and is becoming a critical part of people's lives [1-2].

Network devices and network protocols are two major parts of the Internet architecture [1-3]. The network devices mainly consist of the physical network hardware, such as packet switching electrical switches and circuit switching optical switches. These network devices are interconnected by physical links (transmission media: electrical cable and optical fiber cable, etc.) to construct the underlying network of the Internet. Data of whatever form are converted into electrical signals or optical signals to be transmitted through physical links of the underlying network to adjacent network devices.

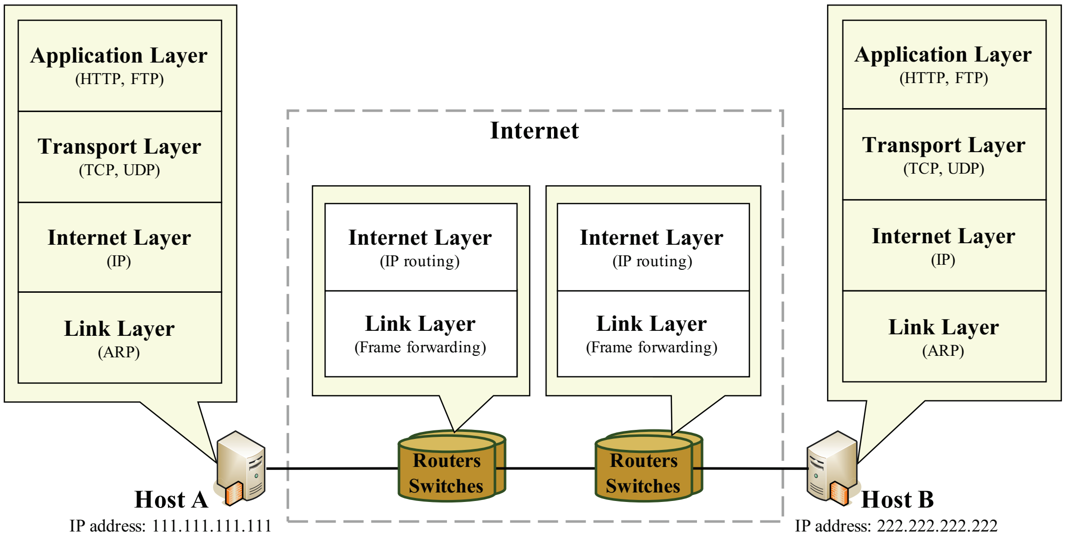

Figure 1.1: Host-centric networking communication model

A network protocol is a set of rules that define how hosts communicate with each other. The Transmission Control Protocol/Internet Protocol (TCP/IP) Internet protocol suite, commonly known as TCP/IP, consists of the core communication protocols of the current Internet architecture and was first implemented in the 1970s [1-4]. TCP/IP focuses on information transmission between just two hosts. TCP/IP adopts the host-centric networking communication model with layered architecture, as shown in Figure 1.1, and defines how data should be packetized, addressed, transmitted, routed, and received.

Briefly, in the TCP/IP model, the application layer is responsible for interfacing user applications and the transport layer. Hypertext Transfer Protocol (HTTP) and File Transfer Protocol (FTP) are common protocols used by the application layer. The transport layer provides reliable data transmission and unreliable data transmission by using TCP and User Datagram Protocol (UDP), respectively. The Internet layer, which is responsible for network routing and addressing, uses globally unique IP address. The link layer is responsible for formatting data packets and forwarding them to the underlying network. Address Resolution Protocol (ARP) is a typical protocol of the link layer and is used

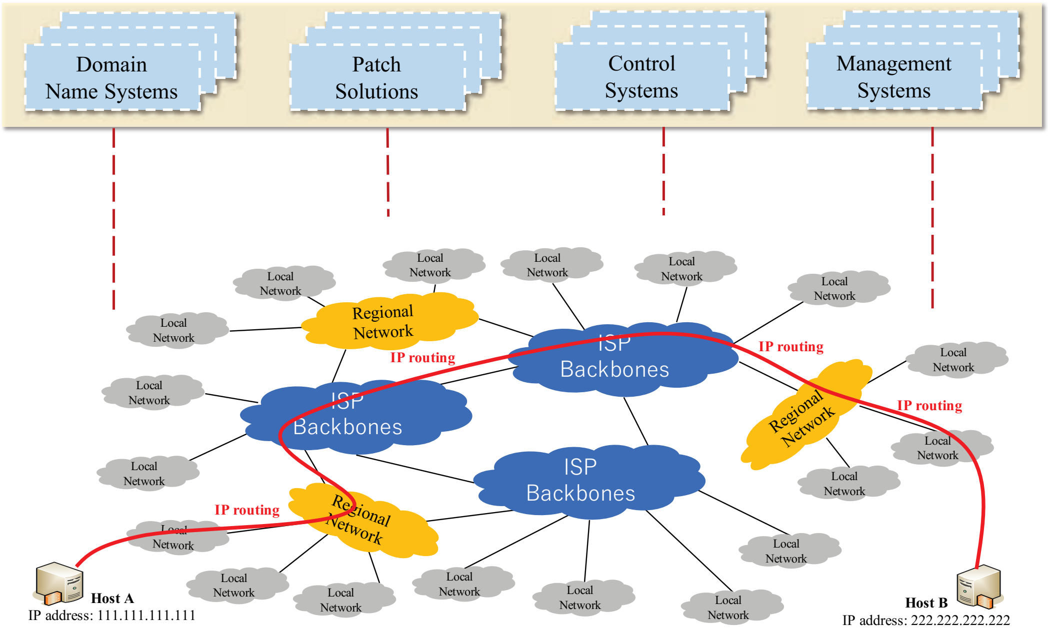

Figure 1.2: Overview of the current Internet architecture

for discovering the physical media access control address associated with a specified IP address. The common protocols of TCP/IP are shown in Table A.1 of Appendix A.

Network devices that support the Internet layer and the link layer include computer-based networking devices used for data forwarding [1-5]. They include network routers, which support the Internet layer by forwarding data packets based on IP addresses from one network to another, Ethernet switches, which support the link layer by forwarding Ethernet frames to another device in the same local area network, and multilayer network switches, which simultaneously support the link layer and higher layers by providing more complex networking functionalities.

The TCP/IP-based Internet has developed from the initial four-node experimental network to an enormous global network system that interconnects many various worldwide networks, such as local area networks, regional and country networks, and Internet Service Provider (ISP) backbone networks, lots of associated network control and management systems, and various functional patch solutions, as shown in Figure 1.2 [1-6]. More-

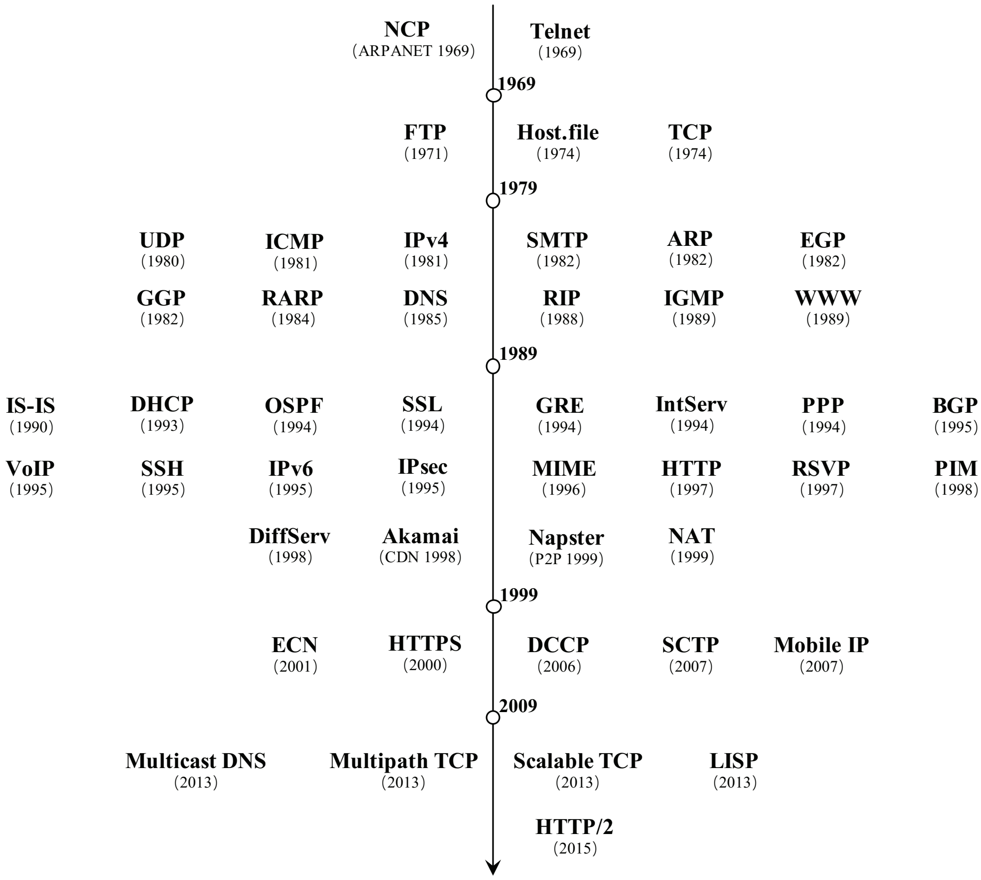

Figure 1.3: Timeline of key patch solutions of the current Internet architecture [1]

over, there are also many applications are running on the TCP/IP-based Internet. For the current Internet, TCP/IP is of crucial importance because so many upper-layer network protocols and applications are based on it, and all data communications depend on IP routing and addressing in the Internet layer.

1.1.2 Problems

The initial design of the Internet did not take into account practical factors, such as scalability, security, and mobility, most requirements emerged with the growth of the Internet. In order to meet the various kinds of new requirements, many patch solutions were

[1]Terms are shown in Table A.1 of Appendix A

used to improve the Internet architecture [1-7]. For instance, as shown in Figure 1.3, IPv6 introduced the 128-bit IP address space to replace IPv4's 32-bit address space. Domain Name System (DNS), which replaced host.file, was integrated into the Internet for scalable and quick hostname resolution. Functionalities as Akamai Content Delivery Network (CDN)[1-8], and Napster Peer-to-Peer (P2P) network [1-9] , were developed for improving content dissemination. Mobile IP was introduced to support the unfixed connection of mobile devices. Like Secure Sockets Layer (SSL), Internet Protocol Security (IPsec), and HTTP Secure (HTTPS) were patched for secure communication. And there are also other patches were made to improve network routing and transmission performance.

Although these patches have improved and perfected the Internet architecture step by step to meet new requirements over the last few decades, there are still some crucial problems:

- **Location-dependence**

  In the current TCP/IP-based Internet, establishing data communication between the user and the data source relies on their locations (IP addresses). This is called location-dependent communication [1-10]. When more and more users access a specific data source, the server load becomes very heavy, which degrades the response time of the application and the delay time, may exceed the QoS limits. Moreover, access concentration is likely to cause network congestion that affects network performance and network resource utilization. Note that the current Internet knows only the IP address of the desired data and does not know what data are being accessed, hence, it is extremely difficult to create efficient strategies for improving information dissemination and distribution, such as in-network caching and content replication.

- **Secure hosts**

  The Internet was safe as long as all users could be trusted, which true only early on. With the popularity of the Internet, network attacks, such as denial-of-service (DoS) attack and distributed denial-of-service (DDoS) attack [1-11], are becoming more and more frequent, so Internet security is now a key problem. There had been some security protocol solutions patched for the Internet, such as SSL, IPsec, HTTPS. However, these solutions only secure the hosts and do not secure the data. In addition, the underlying network is dumb in that it is unable to identify if the data being transferred are normal or suspect and cannot properly handle network attacks. Although applications can use security policies, such as OAuth 1.0/2.0 Authorization Framework [1-12] [1-13], these policies are still based on host security and complicate the process flow.

- **Inefficient mobility support**

  The IP address system of the Internet was designed for continuous data communication between pairs of hosts with fixed IP addresses. However, non-fixed hosts exhibit discontinuous communication characteristic because they frequently change networks and their IP addresses are reassigned with the movements. Hence, non-fixed hosts repeatedly try to re-access the Internet to establish connection for data communication. This overhead of reconnection is huge and increases network and server loads, and also affect the quality of experience of users. Although Mobile IP was patched to improve the mobility of the Internet, Mobile IP is complex and inefficient because it needs to re-route data through agents and networks [1-14]. Given the recent explosion in mobile devices, including mobile data and applications, a new communication paradigm that can support mobility efficiently while ensuring continuous and stable data communication has become an urgent need.

- **Network unawareness**

  The protocol interfaces between upper layers and lower layers in the TCP/IP model were designed for data packet exchange so as to receive and send data [1-4]. There are lots of applications, such as CDN, P2P, file-sharing and video-sharing applications, have been developed and overlaid on TCP/IP network. Because the lower layer network state information, such as network topology, network resource utilization and geographical location, is not available to the upper layers, high performance and intelligent applications are difficult to realize, and the network resources cannot be also used optimally. Hence, another urgent requirement is to share network and application information from the lower layers to the upper layers and indeed the user application layer. This exchange will help to realize high performance network-aware applications and an application-aware network.

- **Electricity consumption**

  With the popularity of the Internet and the explosive increase of users and applications, network traffic has been also increasing rapidly. According to [1-15], annual global IP traffic will grow at a Compound Annual Growth Rate (CAGR) of 25 percent from 2016 to 2021, and will reach 20.6 Zettabytes (ZB) (1.7 ZB per month) by the end of 2021, up from 6.8 ZB (568 exabytes [EB] per month) in 2016. More and more electricity is also consumed by Internet communication networks to carry this increase in network traffic. The total worldwide electricity consumption of communication networks has increased from 219 TWh per year in 2007 to 354 TWh per year in 2012. By a rather conservative estimate, the total worldwide electricity consumption in communication networks will exceed 414 TWh in 2020 [1-16].

Moreover, we are now entering a new era: The Era of the Internet of Things (IoT) with 5th generation wireless systems (5G) [1-17]. More and more ubiquitous IoT devices will connect the Internet and exchange data. In this context, the research communities have discussed the adoption of a new clean-slate architecture approach to designing and building the next generation network that can overcome these existing weaknesses of the current Internet and meet the demands of the IoT era. Continuously patching the current

Internet architecture has become impractical given the complexity created by the many patches already applied [1-18].

1.2 Requirements of the future Internet

The main requirements for the future Internet are detailed below [1-10] [1-19]:

- **Location-independent communication**

  The user does not care where the desired data is, only care the data itself and what the desired data is. The user directly obtains the data from network, rather than access a specified server via its globally unique location address to get the data. The network knows what data is desired by the user and identifies the optimal data source that should respond to the user. The data service provider is only responsible for providing/publishing own data to network. The data service provider does not need to take into account network locations of own and published data, and also does not need to care where the data request comes from.

- **Secure data**

  Security policies should be directed towards data security rather than host security. The network can identify whether the data being transmitted is normal and safe.

- **Efficient mobility support**

  Mobile device allow simple and quick access to the desired data while moving. The network can dynamically locate the nearest optimal data source that can provide data continuously, rather than simply access the fixed original data provider.

- **Efficient data dissemination**

  Like unicast and multicast, the multiple data forwarding model and in-network caching are supported for efficient information dissemination.

- **Network awareness**

  The network architecture is flexible and supports cross-layer communication among different network layers. The status information of each of network layers (network resources and network topology, delay, etc.) can be shared. User applications can process the shared network status information to realize high performance and intelligent network-aware services. Lower network layers like the application-aware network can also provide specific functions for applications.

- **Separation of control plane and data plane**

  The control plane and data plane are separated and have the own dedicated network resources that are not shared such as memory and Central Processing Units. The control plane is used for network control, routing and service control. The data plane is used for data forwarding.

- **Easy network reconfiguration**

  According to network conditions, network size can be dynamically changed, and network resources can be also dynamically adjusted. Such as, adding or dropping network nodes to change network size, and adjusting network bandwidth resources to handle increases or decreases in traffic dynamically. These operations are performed by the network manager easily and quickly, which is a significant advance over the current Internet as they reduce maintenance cost and time.

- **Multiple service paradigms**

  The network not only shares original data services but also shares new composite data services by combining in-network services/processes. The composite data services can not only generate new data to meet new requirements and increase the number of network services but also improve in-network services/processing utilization.

- **High energy efficiency**

  Reducing energy consumption by improving the network's energy efficiency.

Briefly, these requirements can be also categorized according to network perspectives. Like location-independent communication, secure data, efficient mobility support and efficient data dissemination can be considered from the networking paradigm perspective. Network awareness, and separation of control plane and data plane can be considered from the quality of service perspective. Easy network reconfiguration with regard to network size, network resources, and multiple service paradigms can be considered from the network scalability perspective. High energy efficiency can be considered from the network energy consumption perspective.

1.3 Solutions for the future Internet

As shown in Figure 1.4, there are several potential solutions that can be adopted to meet these requirements of the future Internet introduced in Section 1.2. This dissertation focuses on information-centric networking [1-20], network virtualization [1-21] [1-22], dynamic service chaining [1-23] [1-24] and energy efficient data transmission [1-25] solutions to propose a brand-new energy efficient and flexible information-centric network that will support the future Internet.

1.3.1 Information-centric networking

Information-centric networking (ICN) is a new emerging network architecture paradigm that replaces the location/host-centric networking communication model with the information-centric communication model. As shown in Figure 1.5, ICN ensures that each data has an identification name and is secure. Data service provider provides naming and secured data to ICN (Figure 1.5:{(1), (2)}). ICN can directly transmit the data to users and can adopt

Requirements of the future Internet	Solutions
• Location-independent communication • Secure data • Efficient mobility support • Efficient data dissemination	***Information-centric networking***
• Network-awareness	***Network virtualization*** Software-defined networking
• Separation of control plane and data plane	***Network virtualization*** Software-defined networking
• Easy network reconfiguration	***Network virtualization***
• Multiple service paradigms	***Dynamic service chaining*** Static service chaining
• High energy efficiency	Energy efficient hardware Energy efficient network ***Energy efficient data transmission***

Figure 1.4: Solutions for the future Internet

the in-network caching approach to cache data at optimal locations according to the latest network conditions. In-network caching helps to improve performance, such as on data dissemination, network performance and user experience. The user requests the desired data using data name and is provided with the data from the optimal cache location, not necessarily from the data service provider directly (Figure 1.5:{(3), (4)}). ICN provides efficient mobility support, and can quickly decide the next optimal data cache given the mobile user's movements to guarantee the stability of data connectivity (Figure 1.5:{(5), (6), (7), (8)}). The exploring research projects of ICN are introduced in Chapter 2.

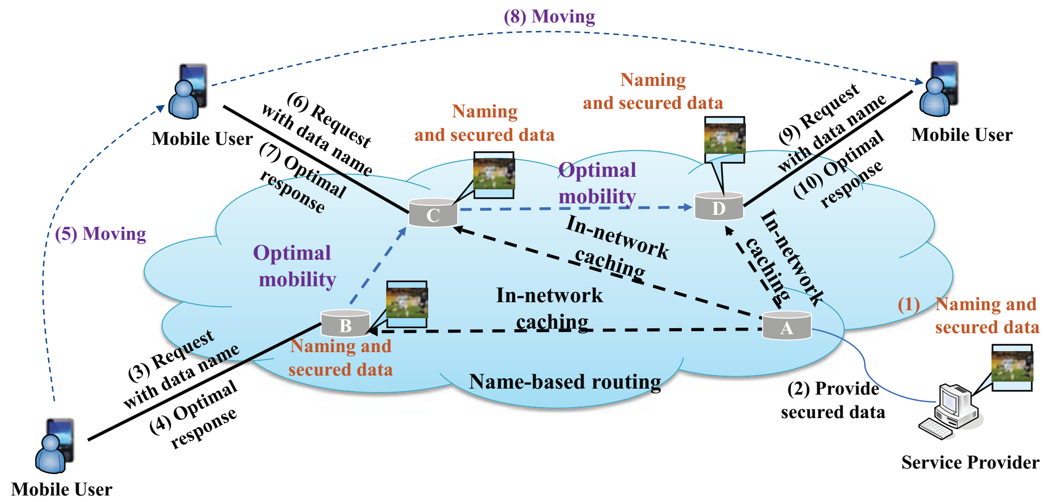

Figure 1.5: Overview of information-centric networking paradigm

1.3.2 Network virtualization

Network virtualization (NV) technology can create multiple virtual nodes (v-nodes) on each physical network device/substrate node(s-node). And NV can also allocate network resource blocks of s-node to v-nodes such that each v-node has its own completely dedicated network resources, including Central Processing Unit (CPU), memory, storage and bandwidth resources. In the NV environment (NVE), v-nodes, which may exist inside different s-nodes, are connected by virtual links (v-links) to construct a virtual network (VN) on the NV platform network/substrate network (SN). V-links are mapping onto substrate data transport paths (s-paths) on SN and realizes data transmission between v-node pairs. Each v-link also has its own completely dedicated network resources provided by the SN. NVE allows multiple heterogeneous VNs to coexist on the same SN. VNs can be dynamically created on demand and embedded in an SN. Arbitrary network architectures and applications can be deployed on VNs. For instance, the current Internet can be deployed on a VN in NVE.

As shown in Figure 1.6, in NVE, traditional Internet Service Provider can be divided into two main roles: Service Provider (SP) and Infrastructure Provider (InP). For SPs and

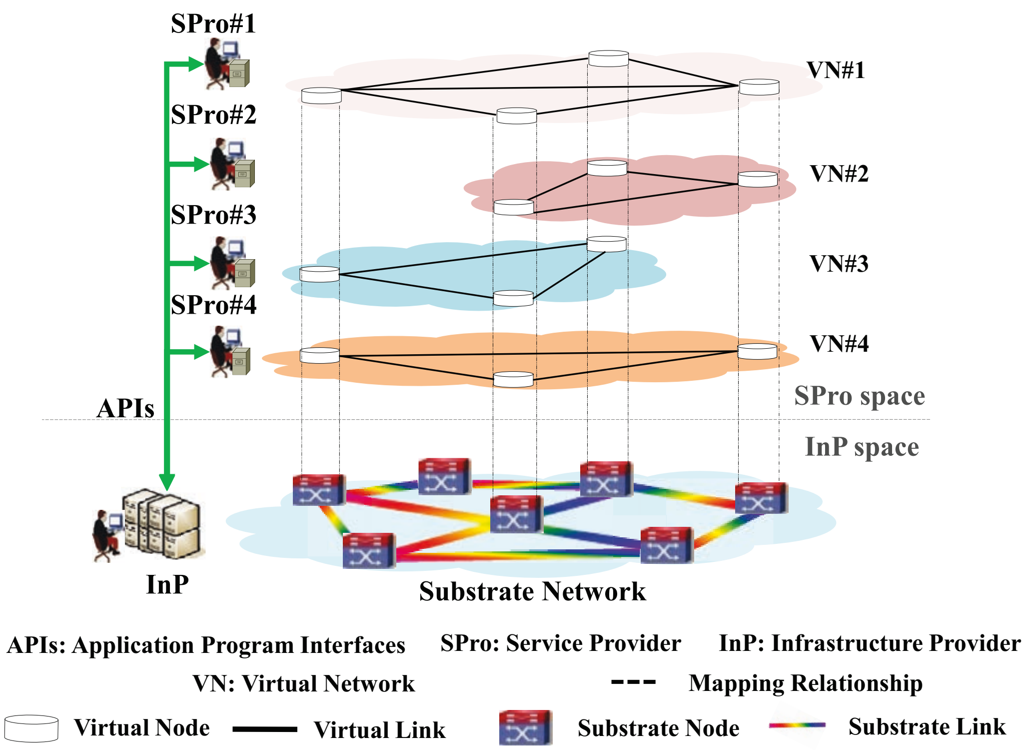

Figure 1.6: Overview of network virtualization environment

InP, NVE can not only improve network resources utilization but also reduce operational and capital expenditures. SP can define its own VN by, for example, specifying network topology, lifetime, and the network resources of the VN, including the network resources of v-nodes and v-links. SP has the full ownership of the VN and can freely operate and manage the VN independently of the SN. SP also can change and adjust network size and network resources dynamically. InP manages SN and is responsible for allocating substrate resources (s-resources) to embed VNs in SN according to the requirements specified by SPs. InP can provide substrate configuration information and network resources information of VN to SP through application program interfaces (APIs), an essential part of achieving network awareness. Based on NV, this dissertation addresses network awareness, network control plane and data plane separation and easy network reconfiguration with the goal being supporting the future Internet.

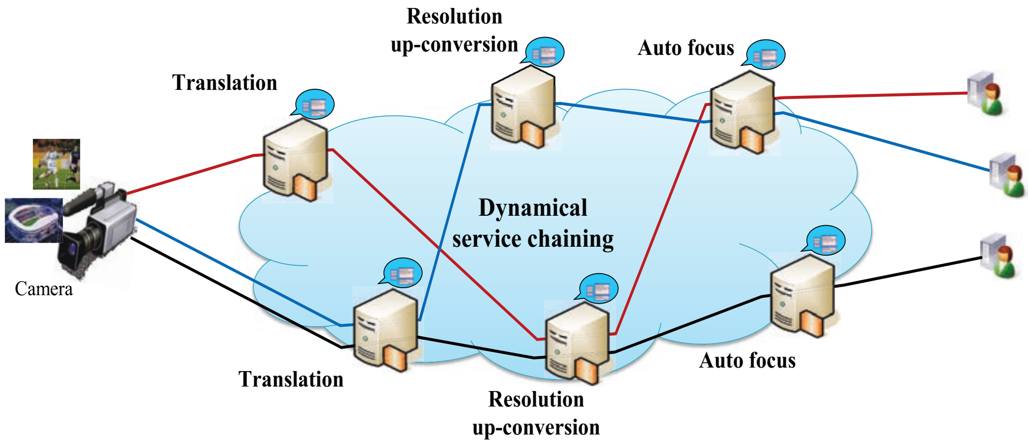

Figure 1.7: Overview of dynamical service chaining

1.3.3 Dynamic service chaining

Service chaining (SC) technology is a new service deployment approach that can combine multiple in-network processing/services/applications and relevant data to generate new data services. SC can increase the number of network services, improve the utilization ratio of network services, and reduce operator investments (CAPEX) and operation costs (OPEX) of the service providers. The service policy of a composite service defines the combination of network services/applications and data needed. There are two types of SC: static service chaining (SSC) and dynamic service chaining (DSC). For SSC, the detailed network services/applications and data are fixed and defined by the original service policy. For DSC, details of the network services/applications and data which are not fixed but are dynamically decided to suit network conditions, as shown in Figure 1.7. DSC ensures that the data generation service is always implemented on the optimal service chaining flow. In this dissertation, we take the DSC approach to achieve multiple service paradigms and increase the number of network services available in the future Internet.

1.3.4 Energy efficient data transmission

The network energy consumption includes base/idle energy consumption and data switching energy consumption. In the idle status, network devices are active but no traffic is flowing, and the network exhibits base consumption. The data switching energy of network is consumed in data transmission [1-25]. The switching energy efficiency of a network device can be considered as a constant and can be calculated by Equation 1.1

$$\eta_{sw}(k) = (E_{sw}(active, k) - E_{sw}(idle, k)) \diagup Vol(traffic) \tag{1.1}$$

where $\eta_{sw}(k)$ is the switching energy efficiency of network device k. which can be considered as a constant and expressed as 'joules per bit (J/b)'. $E_{sw}(active, k)$ is the active energy consumption of network device k, $E_{sw}(idle, k)$ is the idle/base energy consumption of network device k. $Vol(traffic)$ is the switched traffic volume.

The switching energy used in transmitting data from source to destination is consumed along the data transport path formed by several connected network switching devices, and is also expressed as 'joules per bit (J/b)' [1-26]. The switching energy of data is calculated by Equation 1.2:

$$E_{sw}(d, src, dest) = \sum_{(k=0)}^{M} \eta_{sw}(k) \times Vol(d) \tag{1.2}$$

M is the number of network devices along the data transmission path on network. $Vol(d)$ denotes the volume of transmitted data d. $E_{sw}^{v}(d)$ is the data switching energy consumption of d from data source src to destination $dest$.

Reducing the switching energy needed for data transmission is an effective approach for reducing network energy consumption. In this dissertation, we focus on energy efficient data transmission to reduce network data switching energy consumption.

1.3.5 Other solutions

- **Software-defined networking**

  Software-defined networking (SDN), which is a new emerging network architecture paradigm, separates the control plane from the data plane [1-27]. SDN focuses on centralized control, policy managements and network programmability. In SDN, the control logic is decoupled from network devices and assigned to software-based SDN controllers centralized in the control plane. The SDN controller as a network operating system has a global view of the underlying network, and can be directly extended to achieve flexible, complex network services, managements, and operations. Entities such as network-aware applications and application-aware networks can be implemented easily in SDN. Each network device becomes a simple flow-based forwarding device such as the OpenFlow-enabled switch (OFS). Southbound Application Programming Interfaces (APIs) realize communication between OFSs and SDN controllers. Northbound APIs realize communication between SDN controllers and SDN applications. The SDN controller provides intelligent connectivity and enables applications to directly access and control OFS switching devices. SDN is an excellent technology and has been adopted by NVE for InP. It efficiently helps InP to manage and control the SN, and configure virtual networks, such as the s-paths of v-links, by using data flows.

- **Energy efficient hardware**

  Each network device consists of several hardware components. For instance, Ethernet switch contains memory cards, control module, fabric card module, line card module and fans [1-28] [1-29]. Improving the energy efficiency of each hardware components helps to reduce the energy consumed by the network device [1-25]. For example, Double Data Rate (DDR)3 memory has higher access speed than DDR2 and DDR1, as well as lower energy consumption and voltage [1-30] [1-31]. The energy consumption of network devices can also be reduced through the use of additional functionalities, e.g., power on/off button, wake-on-LAN techniques, low power mode, port auto power down [1-32]. The power on/off button and wake-on-LAN techniques enable a network device to be switched off or put into sleep mode when they are not used. The low power mode enables the network device to run in low power mode during periods of low traffic activity to reduce energy consumption [1-33] [1-34].

- **Energy efficient network**

  Network energy savings can be also considered from the whole network perspective [1-25]. Instances of this include the dynamic configuration of network topology with traffic engineering technology, which can aggregate traffic streams and place unused network devices into sleep mode for saving energy [1-35] [1-36] [1-37]. Simple and lightweight protocols can deemphasize the unnecessary functions of network devices and save the protocol processing energy while switching [1-38]. Optimal network designs also achieves energy savings by efficiently exploiting network devices, such as packet switches, circuit switches, and transmission media [1-39] [1-40].

1.4 Target and outline of this dissertation

The target of this dissertation is based on information-centric networking (ICN), network virtualization, dynamic service chaining and energy efficient data transmission, all introduced in section 1.3. As shown in Figure 1.8, the intention is to achieve an energy efficient and flexible information-centric network that can meet the requirements of the future Internet summarized as Figure 1.4.

Chapter 2 describes network architecture technologies on ICN, and then introduces

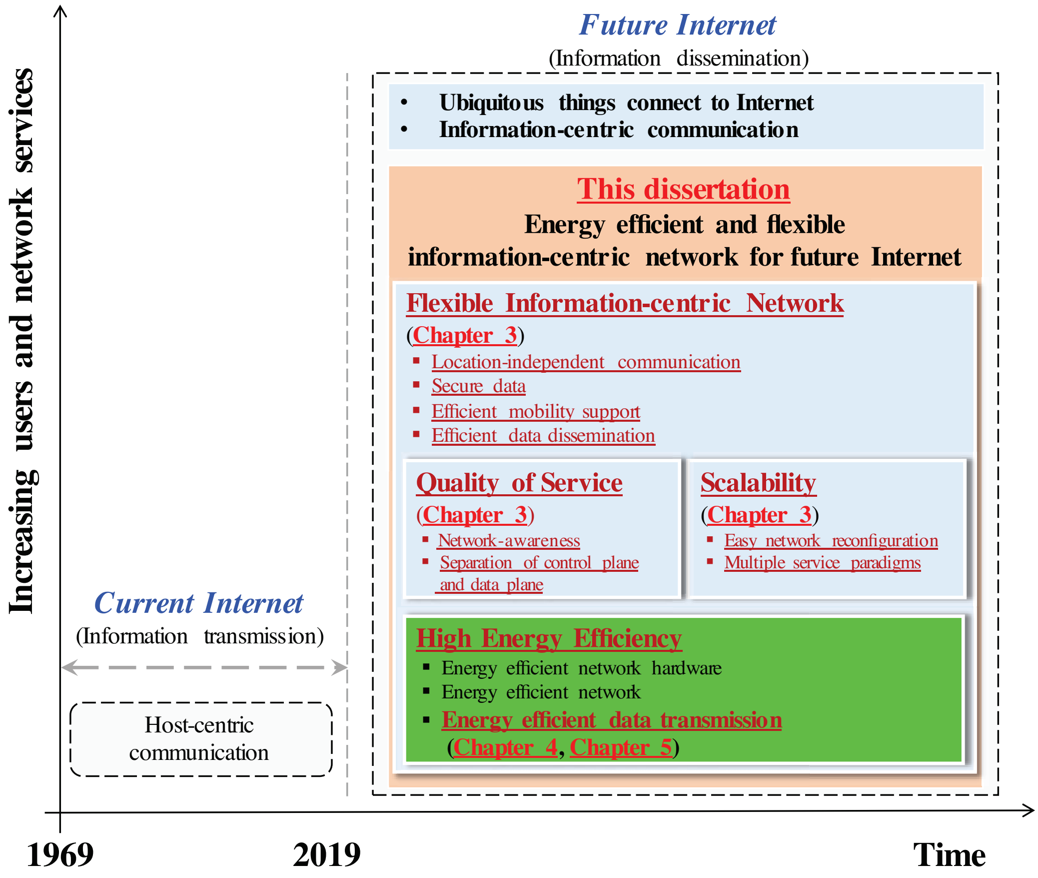

Figure 1.8: Target of this dissertation

related technologies and studies on ICN from the perspectives QoS, scalability, and energy efficiency. The research position of this dissertation is also described at the end of Chapter 2.

Chapter 3 presents an energy efficient and flexible information-centric network called the Energy Efficient and Enhanced-type Data-centric Network (E^3-DCN) for the future Internet. E^3-DCN is based on network virtualization technology, i.e., the multi-layered network design model. Multiple virtual networks, including a virtual network for the network control plane and two virtual networks for the network data plane, are created as the network infrastructure need to satisfy network awareness, control plane and data plane separation requirements for the future Internet. The multiple overlay networks, one supports dynamic service chaining and the other supports information-centric networking, are combined and overlaid on three virtual networks to realize an information-centric network with multiple service paradigms that can provide not only original data services but also provide data generation services which improves network scalability in terms of the number of network services.

For energy efficiency, E^3-DCN supports not only energy efficient dynamic network reconfiguration but also energy efficient data transmission. The targets of Chapter 4 and Chapter 5 are to achieve energy efficient data transmission for E^3-DCN to reduce data switching energy.

In Chapter 4 proposes an energy efficient data discovery and delivery method for E^3-DCN. The proposed method first discovers data sources and then decides the optimal data source and the optimal energy efficient data transmission path according to feedback information from data sources. The proposed method makes the network provide data from the optimal data source and along the optimal data transport path to save data transmission energy.

In Chapter 5, a dynamic energy efficient network resource allocation method is proposed for E^3-DCN to reduce data transmission energy consumption. The proposed method takes into account the available network resources of virtual network and the dynamic characteristics of embeddable network resources of the network virtualization platform, and reallocates the available network resources dynamically to improve data switching energy efficiency of virtual links, which will help to reduce data transmission energy consumption. Finally, in Chapter 6, conclusion is given.

Table.1.1 summarizes the core research topics of this dissertation. Through this work, an energy efficient and flexible information-centric network for the future Internet has been achieved.

Table 1.1: Outline of proposals in this dissertation.

Chapter 3	Purpose	Create a new generation network for the future Internet that offers information-centric networking, network awareness, network control plane and data plane separation, easy network reconfiguration, multiple service paradigms and high energy efficiency.
	Problem	No research contributed to the future Internet has achieved network control plane and data plane separation, dynamic service chaining for multiple service paradigms and enhanced energy efficiency in terms of data-transmission-level.
	Proposal	E^3-DCN, an energy efficient and flexible information-centric network that uses network virtualization technology. a). Separates control plane and data plane with own dedicated network resources. b). Combines information-centric networking and dynamic service chaining for multiple service paradigms. c). Optimizes data transmission energy saving by combining optical switching mode and packet switching mode.
	Achievements	a) Realized flexible data transmission by combining optical switching mode and packet switching mode for E^3-DCN. b) Experiments to validate features of E^3-DCN, including multiple service paradigms, control plane and data plane separation, cross layer communication, network awareness, energy efficiency. The results of these experiments show that E^3-DCN can meet the requirements of the future Internet.
Chapter 4	Purpose	Realizes energy efficient data transmission for E^3-DCN
	Problem	Existing data discovery and delivery methods cannot decide the optimal data source before responding data, and do not suit for E^3-DCN because they cannot decide the optimal data transmission path by combining optical switching mode and packet switching mode.
	Proposal	An energy efficient data discovery and delivery method that first identifies the optimal data source and decide the optimal data transmission path by combining optical switching and packet switching, and then requests data and transfers data along the optimal data transmission path to save data switching energy.
	Achievements	The proposed method can reduce data transmission energy consumption by to 40% compared to traditional methods.
Chapter 5	Purpose	Ensure E^3-DCN always utilizes network resources in the optimal energy efficient manner so as to reduce data transmission energy consumption.
	Problem	The dynamic changes in the network resources used by network virtualization prevent E^3-DCN from achieving the optimal energy efficient data transmission.
	Proposal	A dynamic energy efficient network resource allocation method that reallocates the network resources available to E^3-DCN so as to reduce data transmission energy consumption.
	Achievement	Comparing to traditional methods, the proposed method helps E^3-DCN to reduce data switching energy consumption by 15%-30% and decrease average delay of virtual links by 18%-30%.

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Chapter 2

Network technologies for the future Internet

Information-centric networking (ICN) is the most attractive networking paradigm for the future Internet and as such has been attracting attentions from both academia and industry. Chapter 2 introduces some technologies for ICN that are related to this dissertation. Firstly, technologies related to ICN network architecture are introduced. Then, technologies on quality of service, scalability and energy efficiency issues for ICN are described. Finally, the target and position of this dissertation are clarified.

2.1 Information-centric networking (ICN) architecture

ICN replaces the location/host-centric communication model with the information-centric communication model. In ICN networks, users can directly use data name/identifier to obtain data from network, as they do not need to be concerned about where the data is and where the data comes from, only be concerned about what the desired data is and the data itself is important.

Figure 2.1 shows the key research projects initiated to explore ICN network architecture: Data Oriented Network Architecture (DONA) [2-1], Content Centric Networking (CCN) [2-2], Publish Subscribe Internet Routing Paradigm (PSIRP) [2-3], 4WARD/Network of Information(NetInf) [2-4], COntent Mediator architecture for content-aware nETworks (COMET) [2-5], CONVERGENCE [2-6], Publish Subscribe Internet Technology (PURSUIT) [2-7], Scalable and Adaptive Internet Solutions (SAIL) [2-8], Named Data Net-

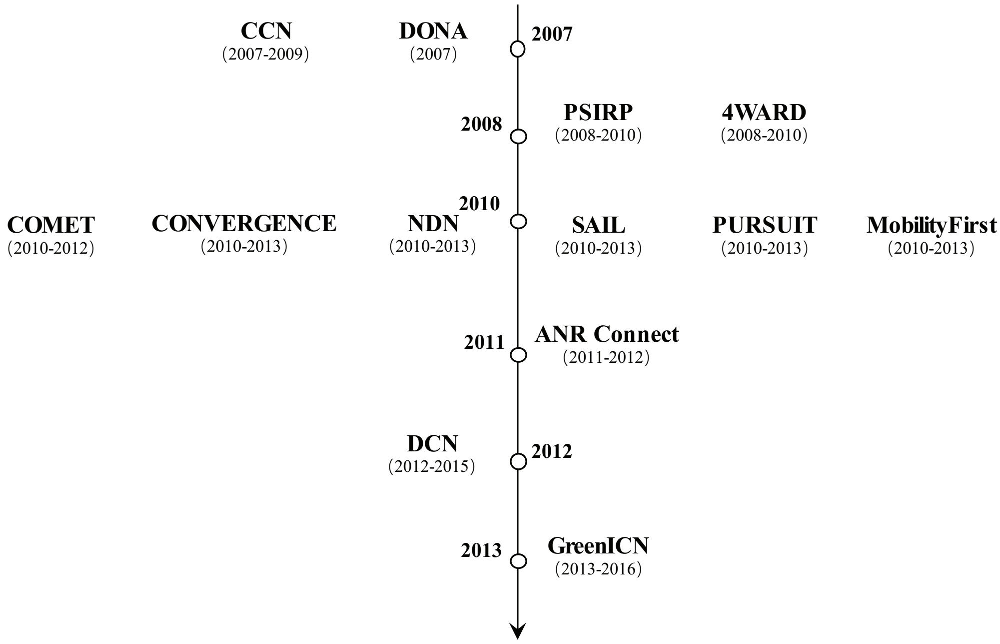

Figure 2.1: Timeline of main exploring projects for ICN architecture

working (NDN) [2-9], MobilityFirst [2-10], ANR Connect [2-11], Data-centric Network (DCN) [2-13], and GreenICN [2-12].

2.1.1 Architecture approaches

The key research projects shown in Figure 2.1 can be broadly classified into two basic approaches: name resolution and name-based.

Name resolution approach

Projects such as DONA, PSIRP, PURSUIT, SAIL, COMET and CONVERGENCE adopt some existing network technologies for the ICN architecture, such as IP routing and addressing, OSPF, and BGP routing. In addition, a Name Resolution System (NRS) is deployed on infrastructure network as an overlay network service to realize separation of name and location. NRS provides name resolution by matching and translating

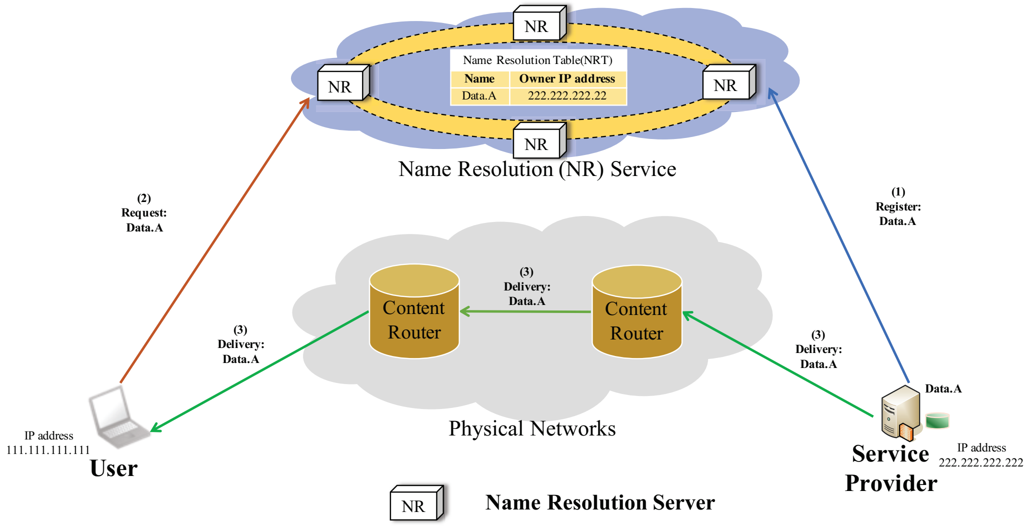

Figure 2.2: Architecture of ICN network using name resolution approach

the requested data name into other information, such as server IP address of data service provider. As show in Figure 2.2, the data service provider first registers data information including server IP address with NRS for publishing data service (arrow: (1)). NRS registers and distributes the data information across NR tables in relevant NR servers for efficiently matching data requests. The user sends a data request with data name and own information, such as own IP address, to obtain data (arrow: (2)). NRS extracts data name from data request and matches requested data name to get IP address of data provider server. Finally, based on routing policy, actual data transmission between data service provider and end-user is established on the infrastructure network (arrow: (3)).

Name-based approach

Projects such as CCN, NDN and DCN, these research projects achieve a brand-new and pure hop-by-hop name-based networking paradigm; they do not adopt any existing network technologies. Data service provider uses a trusted medium to directly publish data information including data name for user access. User directly uses data name to

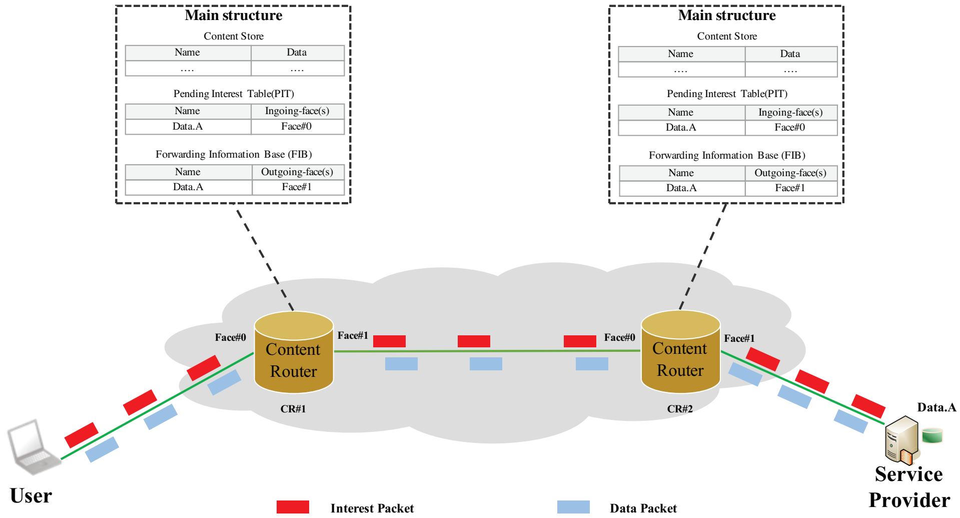

Figure 2.3: Architecture of ICN network using name-based approach

obtain data from the network. The data service provider and user do not need NRS to find each other.

As shown in Figure 2.3, the content router has three main data structures: content store (CS), pending interest table (PIT) and forwarding information base (FIB). CS is used for caching data or data packets. PIT is used for recording ingoing interface information that indicates where the data request comes from so that the requested data can be forwarded back to end-user. FIB is used for recording outgoing interface information that indicates where the data requests are forwarded out from.

These three data structures allow hop-by-hop name-based data routing and data delivery, and in-network caching to be realized for the ICN network. User sends Interest Packet with data name to the network for obtaining the desired data. Content router first extracts the data name from Interest Packet and looks up data name in CS. Data Packet with data name is returned in response to Interest Packet. If data name is found in CS, content router will send Data Packet back to respond to Interest Packet based on ingoing interface information of Interest Packet recorded in PIT, and Interest Packet is discarded, it is not forwarded out. If data name is not found in CS, content router will match data name in PIT. If data name is found in PIT, PIT will update ingoing interface information for Interest Packet to indicates that an Interest Packet with the same details has already been forwarded to explore the data source, and Interest Packet is discarded. If data name is not found in PIT, PIT and FIB will create requested data information according to Interest Packet and forward Interest Packet from all outgoing interfaces to continually explore data sources. If a data source is found, Data Packet is sent to end-user according to incoming interface information in PIT.

2.1.2 Summary and open issues

Although they use different architecture approaches, the above research projects have explored some common core functionalities for the location-independent ICN network as follows:

- Naming: defines data name separated from its location.
- Routing: uses name resolution service or pure hop-by-hop name-based routing.
- Caching: caches data in ICN nodes.
- Mobility: realizes simple and quick reconnection between mobile device and data source.
- Security: secures data.

These functionalities enable ICN to seamlessly meet a part of the requirements of the future Internet described in Section 1.2.

These key advances have laid the foundation of ICN, but there are still some open issues in ICN that must be resolved, such as quality of service, scalability and energy efficiency. In the following sections, existing studies and techniques applicable to these open issues are described.

2.2 Quality of service on ICN

In this section, technologies for providing quality of service (QoS) assurances for ICN are described.

2.2.1 Naming scheme

In ICN, data is discovered and delivered depending on its name rather than its location. According to data name, each content router can understand and decide data forwarding direction, and the ICN network can find the optimal data source to respond to the user request. Therefore, the naming scheme is an important part of ICN as it affects attributes, such as delay, throughout and control overheads [2-14]. The current naming schemes fall into three broad categories: flat naming, hierarchical naming and attribute naming.

Flat naming

The form of flat naming is as '*namespace:identifier*'. As shown in Figure 2.4.A), where *namespace* may refer to the hash value of data owner or publisher, identifier refers to data name or data label. The flat name is usually not human-readable, and is also called self-certified naming because the *namespace* field is usually assigned a cryptographic hash of the owner's public key for data security. The flat name yields efficient lookup because simple hash-table lookup can determine the next hop for the data request. In general, backbone routers take advantage of parallel processing to lookup by partitioning the flat namespace based on computational ability.

Hierarchical naming

The hierarchical naming scheme is human-readable, and has a name structure similar to Uniform Resource Locators (URLs), such as `'/YouTube/sports/football.avi/`

namespace:identifier

A). Flat naming

/YouTube/sports/football.avi/_ver<*timestamp*>/_seg#1
/YouTube/
/YouTube/sports/

B). Hierarchical naming

{
FileType <String>: pdf
Title<String>: pairs
Author <listofString>: author#1
Organization <String>: org#1
Year <integer>: 2018
}

C). Attribute-based naming

Figure 2.4: Naming schemes for ICN

ver<timestamp>/_seg#1', as shown in Figure 2.4.B). Furthermore, the hierarchical naming scheme supports name prefix matching in routing to aggregate routing table information, such as '/YouTube/' and '/YouTube/sports/', which can reduce routing table size and improve routing performance and scalability.

Attribute naming

The form of attribute naming is shown in Figure 2.4.C); a set of human-readable attribute-value pairs. An attribute has a name, a type and a set of possible values. Attribute naming is more expressive and richer in semantic structures than flat and hierarchical naming schemes, and can be combined with the two other naming schemes to improve routing performance.

These three naming schemes can aggregate and reduce routing table size to some level and improve the QoS of ICN with regard to routing, such as reduce lookup latency in each content router. In addition, by extending these three naming schemes with other related lookup and routing technologies, QoS can be enhanced for ICN [2-15] [2-16].

2.2.2 Intelligent strategy

Intelligent data discovery/routing and delivery strategy can improve the QoS of ICN networks, by reducing the data retrieval time and download time. In [2-17], an advanced perceptive forwarding strategy is proposed that intelligently perceives closer temporary content replicas to respond to user requests more quickly. In [2-18] [2-19], according to content characteristics, server load, and network distance and some other factors, intelligent data routing strategies are achieved to locate the optimal cached content, optimize network utilization, and maximize the user's quality of experience. Like DCN [2-13], according to network topology and routing table configuration information of ICN router, an intelligent routing strategy is realized for name-based ICN networks; it can automatically and dynamically reconfigure and optimize routing tables to reduce routing table size and data retrieval time.

2.2.3 In-network caching

In-network caching is an efficient approach to enhancing the QoS of ICN networks by accelerating data delivery, increasing data availability, mitigating server load, reducing overall network traffic, and improving user experience, [2-20].

Existing in-network caching mechanisms can be mainly classified into on-path caching and off-path caching, see Figure 2.5 [2-21]:

- On-path data caching: data packets are cached at each content router along the transport path from data sources to the end-users.
- Off-path data caching: data packets may or may not be cached at each content router along the transport path, and may be cached in other content routers.

In ICN networks, the cache function of content routers can be switched on/off. On-path caching is inherent in ICN. Off-path caching needs a network manager to decide where

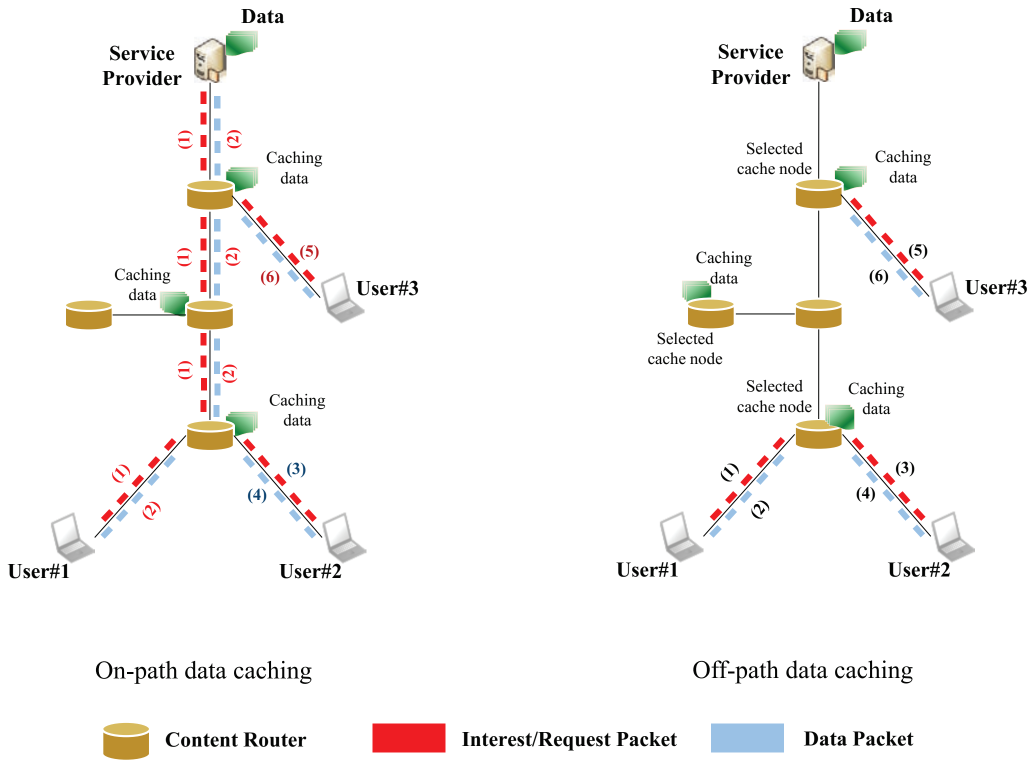

Figure 2.5: Overview of in-network caching

and how to cache data packets.

Multiple caching technologies have been developed to realize on-path caching and off-path caching [2-22]. For example, the homogeneous caching approach enables each content router to cache data packets by providing the same cache resources [2-2]. In caching data packets, the heterogeneous caching approach assumes that each content router will have a different cache size [2-23]. Cooperative and no-cooperative caching approaches adopt the cache state advertisement mechanism to cache more data packets and improve the utilization efficiency of cache resources and network performance [2-24] [2-25].

2.2.4 Network optimization

Network optimization can improve the performance of ICN networks because it can efficiently reduce network congestions and delay for better QoS.

The many studies on network optimization for ICN have different perspectives [2-26] [2-27] [2-28] [2-28] [2-30] [2-31], which can be classified as follows:

- Resource fairness: achieves network resources and content resources fairness in ICN network, such as bandwidth fairness, throughput fairness and cached content fairness.

- Congestion control: predicts the future occupancy of the forwarding queue of ICN routers by monitoring several factors, such as recorded flow information, current queue utilization, bandwidth, cache and buffer capacity, to estimate whether congestion is likely to occur.

- Delivery performance: optimizes overall network delivery performance based on dynamic network status to provide network delay guarantees for different services such as delay-sensitive applications.

2.2.5 Virtualized ICN

Network virtualization (NV), introduced in Section 1.3.2 , can help the service provider achieve content awareness, network topology awareness, and network resources awareness applications. In addition, NV can guarantee each virtualized network holds own dedicated network resources, and allow each virtualized network to be dynamically established and reconfigured.

Because these advantages of NV can promote high QoS, several studies have examined the virtualized ICN network wherein a ICN network is established on top of a virtual

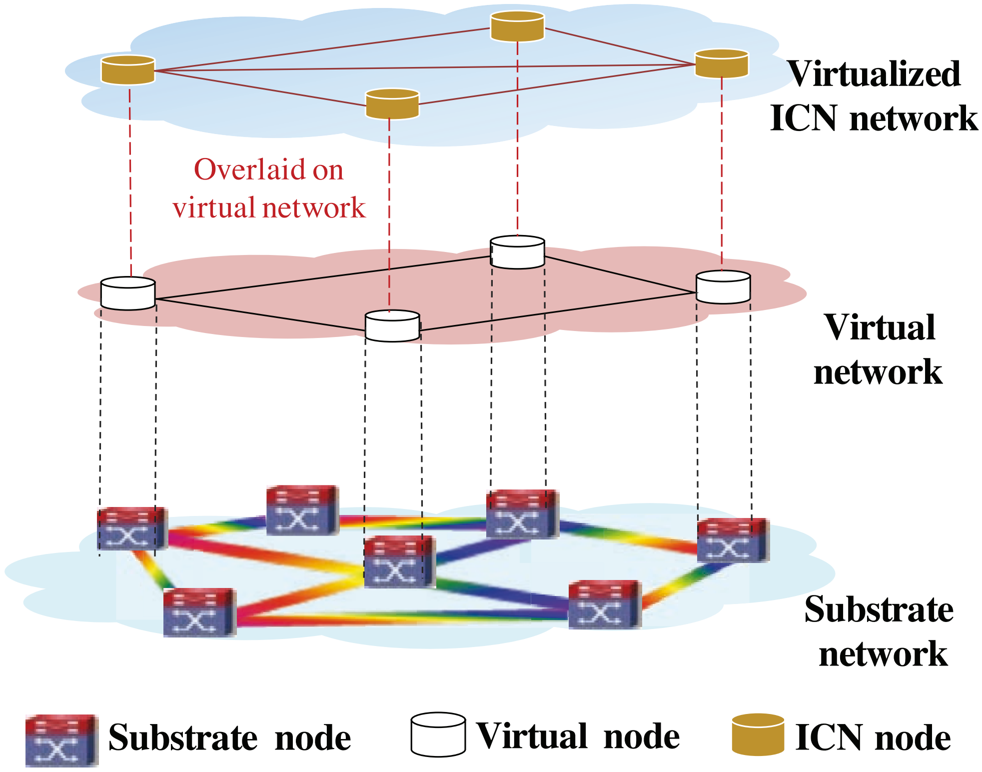

Figure 2.6: Overview of virtualized ICN network on network virtualization environment

network, as shown in Figure 2.6. Delay-bounded QoS approaches for time-sensitive applications can be realized on virtualized ICN networks as described in [2-32] [2-33]. To improve data delivery performance, like [2-34] [2-35] [2-36], these studies adopt optimal network and content configuration approaches based on the virtualized ICN network.

2.3 Scalability on ICN

In this section, technologies relevant to ICN scalability are described. In this dissertation, ICN network scalability is considered from multiple perspectives, such as supporting the huge number of end-user and mobile devices expected, sophisticated data and in-network services, and network size reconfiguration.

2.3.1 Scalable architecture

Scalable naming scheme

The naming scheme described in Section 2.2.1 will impact not only routing speed and thus QoS, but also the scalability of the ICN network. Hierarchical name, which supports name prefix matching to sets of routing entities, allows more routing entities to be registered in the routing tables of content routers and scale up the routing range of the ICN network and so process massive numbers of different data requests efficiently. Flat naming suits large-scale networks composed of several domain networks because it can efficiently and securely support routing between different domains.

The scalability of the ICN network can be also improved by combining different data naming schemes according to scalable routing policies [2-10] [2-6] [2-37], such as `'hierarchical_name:flat_name:public_key:attribute_name'`.

Hybrid ICN network architecture

The hybrid ICN network architecture is an efficient approach to realizing the large-scale ICN network as it combines name resolution and name-based architecture approaches, described in Section 2.1.1, such as NetInf [2-4] and MobilityFirst [2-10]. As shown in Figure 2.7, the hybrid architecture approach first performs hop-by-hop name-based routing to find the requested data in the local name-based ICN network (ICN#A). If the data is not found, the content router that is connected to the name resolution ICN network (ICN#M) will redirect the data request with the data name to NRS of ICN#M to locate the requested data in the global network. NRS then sequentially redirects the data request to associated networks, such as ICN#B. Finally, the server provider responds by sending the requested data to the user.

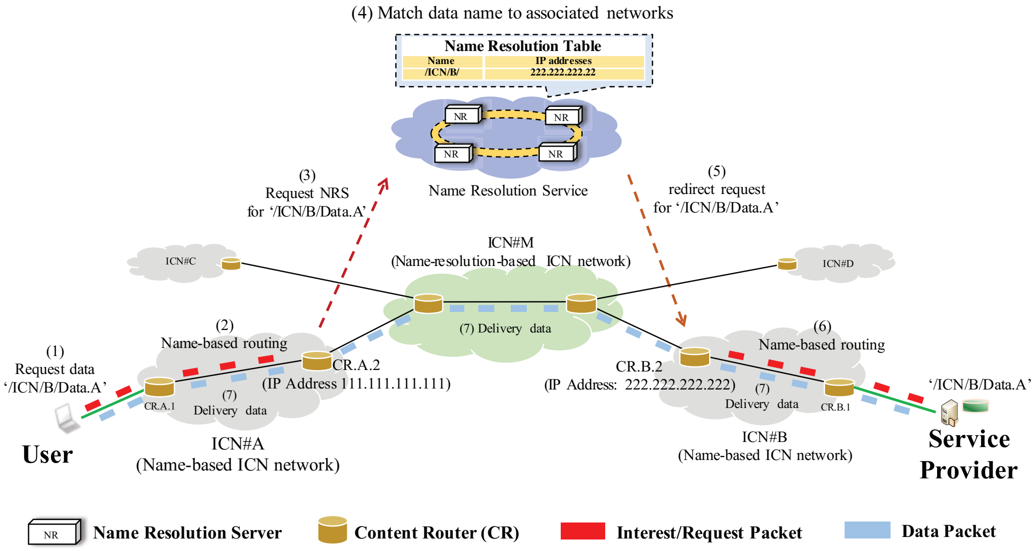

Figure 2.7: Example of hybrid ICN network architecture

Mediation plane

The mediation approach employs a dedicated assist system, like today's domain name system (DNS), to help the large-scale ICN network achieve high speed data access/discovery and delivery [2-38] [2-39] [2-40] [2-41]. The mediation plane, which overlays the network infrastructure as a top layer, communicates with different domain networks and service providers. As shown in Figure 2.8, the mediation plane may include a content mediation plane and network mediation plane. The content mediation plane offers data awareness, e.g., data characteristics and server load condition, which helps to locate the optimal data source or data replica. The network mediation plane, offers network awareness, e.g., network topologies, network resources and network separations, which help to implement the best transport strategy.

Network virtualization

Network virtualization (NV), introduced in Section 1.3.2, can help to achieve not only high ICN QoS as described in Section 2.2.5, but also ICN high scalability [2-42]. NV

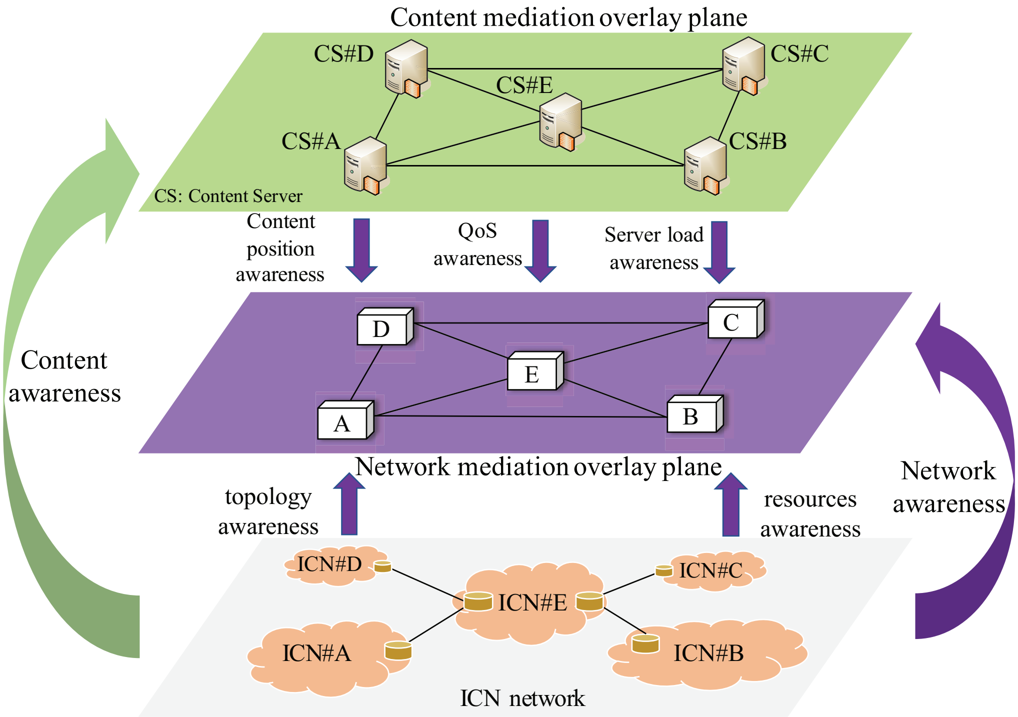

Figure 2.8: Overlay content and network mediation plane for large-scale ICN network

supports network awareness, dynamical network topology configuration and reconfiguration for the service provider (SP). SP can freely add network nodes to scale up network to meet new requirements, e.g., network traffic load, number of users and geographical locations.

2.3.2 Data placement

As shown in Figure 2.9, optimizing data placement can improve the scalability of the ICN network efficiently and so supports a huge number of end-users and mobile devices. The technologies for efficient data placement can be broadly classified as follows:

- Content router placement: For the large-scale ICN network, the positions of content routers influence on the overall performance that indicates how much cache capability is placed in a specific area [2-43]. Based on network size, topology, and other

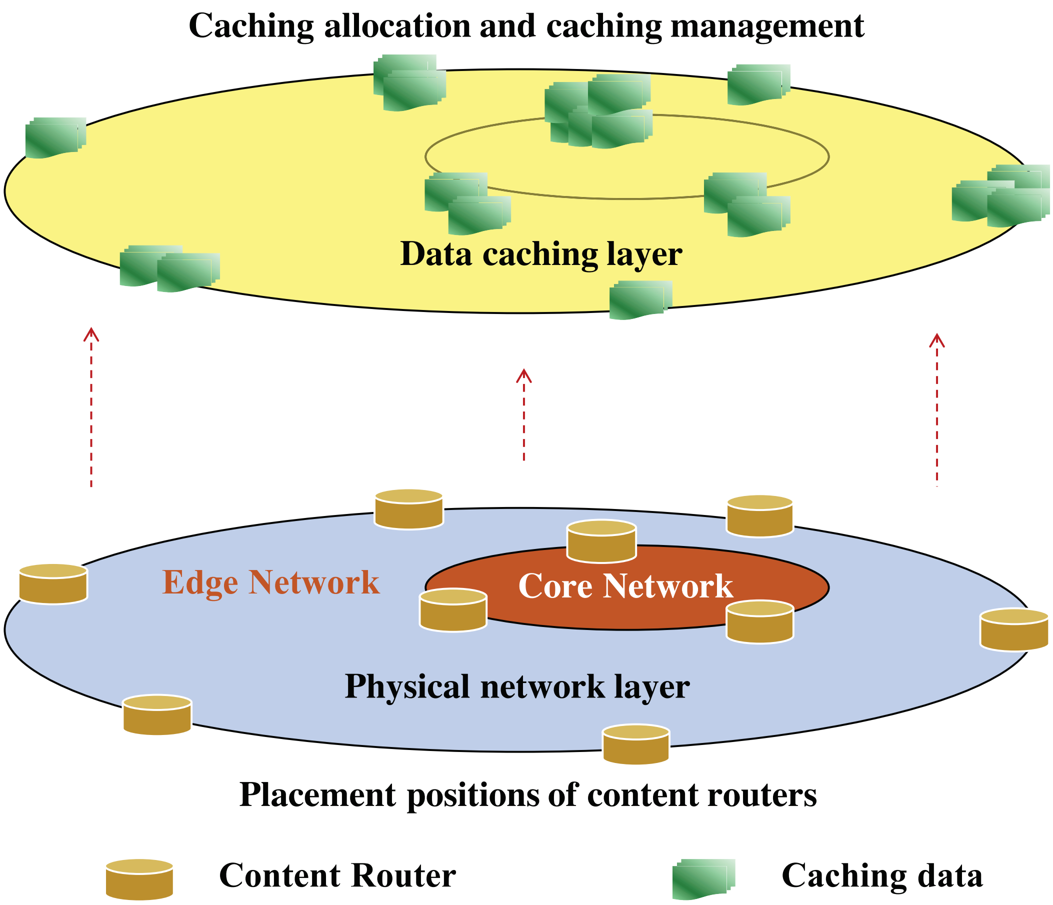

Figure 2.9: Overview of data placement for large-scale ICN network

factors, the placement positions of the content routers can be determined, such as deployed in the core network or the edge network.

- Cache allocation: Cache allocation determines where and how the cache data are sited in the network. The two key cache allocation approaches are in-network caching and data replica [2-44] [2-45]. The in-network caching described in Section 2.2.3 is inherent to ICN as the caching of data packets can raise the QoS. Data replica caching, which is similar to today's Content Delivery Network (CDN), caches a whole data in network, and so is efficient for the large-scale ICN network.

Existing CDN technologies can be adopted for the ICN network in order to realize data replica caching [2-46].

- Cache management: Given the sheer scale expected for the ICN network, it is very important to dynamically manage massive amounts cache data [2-47]. The cache controller, which is integrated within the ICN network, collects related information, such as link capacity, cache capacity, and determines the optimal caching strategy and makes the routing decision needed to meet the requests issued by the huge numbers of end-users and mobile devices, while minimizing the management overhead [2-48] [2-49].

2.3.3 In-network processing

In-network processing is an efficient approach to the ICN network that can create more data and network services by chaining and combining various in-network services/processes and data. Examples include providing video with different qualities to different users by running the original video through several different video processes [2-50]. In-network processing yields an ICN network that can provide not only original name-based data services but also composite data services. This reduces the number of data files and data names needed, increases the utilization of network services, and improves the scalability of the ICN network in terms of supporting more data services to handle all kinds of user requests.

In-network processing within the ICN network can be classified into two categories:

- Static service chaining: The chaining policy is defined in advance, including specified data and services information, such as server IP address. When the requested data is not found, the network triggers service chaining function to generate the requested data by combining the fixed data with the appropriate service according

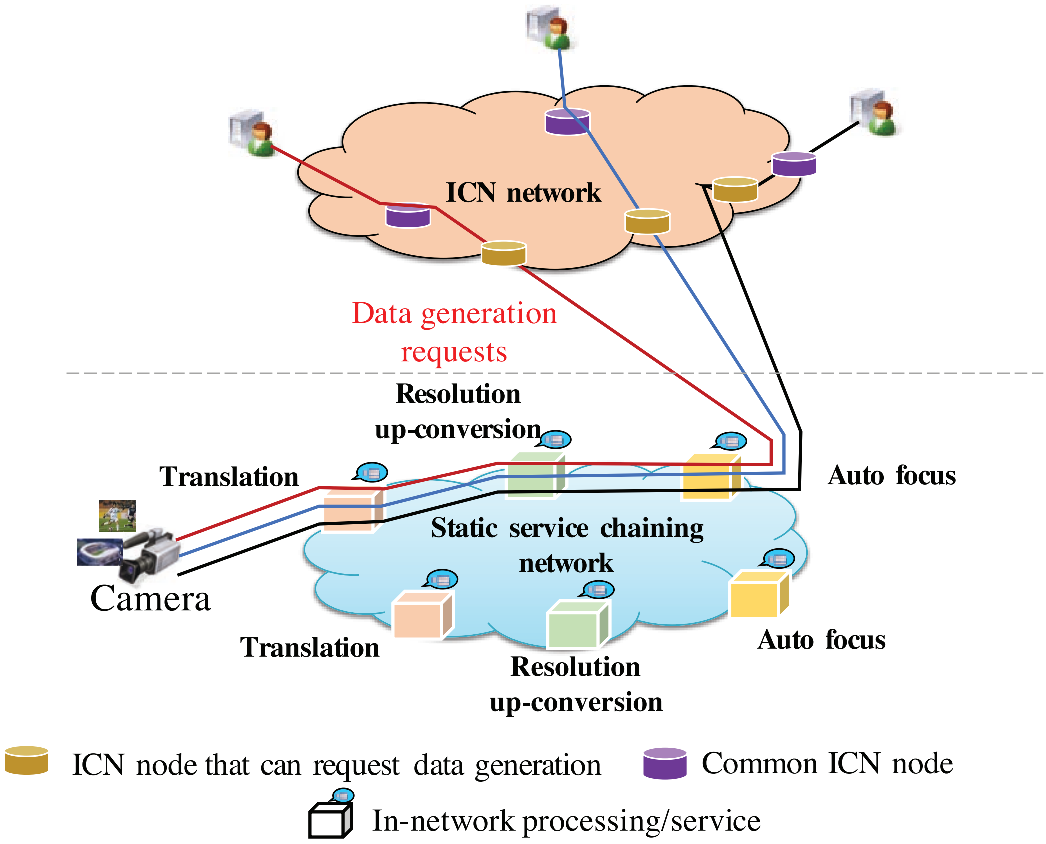

Figure 2.10: Overview of ICN network integrated with static service chaining

to the appropriate chaining policy, see Figure 2.10. As detailed in [2-51] [2-52], the static approach can combine data and services in layer 2~4 to create new data services.

- Dynamic service chaining: The static service chaining approach ignores the current situation in performing service chaining, such as actual server load, bandwidth resources available. Dynamic service chaining rectifies this omission by dynamically chaining the in-network data services and data according to the actual conditions of servers and the network.

This dissertation adopts the dynamic service chaining approach in scaling up the ICN network with regard to the number of network services and data sources.

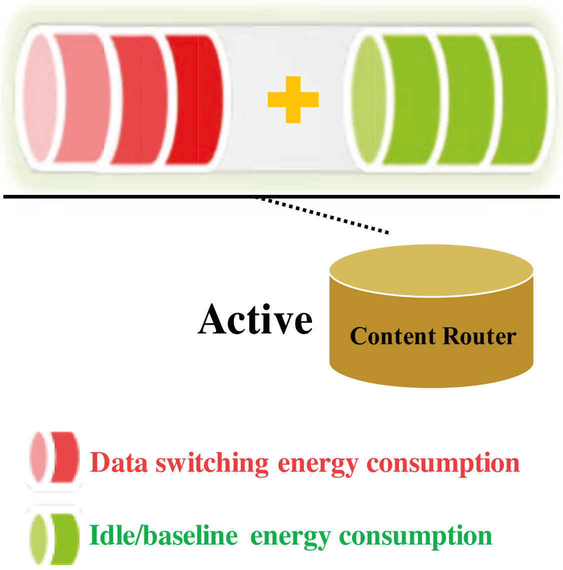

Figure 2.11: Energy consumption of ICN network hardware

2.4 Energy efficiency of ICN

The energy consumption of the ICN network is a crucial issue given the explosive growth in network traffic [2-53]. This section describes technologies that address the energy efficiency of the ICN network.

2.4.1 Energy efficient hardware

As shown in Figure 2.11, the energy consumption of the ICN content router contains data switching energy consumption and idle/baseline energy consumption. The data switching energy of the ICN content router is consumed by switching data traffic. The idle/baseline energy of the ICN content router is consumed by active hardware. Improving the energy efficiency of the hardware can reduce energy consumption. This can be achieved by optimizing the energy efficiency of each component of the content router.

Components

The ICN content router, which is the same as the traditional router, basically consists of storage disk, interface line card, memory and routing processing components. There are technologies for improving the energy efficiency of these components, as described in Section 1.3.5. Especially, like high-speed solid-state disk (SSD) and dynamic random-access memory (DRAM) is suggested to build energy efficient cacheable ICN content router [2-54] [2-55].

Content router

Adding power control functionality to the ICN content router can save energy, e.g., power on/off, low power mode, sleep mode, and slowdown [2-54] [2-55] [2-56] [2-57]. Similar to existing studies described in Section 1.3.5, power on/off can switch off content routers when they are unused. Like low power mode, sleep mode and slowdown make the content router enter energy-saving modes according to network conditions and actively reduce the energy consumption of the content router.

These functions help to optimize the whole ICN network energy consumption according to network-level energy efficient strategy.

2.4.2 Energy efficient network

Network energy optimization

Network infrastructure is designed based on the assumption of running at full capacity (maximum network capacity/traffic load) at all times. However, the actual utilization of network resources is low, e.g. the average utilization of current backbone network links is just 40% and indeed can be lower [2-58]. Therefore, by optimizing the utilization of network resources by switching off some network devices and network interfaces (or switch

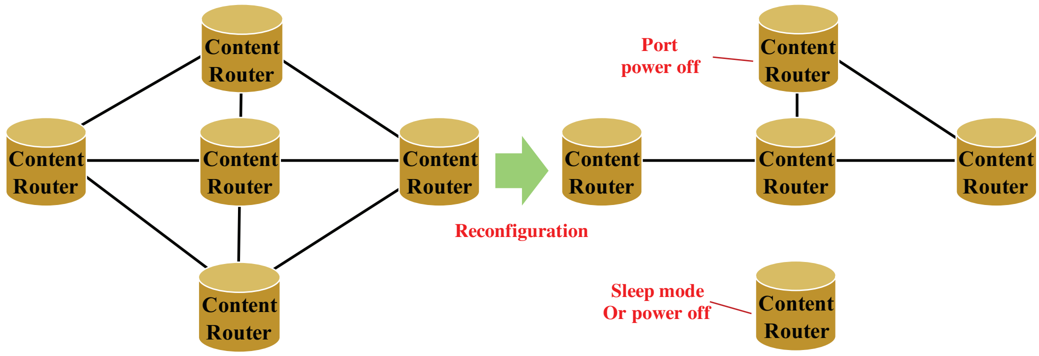

Figure 2.12: Energy efficient ICN network reconfiguration

them into sleep mode) can reduce the network energy consumption [2-56]. For instance, during low-traffic periods, energy-aware traffic engineering may put some links to sleep by moving their traffic to other links and aggregate the traffic through one common router or common sub-path. This enables more content routers and network devices and interfaces to switched off or placed into sleep mode [2-59], as shown in Figure 2.12. Energy efficient rate adaptation techniques can reduce the energy consumption of content routers and network devices by dynamically adjusting the power consumption to the actual traffic load [2-60].

Data placement

In the ICN network, the placement of content routers influence not only QoS and scalability, as described in Section 2.2.3 and 2.3.2, but also energy efficiency. The deployment optimization problem involves a trade-off between storage energy and transmission energy [2-61]. In general, content routers are far away from users; using fewer content replicas consumes less storage energy but more transmission energy. Placing the content routers closer to users consumes more storage energy but less transmission energy. Several studies have tackled the content router deployment optimization problem, such as [2-62] [2-63], by comparing with 20% and 100% content routers in the ICN networks, the content routers 20% deployed in edge networks are better than in core network from overall energy consumption perspectives.

The data caching location problem, which is similar to the content router placement problem, also involves a trade-off between transport energy and caching energy [2-64]. The most basic analysis of overall network energy consumption and data delivery under in-network caching shows that if each node should cache the data only if the transport energy consumed in satisfying the user requests is much higher than the caching energy. There are some studies on the energy efficient data caching problem. Their aim is to minimize the sum of the energy consumed by storage devices for content caching and the energy consumed by network devices for content delivery by considering content popularity, equipment energy efficiency, network topology, network bandwidth resources, caching capability, and other factors [2-65] [2-66] [2-67].

Data discovery and delivery

As shown in Figure 2.11, data switching energy consumption is also an important part of the overall ICN energy consumption. Energy efficient routing/discovery and delivery is an efficient solution to reducing the energy consumed by the ICN network.

Data name aggregation can be one part of energy efficient discovery and delivery approaches. In [2-68], greening domain adopts domain-based aggregation to compress the name space and while intelligent ant colony-based forwarding reduces data forwarding energy based on traffic load, delay and some factors. In [2-69], aggregable name-based routing integrated with combined CCN and NetInf is proposed for quick data retrieval and global data discovery based on information islands. Like [2-70], a robust ICN-based forwarding strategy is proposed that utilizes hybrid broadcast and unicast routing to guarantee a shorter content retrieval delays and a lower energy consumption. There are studies on data discovery and delivery combined with data caching strategies, such as [2-65] [2-

66] [2-67], to save overall network forwarding energy.

This dissertation focuses on reducing the energy consumed by data discovery and delivery.

2.5 Position of this dissertation

Based on the technologies and studies described from Section 2.1 to Section 2.4, the positions of this dissertation are summarized in Figure 2.13 and Figure 2.14. Network virtualization plays an important role because it can guarantee network resources, and support network awareness and scalability seamlessly. The researches underlying this dissertation is based on network virtualization. The ultimate goal of this dissertation is to realize an energy efficient and flexible information-centric network for the future Internet that offers high QoS, high scalability and high energy efficiency.

Position about QoS and scalability

The QoS and scalability of the ICN network interact with each other. As shown in Figure 2.13, the existing studies on QoS and scalability of the ICN network can be classified into four types: data discovery and data delivery, network performance, virtualized ICN, and multiple service paradigms. Associated with in-network caching, data placement can reduce the distance and delay of data discovery and data delivery, and also efficiently handle a huge numbers of end-users in large-scale ICN networks. Efficient naming schemes and routing strategies can make good use of routing table space and improve data discovery speed. Like virtualized ICN, optimal network performance and in-network data service chaining all positively impact on the QoS and scalability.

In this dissertation, Chapter 3 proposes an Energy Efficient and Enhanced-type Data-centric Network (E^3-DCN) that supports the information-centric networking communi-

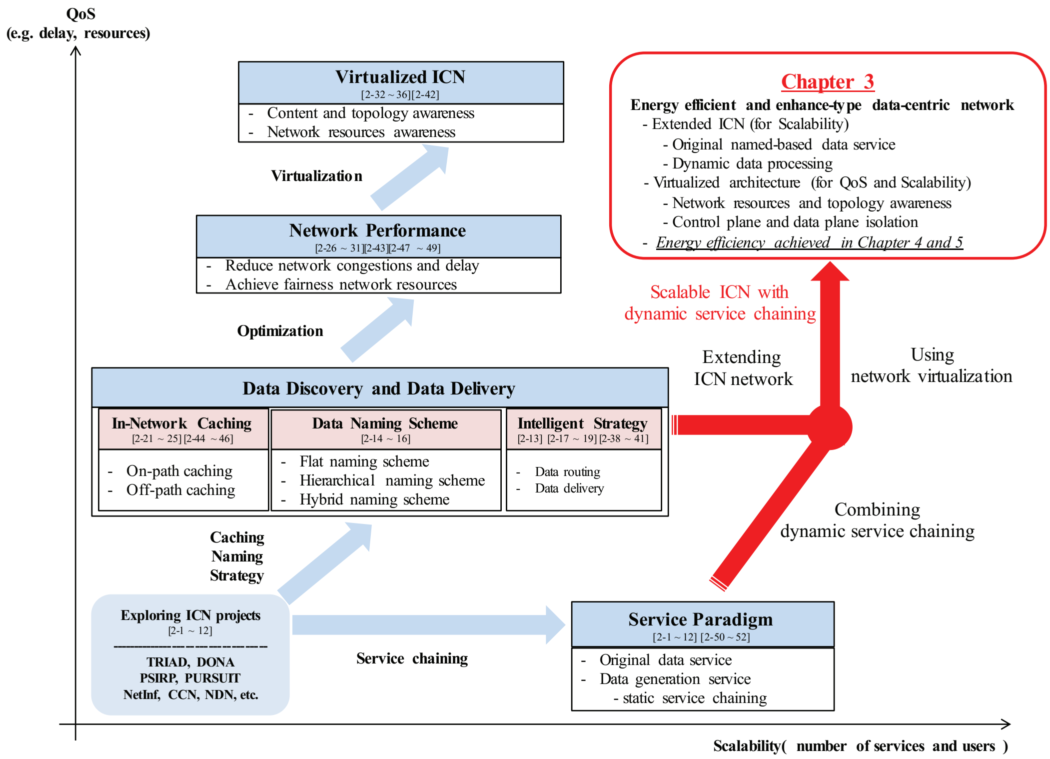

Figure 2.13: Position of this dissertation about QoS and scalability

cation model and also considers ICN QoS, scalability and energy efficiency. E^3-DCN supports efficient routing for data discovery and combines dynamic service chaining technology for in-network processing to scale up the number of services and minimize name and data storage spaces. Furthermore, network virtualization technology also helps E^3-DCN to realize network awareness and network control plane and network data plane separation to improve QoS and scalability.

Position about QoS and energy efficiency

The QoS and energy efficiency of the ICN network are linked to each other. As shown in Figure 2.14, the existing researches on ICN QoS and energy efficiency can be summarized as four types: network hardware, energy efficient data discovery and delivery, energy efficient placement, and optimization between network performance and energy

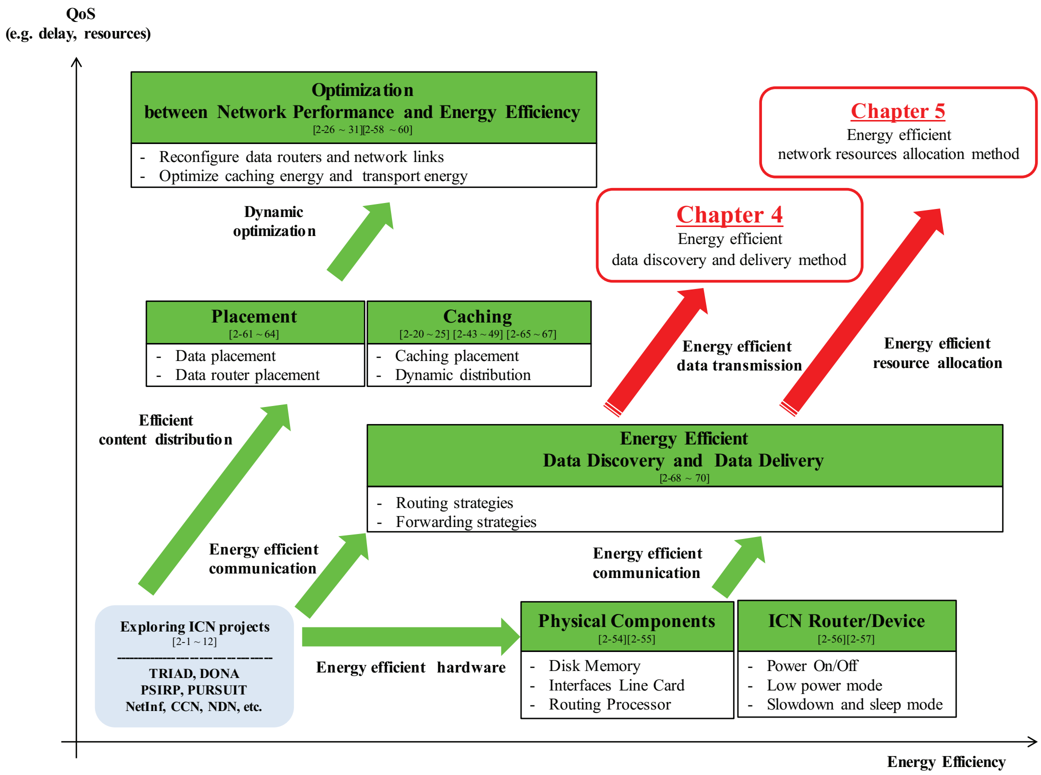

Figure 2.14: Position of this dissertation about energy efficiency and QoS

efficiency.

Content router and data placement can reduce the distance and delay of data discovery and data delivery, and also reduce data switching energy. Energy-aware routing and forwarding approaches also improve routing speed and save data transmission energy. Technologies that focus on the optimal trade-off between network performance and network energy efficiency have been developed.

This dissertation details the research conducted by author with regard to ICN QoS and energy efficiency. Chapter 4 proposes an energy efficient data discovery and delivery method that can decide the optimal data source and the optimal energy efficient data transmission path to save data transmission energy based on packet switching and optical circuit switching. Chapter 5 proposes an energy efficient network resources allocation method. The proposal saves data transmission energy and reduces data transmission delay to enhance QoS by allocating available network resources dynamically.

Relationship of chapters

The target and relationship of chapters in this dissertation are shown in Figure 2.15.

The research of Chapter 3 focuses on the architecture of E^3-DCN for the future Internet. E^3-DCN offers high QoS and high scalability, as well as information-centric networking, the multiple service paradigms, network awareness and easy network reconfiguration, network control plane and data plane separation, and network resources isolation to meet the requirements of the future Internet.

Chapter 3 addresses the network architecture issue of E^3-DCN. The work described in Chapter 4 and Chapter 5 target the energy efficiency of E^3-DCN and focus on reducing the data transmission energy consumption of E^3-DCN. Chapter 4 presents an energy efficient data discovery and delivery method for E^3-DCN to achieve energy efficient data transmission. Chapter 5 presents a dynamic network resources allocation method that is able to allocate energy efficient network resources to reduce the data transmission energy consumed by E^3-DCN.

The results detailed in this dissertation ultimately achieve an energy efficient and flexible information-centric network for the future Internet that offers high QoS, high scalability, and high energy efficiency.

2.6 Chapter conclusion

This chapter started by exploring network architecture technologies for information-centric networking (ICN) for the future Internet, and then existing studies on the quality of service, and scalability issue of ICN were introduced. This chapter also described energy-saving techniques from hardware-level to network-level with regard to the ICN network.

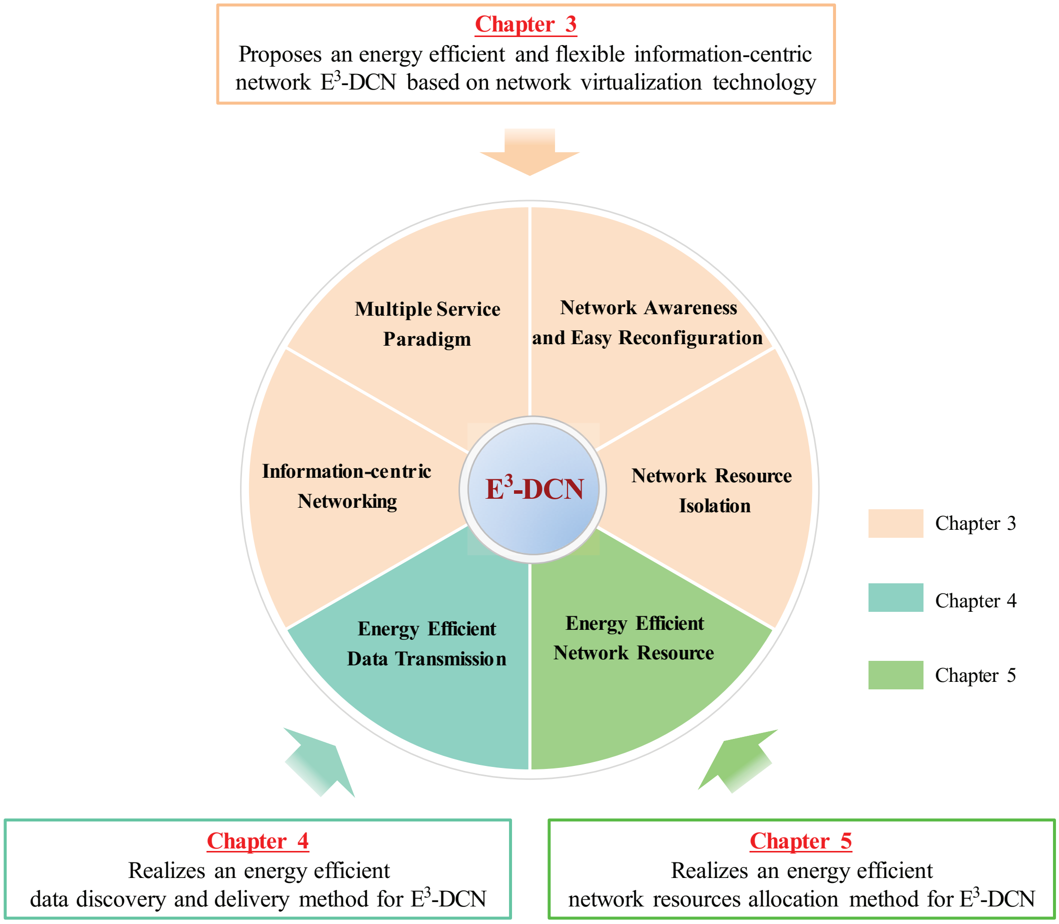

Figure 2.15: Target of relationship of chapters in this dissertation

Finally, the position of the research conducted and the relationship of the chapters in this dissertation were clarified.

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Chapter 3

Energy efficient and enhanced-type data-centric network

This chapter proposes an Energy Efficient and Enhanced-type Data-centric Network (E^3-DCN) that uses network virtualization technology for the future Internet [3-1]. E^3-DCN not only supports information-centric networking (ICN) communication for efficient information dissemination, but also efficiently implements network awareness, separation of control plane and data plane, easy network reconfiguration, multiple service paradigms, and high energy efficiency requirements as described in Section 1.2 for the future Internet.

3.1 Introduction

The Internet has become a global social infrastructure and is now impacting various fields such as industry, economics, education, healthcare, government and entertainment, etc., and playing a bigger and bigger role in people's life. Moreover, with the tremendous growth of the Internet, its usage is gradually shifting from information transmission, such as E-mail and file transmission, to information dissemination, such as video sharing, web pages and live streaming. However, as mentioned in Chapter 1, the architecture of the current Internet, which was designed and implemented in decades ago, still focuses on information transmission between exactly two hosts based on the TCP/IP host-centric networking communication model. This causes some crucial problems, such as location-dependence, data insecurity, and weak mobility, that make the current Internet unsuitable

Category	Requirements of future Internet			Solution States (Existing researches)	Chapter 3
Networking	Information-centric networking			○	○
Quality of service	Network awareness			○	○
	Separation of control plane and data plane			×	○
Scalability	Easy network reconfiguration			○	○
	Multiple service paradigms	Original data service		○	○
		Data generation service	Static service chaining	○	○
			Dynamical service chaining	×	○
Energy consumption	High energy efficiency	Energy efficient data transmission		×	○

○ : Solved × : Not solved

Figure 3.1: Summary of existing studies and Chapter 3 for the future Internet

for efficient information dissemination.

In this context, information-centric networking (ICN) was presented as the most attractive networking paradigm for the future Internet; it has received much attention from both academia and industry in recent years. As mentioned in Chapter 2, several research projects have explored the ICN network architecture, such as DONA, CCN, NDN, PSIRP, NetInf, SAIL, DCN, and so on. They take different approaches to the ICN communication model while offering location-independent communication, data security, efficient mobility support, and efficient data dissemination for the future Internet. Furthermore, based on these ICN network architectures, there are also some studies on to ICN from the aspects of QoS, scalability and network energy consumption perspectives, as summarized in Section 2.2, Section 2.3 and Section 2.4.

However, to the best of our knowledge, there is no study that can meet all the requirements of the future Internet as summarized in Section 1.2. In this chapter, we propose an energy efficient and flexible ICN network architecture, called Energy Efficient and Enhanced-type Data-centric Network (E^3-DCN), that can meets all the requirements set for the future Internet. In particular, E^3-DCN offers network control plane and data plane separation, dynamic service chaining and energy efficient data transmission from the network architecture perspective, as shown in Figure 3.1.

The idea of E^3-DCN is based on network virtualization and the multi-layered network design model. The architecture of E^3-DCN is based on network virtualization (NV). NV described in detail in Section 1.3.2 can create multiple virtual networks (VNs) on a shared physical network and allocate physical network resources for every VN. Each VN can be used as an independent network infrastructure, like the underlying physical network of the current Internet. In order to solve requirement for separation of the control plane and data plane with dedicated network resources, three VNs are used to construct E^3-DCN. One is used as the control plane, the other two are used as the data plane. By combining the information-centric networking communication overlay network with the dynamic service chaining overlay network, E^3-DCN realizes multiple service paradigms that support not only information-centric networking communication for efficient information dissemination but also dynamic service chaining to generate requested data. In addition, E^3-DCN focuses on network energy efficiency from every aspect, from data transmission to the whole network. In the data plane, one VN is used to implement optical switching transmission, the other implements packet switching transmission. By combining optical switching and packet switching modes, E^3-DCN addresses every aspect of data transmission energy saving. Moreover, E^3-DCN as independent network offers full compatibility and can supports existing energy-efficiency strategies to optimize network energy consumption, such as existing network reconfiguration, circuit switching bypass, and data in-network caching to improve overall network energy efficiency. In this way from the network architecture perspective, E^3-DCN meets all the requirements of the future Internet.

The rest of the chapter is organized as follows: related works are introduced in Section 3.2. The proposed architecture of E^3-DCN is detailed in Section 3.3. Experiments on E^3-DCN are introduced in Section 3.4. Finally, a conclusion is given in Section 3.5.

3.2 Related works

Related works on data-centric network and dynamic service chaining techniques are introduced in this section.

Data-centric network

Data-centric network (DCN) is one of the active ICN projects and adopts the hop-by-hop name-based networking paradigm to realize a ICN network [3-2]. For CCN and other ICN projects described in Section 2.1, the large volume of data names is a critical problem for ICN. This is because these data names occupy a lot of routing table memory space and increase routing processing latency, both of which negatively impact on communication delay. DCN realizes an intelligent hop-by-hop name-based routing to address this problem.

DCN extended CCN to support the huge volume of machine-to-machine communications including mobile communications anticipated in the future. In DCN, data names are hierarchical. As shown in Figure 3.2, each DCN node is also called an aggregator node. Each aggregator node records data name and route information in its route information table. An aggregator node may connect with its parent node, child nodes and neighbor nodes. The top aggregator node, Node#00 in Figure 3.2, is responsible for forwarding data requests or returned data between different sub-networks (name domains) using only the data name, connects with just child nodes that are mapped to different name domains.

In DCN, the data registration message is recorded in the route information table by the aggregator node from the nearest tier to upper tiers, till top tier aggregator node. The data information update is also the same order from the nearest aggregator node to upper tier aggregator nodes. Data requests are also forwarded from the nearest tier to upper tier or to other name domains. As shown in Figure 3.2, the data request of Data#1 Req&Res#1 is forwarded as follows: Node#222 → Node#22 → Node#02→ Node#00 → Node#01

→ Node#11 → Node#111. The route information is also recorded in the data request while it is being forwarded. The found data is returned by using the data request route information. If the aggregator node has neighbor nodes and discovers its neighbor nodes from the request route information when the returned data is forwarded through it, the aggregator node gets the optimal data route based on the route information and so can better handle another request for the same data request in the near future. As shown in Figure 3.2, aggregator node Node#02 gets the optimal data route for Data#1 from its route information: Node#111 → Node#11 → Node#01 → Node#02. In the near future, when the data request Req&Res#2 arrives, the data request is not forwarded to upper aggregator node Node#00, but is directly forwarded to the neighbor node Node#01 to retrieve the data.

DCN has two excellent advantages over alternatives CCN [3-2], NDN [3-3], and other name-based ICN networks:

- When the data migrates into the local area, processing load and data information update time in relevant aggregator nodes are reduced.
- Route optimization reduces processing load on relevant aggregator nodes and data retrieval time.

These advantages identify DCN as suitable for large-scale ICN networks with a huge volumes of data. Unfortunately, DCN can support only original data services and cannot combine and chain in-network data services/processes to generate new data so as to handle complex end-user requests.

Dynamic service chaining technique

The Ubiquitous Grid Networking Environment (uGrid) has been proposed for the ubiquitous communication society of the future, as shown in Figure 3.3 [3-4]. In uGrid, every-

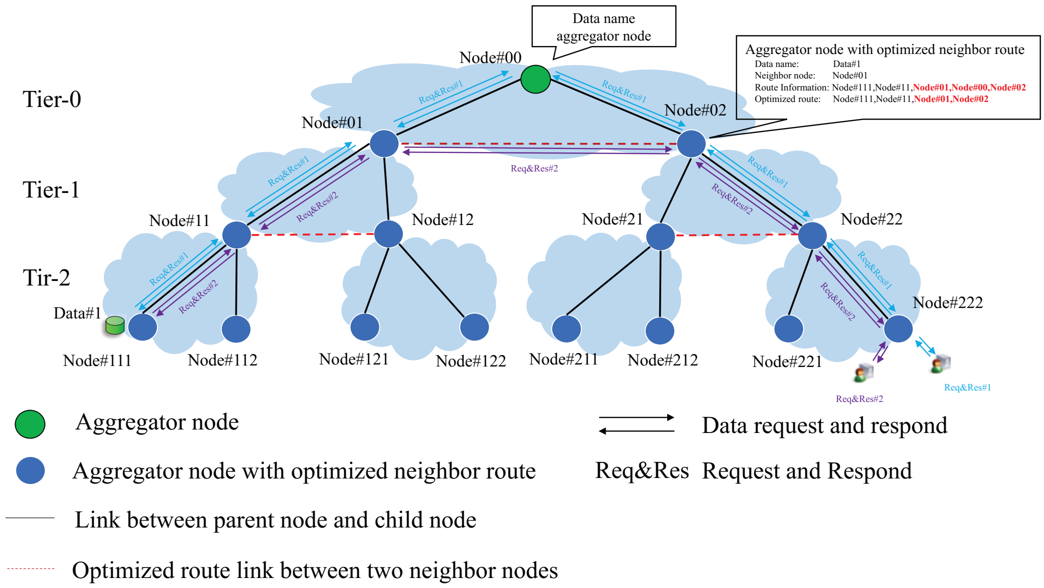


Figure 3.2: Intelligent name-based routing of data-centric network

thing from devices to programs, is called Service-Part (SP), and has its own IP address. uGrid can provide not only original network services as SPs, but also the multiple mash-up service paradigm by chaining and combining several different SPs.

Dynamic service chaining techniques, as shown in Figure 3.4, include Service-Routing (SR) and Service-Signaling (SS); they have been studied to provide multiple mash-up services [3-5] [3-6]. SR is used for searching relative SPs and computing the optimal service flow path for each mash-up service. 3D-Dijkstra is a typical method researched for SR, as shown in Figure 3.5. The 3D-Dijkstra method first creates a service chaining network topology according to network with service parts topology (uGrid Topology), and then applies Dijkstra, a source-destination pair path algorithm, to calculate service chaining flow paths. Parameters, such as network link bandwidth, delay, switching energy, etc., can be defined as the link weights processed in 3D-Dijkstra for obtaining the optimal service chaining flow path. Service-Signaling is used for establishing a service chaining flow path for each mush-up service. Data, which is processed while passing through these

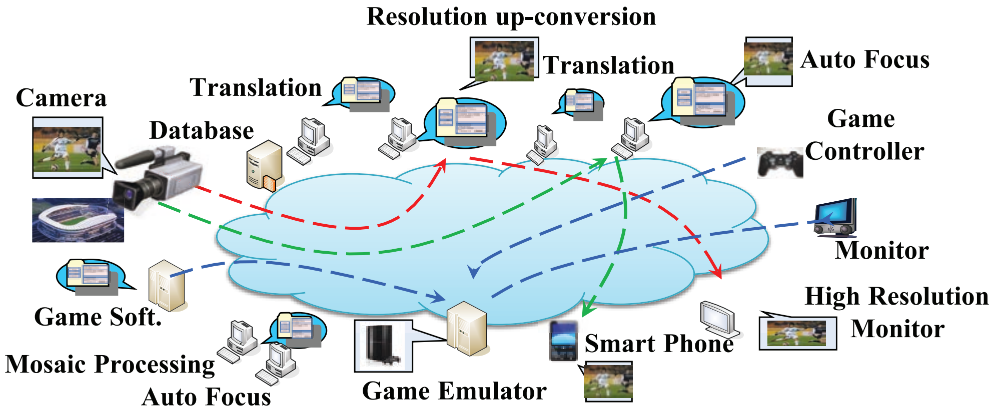


Figure 3.3: Ubiquitous grid networking environment (uGrid)

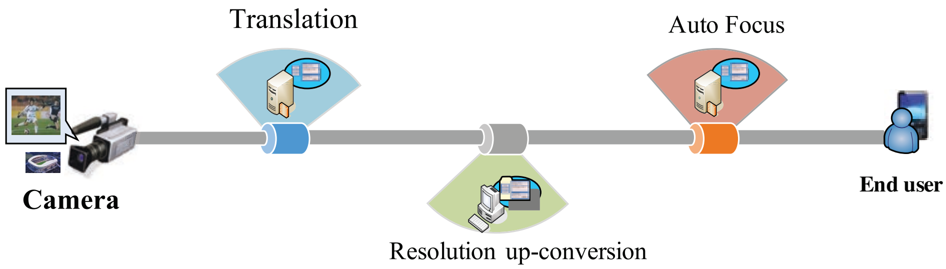
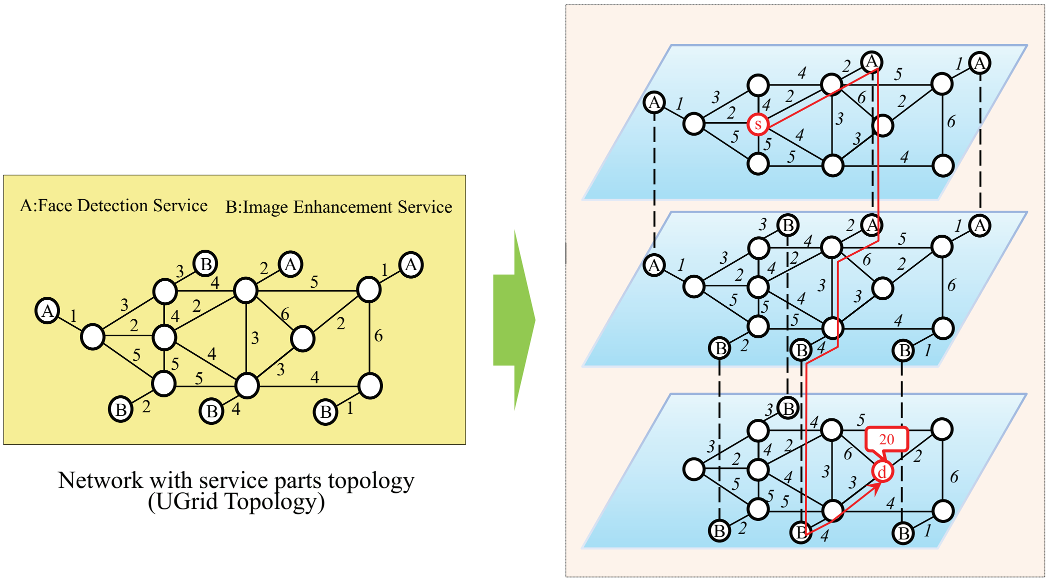


Figure 3.4: Mush-up service of uGrid based on dynamical service chaining technique

SPs, is transported under established service chaining flow paths to the end-users.

The dynamical service chaining techniques of uGrid network can be adopted for multiple service paradigms and scale up the number of network services. However, these technologies has also been limited by some problems described in Section 1.1.2 because they are also based on IP host-centric networking paradigm. In addition, these technologies only support source-destination pair transfer mode and do not support multicast transfer mode for efficient information dissemination.



Network with service parts topology
(UGrid Topology)

Service chaining network topology
(3D Topology)

Figure 3.5: 3D-Dijkstra service-routing for dynamic service chaining

Summary

DCN realizes ICN and is suitable for efficient information dissemination of large-scale ICN network, but does not support data generation by combing and chaining in-network data services/processing. The dynamical service chaining techniques of uGrid network can be used for data generation by chaining in-network data services/processing, but it does not support like multicast transfer mode for efficient information dissemination. The advantages and disadvantages of both complement each other. Hence, by combining these two networks with their own technologies, the multiple service paradigms requirement of the future Internet can be realized. In this dissertation, we will make enough use of these advantages to realize multiple service paradigms in our proposal. How to combine these techniques as an issue will be described in our proposal from next section in detail.

3.3 Network architecture

3.3.1 Overview

The proposed E^3-DCN is based on network virtualization technology and multi-layered network architecture design model.

As shown in Figure 3.6, E^3-DCN is built on network virtualization platform (NVP) and adopts multiple overlay networks and multiple infrastructure networks architecture model. Data Centric Overlay Network (DCON) and Data Generation Overlay Network (DGON) two overlay networks are designed to realize network functions through combining them. DCON is an extension of DCN, and realizes a non-IP network that supports information-centric networking. DGON is an extension of uGrid with dynamic service chaining techniques, and realizes data generation function by chaining in-network data services/processing. DGON can receive the data generation request from DCON and provide the generated data to DCON. DCON receives the data request from end-user, and provides the requested data by information-centric networking communication model to end-user.

As described in Section 2.2.5, there have been existing researches about virtualized ICN that a virtual network is used as network infrastructure and ICN network is overlaid on the virtual network. Adopting network awareness character of virtual network, such as network topology awareness and network resources awareness, these existing researches realize high QoS ICN network. However, in these researches, control plane and data plane are not separated and have no dedicated network resources. Network resources are still shared between control plane and data plane. In addition, their architectures only suit for single-switching mode network, packet switching network or optical switching network, that does not help to save data transmission energy consumption. These do not meet the future Internet requirements and not suit for network flexible and optimization.

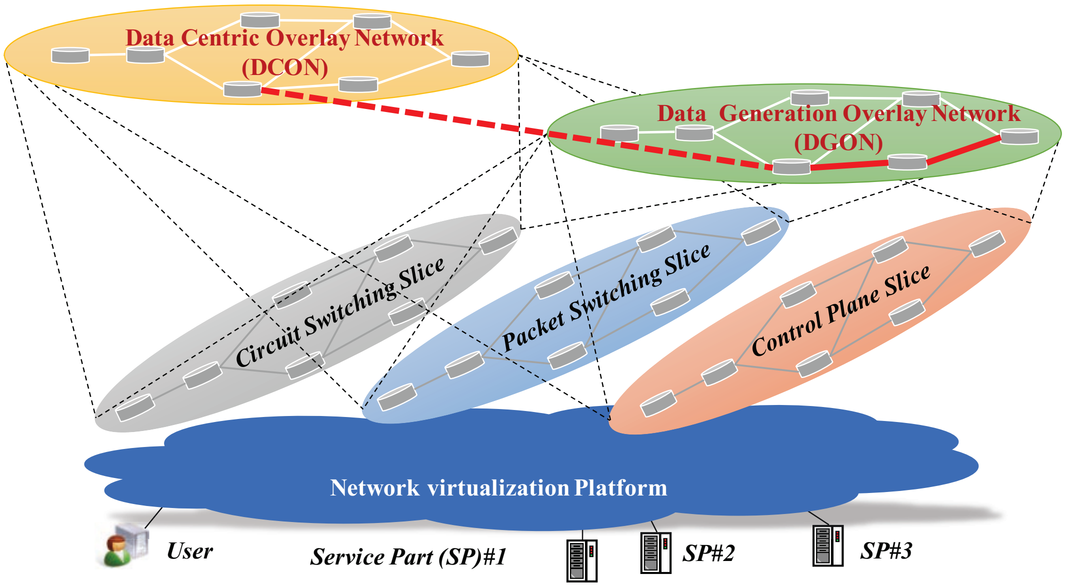


Figure 3.6: Overview of E^3-DCN architecture

In order to solve these disadvantages and realize network optimization on network resources and energy consumption, three slice/virtual networks as network infrastructure are used to construct E^3-DCN that realizes network control plane and data plane separation, as shown in Figure 3.6. One slice network, called Control Plane Slice (CPS), is used as control plane of E^3-DCN. The other two slice networks, Packet Switching Slice (PSS) and Circuit Switching Slice (CSS), are used as data plane of E^3-DCN. DCON and DGON is overlaid on CPS to realize network functions. Like network management, network control and routing are also realized on CPS, And PSS and CSS are only used to data delivery.

CPS communicates with overlay networks DCON and DGON, and with underlay networks PSS and CSS. CPS also collects underlay networks resources information to manage and control underlay network, and share them to DCON and DGON to make some decisions, such as where and how traffic is sent. In current Internet, overlay network service receives all data requests, and data is transmitted via underlay network, such as current peer-to-peer (P2P) overlay network application [3-7]. Because the overlay network services of the current Internet cannot collect detailed underlay network resources information, it cannot manage and control the underlay network. In other words, it is impossible to realize the optimization of underlay network resources for high QoS and energy efficient network. In order to solve this problem, we establish communication tunnels between CPS node and its matching PSS node and CSS node, respectively. With control technology [3-8], the underlay network information can be collected and the underlay network can be controlled by CPS through these communication tunnels.

In addition, in NVP, a slice network consisted of virtual nodes (v-nodes) and virtual links (v-links) has independent and dedicated network resources and computational resources. One slice network can be used as one independent network infrastructure. And meanwhile, the slice network resources information can be collected from Infrastructure Provider at any time, such as bandwidth, traffic situation, underlay physical/substrate path of v-link, geographical location of v-nodes, and so on. Therefore, based on above control mechanism between control plane (CPS) and data plane (PSS and CSS), such as, the optimization of network resources for high QoS, network energy consumption, optimal data transport path, which are as special research topics and studied for E^3-DCN, can be all achieved based on slice network according to collected network resources information.

NVP supports optical switching and packet switching transmission modes, such as multiple layer Japan Gigabit Network eXtreme (JGN-X) [3-9]. Therefore, for the optimization of data transmission energy, in the data plane of E^3-DCN, PSS is defined as packet switching network and CSS is defined as optical switching network. And moreover, according to collected network resources information, the optimal energy network topology and optimal energy data transmission path, which are as special research topics and studied for E^3-DCN, can be also computed and reconfigured at any time.

The separation of network control plane and network data plane in E^3-DCN meets the requirement of the future Internet. There are main metrics from such network architecture design model:

- Control plane CPS and data plane PSS and CSS don't share network resources of network device and has dedicated network resources that helps to improve network performance.
- Control plane CPS can flexibly control and manage the data plane PSS and CSS, such as network topology reconfiguration, network node power on/off.
- Data plane PSS and CSS supports data switching and optical switching modes, that can realize data switching energy optimization under control plane.

In the next sections, network infrastructure, including CPS, PSS and CSS, and network functions, including DCON and DGON, are described in detail.

3.3.2 Network infrastructure

The separation of control plane from data plane is a key feature of E^3-DCN architecture. Three virtual networks as network infrastructure of E^3-DCN are as shown in Figure 3.6.

CPS is as control plane network and collects network resources information and manages and controls networks. The data plane is used for forwarding traffic dedicatedly based on the decision of control plane. Packet switching based on statistical multiplexing is very efficient because it can share link resources with other end-users. But switching energy and latency problems exist in packet switching. Circuit (optical path) switching is low-energy and low-latency. Circuit switching is suitable for real-time application, delay-sensitive application and large data transmission. But circuit path established between sender and receiver must set up prior to data transmission and cannot share link resources to others, hence it doesn't suit for small data transmission. Therefore, in order to achieve the optimization of data transmission energy and performance, PSS and CSS are used as data plane of E^3-DCN. According to data transmission requirements and network resources status, the optimal energy data transmission can be achieved on E^3-DCN.

CPS is used as control plane and exchanges kinds of routing and management messages such as routing messages of DCON, data information, Service-Routing and Service-Signaling protocol messages of DGON. PSS provides a main network topology of E^3-DCN. The topology of PSS should be projected to a logical topology of CPS. The communication tunnel established based on Generic Routing Encapsulation (GRE) tunnel technology is used between two v-nodes of CPS and PSS to match both topologies. The topology of CSS is not fixed and can be controlled and reconfigured dynamically. For example, an optical path is set-up or tear-down between two v-nodes of CSS at the beginning or end of data transmission. In E^3-DCN, data are mainly exchanged via PSS. For example, if high bandwidth transmission is required and/or long time transmission is required, by control technology [3-8], CSS can be configured and used to bypass packet switching to reduce data transmission energy consumption and ensure Quality of Service (QoS).

Two overlay networks DCON and DGON are constructed on these three slice networks. The query of end-user is sent to DCON, if the requested data is found in DCON, the data is transported to end-user via PSS or CSS. If the requested data are not found in DCON, then the query is sent to DGON. In DGON, the requested data is generated by chaining and combining Service-Parts and provided to DCON via PSS or CSS. Figure 3.7 shows a semantic diagram of E^3-DCN logical node architecture. The logical node is connected to three slice/virtual networks and end-users. Ethernet is used as a kind of access methods. And Virtual Local Area Network (VLAN) technology is applied to distinguish these slice networks. Finally, the logical architecture will be mapped into NVP, as shown in Figure 3.8.

In NVP, connection links are necessary to connect each pair mapping v-nodes that be-

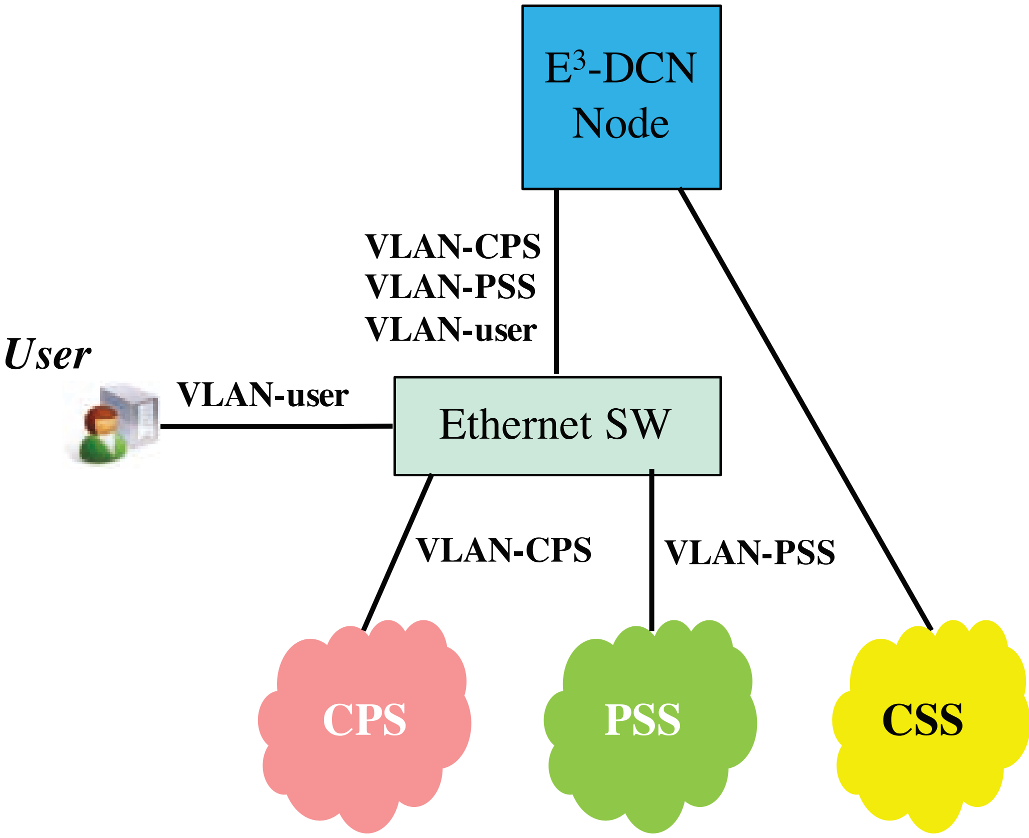


Figure 3.7: Architecture of E^3-DCN logic node

long to two different slice networks (CPS and PSS, or CPS and CSS) for communication. The connection links between E^3-DCN node and each slice network shown in Figure 3.8 connect at each v-node within each slice. As a result, E^3-DCN node is composed of a group v-nodes, including a v-node of CPS, a v-node of PSS and a v-node of CSS. These v-nodes are connected via network tunnels in the real world through network connector (NC) mediums. Figure 3.8 shows a composite structure diagram of E^3-DCN node including NC and three v-nodes. The v-node of CPS has main for E^3-DCN node because DCON and DGON node overlay on it, other two v-nodes have a role as Ethernet Bridge or Ethernet switch which connects the v-node of CPS through NC with real network. As shown in Figure 3.8, VLAN-PSS connects the v-node of CPS and the v-node of PSS, VLAN-CSS connects the v-node of CPS and the v-node of PSS [3-10].

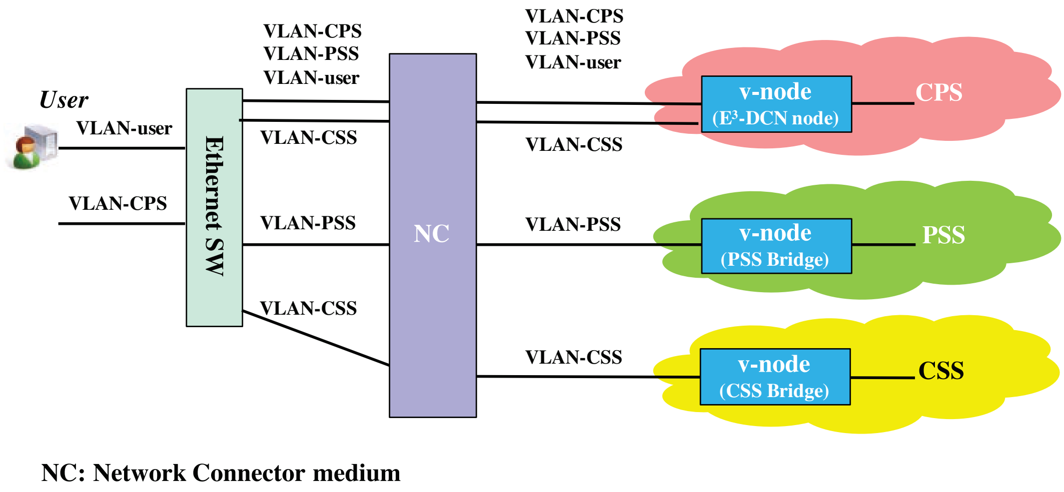


Figure 3.8: E^3-DCN node on network virtualization platform

3.3.3 Network functions

Two overlay networks DCON and DGON are overlaid on control plane CPS. The nodes of DCON and DGON are deployed inside the v-node of CPS. E^3-DCN is different from the current Internet whose overlay networks do not know the information of underlying network. E^3-DCN is built on NVP and supports network awareness that can make overlay network layer DCON and DGON know the information of underlying network CPS, PSS and CSS, such as, bandwidth, delay, hops, geographical location, switching energy efficiency. As shown in Figure 3.9, overlay network link Link[O.1,O.2] knows its underlying configuration information and resources status. These information helps to achieve high QoS network services.

Data-centric overlay network

DCON handles original pre-registered data and receives the data request of end-user. End-user sends data request to DCON and obtains the exact matched data from DCON. If the requested data is not found in DCON, the network will automatically redirect the

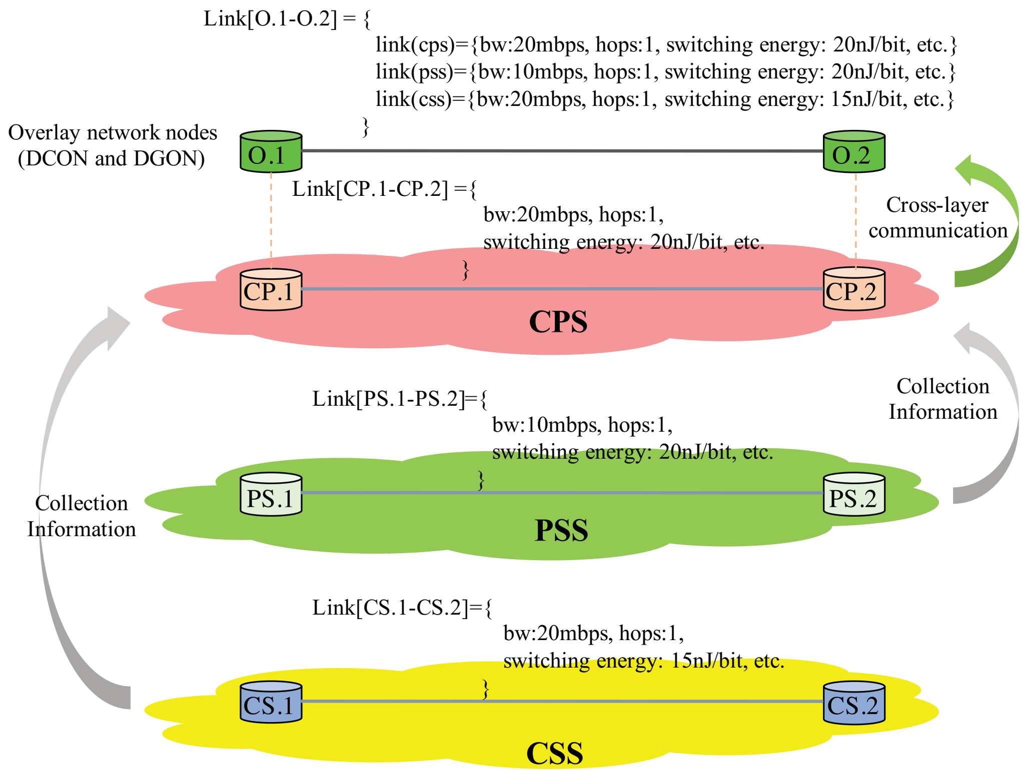


Figure 3.9: Underlying network awareness on E^3-DCN

data request from DCON to DGON to generate the requested data by combining Service-Parts. Then, the generated data will be pushed into DCON and provided to end-user from DCON. If E^3-DCN cannot provide the requested data from DCON and DGON, the end-user will receive a "NACK" message which indicates that service provider has not published the requested data into E^3-DCN. DCON inherits features of DCN, such as large-scale routing and namespace automatic aggregation, and realizes a hop-by-hop name-based information-centric network. In addition, based on underlying network awareness mechanism of E^3-DCN, more excellent strategies based on collection network information can be achieved for DCON. For example, in Chapter 4, an energy efficient data discovery and delivery method is proposed for DCON to reduce the data transmission energy consumption.

DCON holds network topologies and network resources information of CPS, PSS and CSS. The routing topology of DCON is an abstracted complex topology in which two adjacent DCON nodes may be connected with two and three abstracted links. Actually, an abstracted link is mapping to a transport path on underlying network, as shown in Figure 3.9. The case of two abstracted links shows a transport path is on CPS and another transport path is on PSS or CSS. The case of three links shows there are three mapping transport paths on CPS, PSS and CSS, respectively. Each abstracted link has kinds of link properties, such as data transmission energy cost, delay, hops, they are calculated based on its mapping transport paths.

DCON node model is shown in Figure 3.10. Three tables, Backtrack Query Table (BQT), Forwarding Query Table (FQT) and Link Cost Table (LCT), are designed for DCON routing. LCT maintains link cost used for computing the optimal transmission path. BQT is used for recording track where the data request comes from. FQT records forwarding directions where the data request is forwarded out. DCON node also contains four engines, Extracting Engine, Analyzing Engine, Forwarding Engine and Caching Engine, four directories G-DCON, G-DGON, L-DCON and L-DGON Directory (G: Global, L: Local). Extracting Engine is mainly responsible for extracting information from data request. The extracted information such as data name is delivered to Analyzing Engine to judge whether the requested data exists and whether can be provided from current node. Then, based on the judged result, Forwarding Engine continues to explore the requested data, or responds the requested data from current node. Caching Engine is responsible for caching data. G-DCON keeps all data information of DCON which indicates these data can be directly provided from DCON. G-DGON keeps the information of data generated in DGON. When the request data information does not exist in G-DCON and G-DGON, the current node as Sorry Server sends the ”NACK” message to response end-user [3-11]. L-DCON keeps local data information that shows what data can be directly provided from current node. And L-DGON keeps generated data information. If the requested data exists in L-DGON, Forwarding Engine requests DGON to generate the requested data. Retrieval strategy can be adopted into these directories for quick lookup, such as Least Recently Used [3-12]. Data Transceiver of DCON node is responsible for receiving and forwarding packets from interfaces such as V#CPS.1, V#PSS.1, V#CSS.1 shown in Figure 3.10, and can communicate with other engines. Figure 3.10 is shown an E^3-DCN node holds three branches and adopts virtual interfaces to connect three slice networks based on VLAN technology.

Data generation overlay network

DGON is responsible for data generation based on dynamic service chaining technologies Service-Routing and Service-Signaling.

DGON node, as shown in Figure 3.10, contains uGrid Engine, Caching Engine and Generation Data Table. uGrid Engine includes Service-Routing and Service-Signaling modules. Generation Data Table keeps data generation information such as the mapping information about data name and Service-Parts. The request of data generation is sent from DCON when DCON can't directly provide the requested data. According to data name, Service-Part information is resolved by Generation Data Table. Then, uGrid Engine performs Service-Routing to get services chaining path based on abstracted complex topology, and then, executes the Service-Signaling to establish the service chaining path to connect Service-Parts to generate data. The generated data are cached by Caching Engine and its information is also registered into DCON. At last, the generated data are provided to end-user from DCON. Data Transceiver is the same as DCON's.

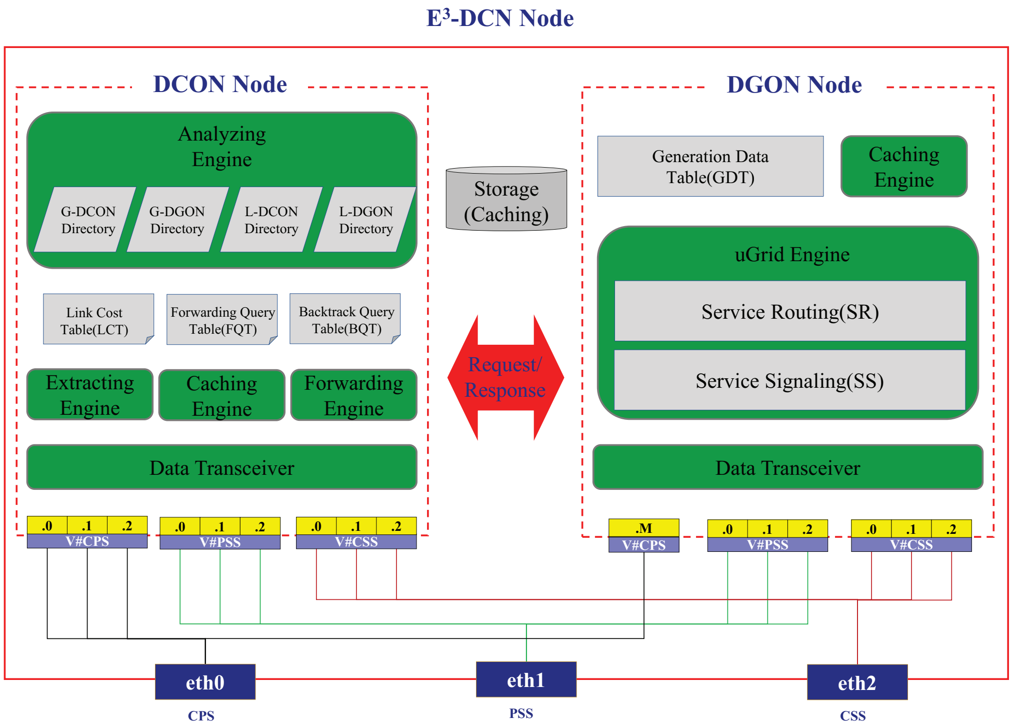


Figure 3.10: Architecture of DCON node and DGON node

3.3.4 Workflow

An overview and workflow of E^3-DCN service is as shown in Figure 3.11 (The unused links are not drawn in DCON and DGON). E^3-DCN node connects with three slices and includes two overlay network nodes. Service provider publishes data "a.avi" into E^3-DCN using publishData Application Programming Interface (API). The data "a.avi" can be generated by combining Service-Parts A and B. Its data information is registered into GDT of DGON and directories of DCON. User1, User2 and User3 request the same data "a.avi" using getData API. Their requests are sent to DCON. The data generation request is sent to DGON from Node5 of DCON. The optimal data source and transmission path of DCON is determined based on overall network resources status. By using hop-by-hop name-based routing, the optimal data transmission path to transmit data "a.avi" from Node5 of DCON is finally formed as a multicast tree. The energy efficient data

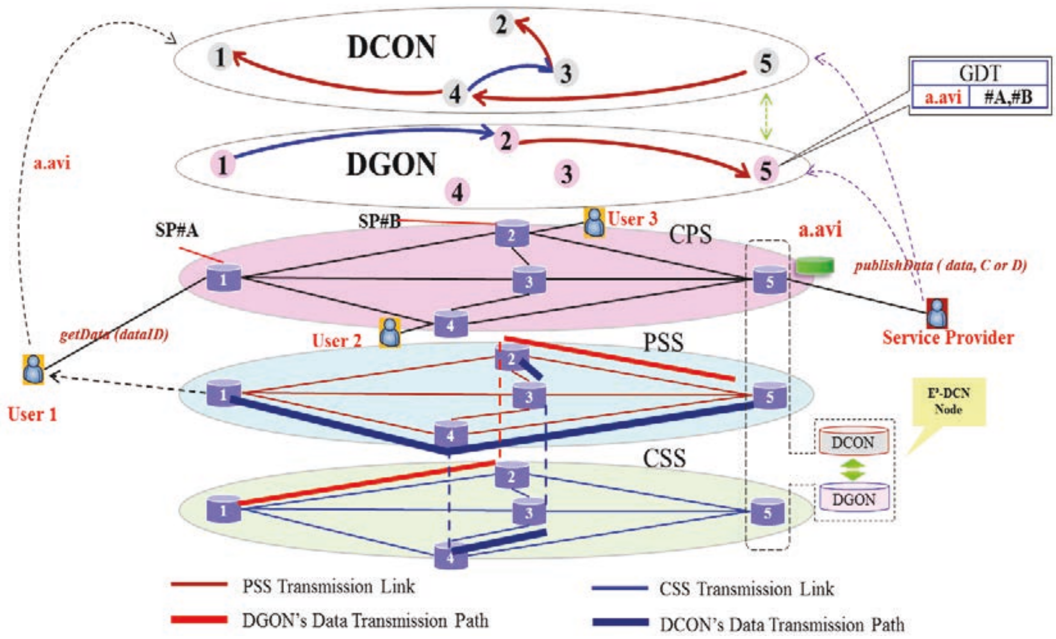


Figure 3.11: Overview of E^3-DCN workflow

transmission path is formed based on CSS and PSS. DGON's data transmission path is changed at Node2 from CSS to PSS, and DCON's data transmission path is changed at Node4 and Node3. By combining an optical switching path with an packet switching path, the energy consumption of data transmission is reduced.

3.3.5 Energy efficient strategies

Three different level approaches, device-level, equipment-level and network-level, can be applied to achieve energy efficient networks [3-13]. E^3-DCN mainly focuses on the network-level approach to achieve network-level energy optimization, such as network topology and data transmission optimization, data/service relocation and data caching optimization, reducing traffic peaks, and optical switching of bulk traffic. Three energy optimization strategies are applied to E^3-DCN. The main directions of these strategies are introduced in the next subsections, and the each approach is studied for E^3-DCN as separate research topics.

Strategy I: Dynamic network reconfiguration

Network topology is usually designed based on some requirements, such as minimum transport delay, minimum network resources, accommodation traffic demand, and assurance of network resiliency. In addition, while the network is designed to handle the maximum traffic demand, actual traffic demand changes dynamically. In case of the lower traffic demand, energy efficient traffic engineering (TE) can be applied to concentrate the traffic into a limited number of links and nodes, and then unused links and nodes are shutdown to reduce operating power consumption [3-14]. In E^3-DCN, the energy efficient TE is applied to slice networks CPS, PSS and CSS. Their topologies are dynamically reconfigured to contain the minimum number of nodes and links and shutdown unused substrate nodes and links for reducing operation energy consumption, as shown in Figure 3.12. Service-Copy is also a dynamic reconfiguration approach [3-15]. A Service-Part, which provides a processing function i.e. software, can be easily copied from one node to other nodes. Although Service-Copy consumes additional energy, there are significant advantages as follows: 1) Shorter data transmission routes/paths can be realized. Data transmission energy consumption can be reduced. 2) The copied Service-Part can be shared among more other end-users. 3) By Service-Copy, the same Service-Parts are placed at multiple places, so that network congestions can be reduced to some degree. 4) There is no need to add a new node to run the copied Service-Part.

Strategy II: Circuit switching bypass

In general, packet switching networks have lower data transmission costs than circuit switching networks. This is because the bandwidth can be shared among traffic flows by using the statistical multiplexing possible in packet switching networks. However, packet

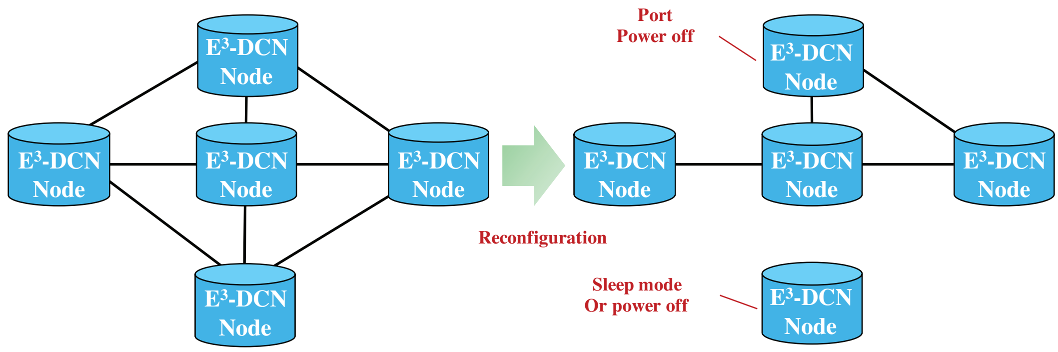


Figure 3.12: Energy efficient network reconfiguration of E^3-DCN

switching raises issues such as routing and transmission delay. Therefore, when a large dataset is to be transmitted with strict QoS constraints, circuit switching is preferred, and packet switching should be avoided as far as possible. This is called ”circuit switching bypass” [3-16]. In E^3-DCN, a link of DCON and DGON may be mapped to a transport path on CSS or PSS consisting of several links. A CSS link is composed of link termination Ethernet switches, transmission links, and circuit switches on the physical network of the network virtualization platform (NVP). A PSS link is composed of link termination Ethernet switches, transmission links, and packet switches on the physical network of the NVP. In [3-17], it was stated that optical circuit switches consume 0.5 nJ/bit switching energy while electrical packet switches such as an Ethernet switches and IP routers consume 10 nJ/bit switching energy. PSS links consume more energy, but offer lower transport cost. On the contrary, CSS links consume less energy but incur higher transport cost. Therefore, as shown in Figure 3.13, by applying circuit switching bypass and considering parameters such as data size and QoS constraints, we can achieve energy optimal data transmission paths.

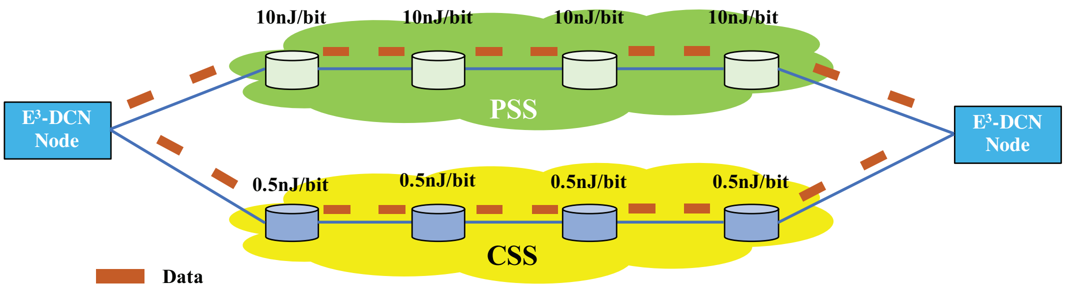


Figure 3.13: Energy efficient data transmission of E^3-DCN

Strategy III: Data caching optimization

Sophisticated caching strategies can not only shorten data response time but also reduce routing and transmission distance between data source and end-user, and so reduce forwarding energy. Meanwhile, data caching inside the network can further reduce the total network load and avoid network congestion [3-18]. Because E^3-DCN can be used as a CDN application, the data caching strategy used becomes a very important issue. The optimal data caching strategy for DCON and DGON can help to reduce energy consumption and improve network scalability.

3.4 Experiments

A E^3-DCN prototype has been implemented to validate the practicality of E^3-DCN in terms of energy consumption, and its feasibility when implemented with network virtualization.

3.4.1 Data transmission mechanism

The information-centric network DCON and data generation network DGON of E^3-DCN are implemented according to Section 3.3. DCON and DGON enable to combine

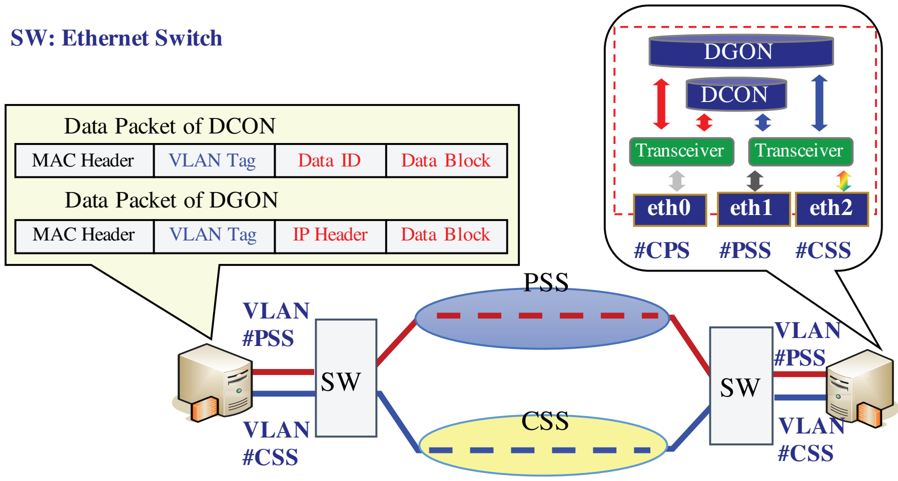


Figure 3.14: Data transmission mechanism of E^3-DCN

packet switching mode and optical circuit switching mode for data transmission. The prototype implementation of the transmission mechanism is shown in Figure 3.14. The raw socket technology, which can directly send and receive data from the data link layer with the specified interface, is used for DCON data transmission. DCON is a non-IP network as data packets are encapsulated in Ethernet Frames, together with Data ID, Data Block. DGON is an IP-based network, and the Service-Routing and Service-Signaling technologies of DGON is also based on IP networking. In order to freely set the switching mode to packet switching or circuit switching for data transmission, we use the VLAN technology to distinguish PSS and CSS slice networks; the VLAN Tag is also encapsulated in Ethernet Frames. While transmitting data, the data transmission function uses the VLAN Tag to alter which slice network the Ethernet Frames are being transmitted over.

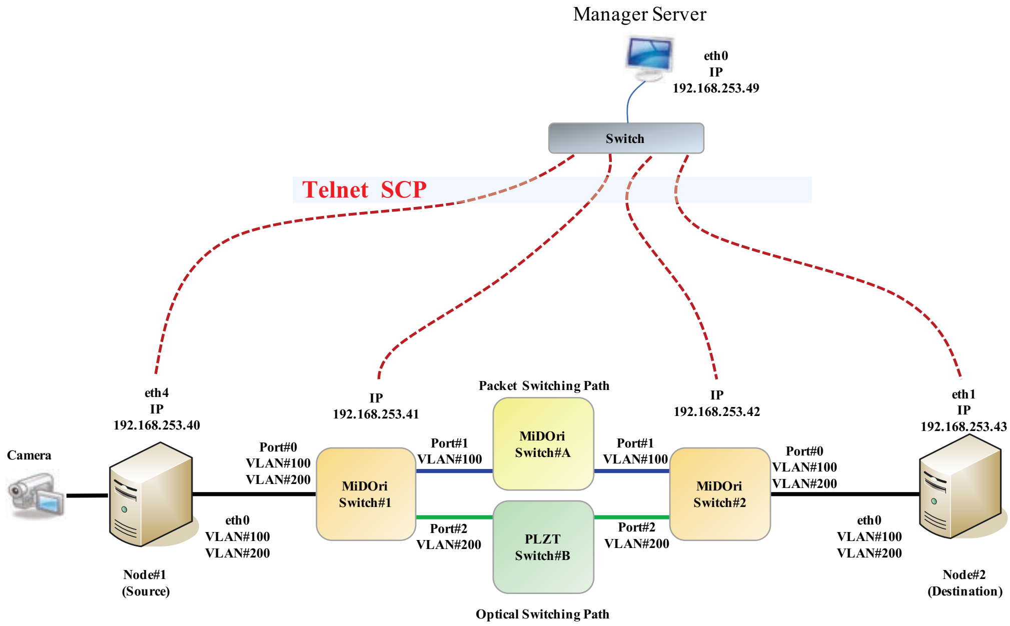


Figure 3.15: Network structure of E^3-DCN prototype with two nodes

3.4.2 Evaluations of energy consumption

Network structure

The evaluated network structure, shown in Figure 3.15, includes two E^3-DCN nodes (Node#1 and Node#2), three MiDOri Ethernet Switches (MiDOri Switch#1, MiDOri Switch#2, MiDOri Switch#A), a PLZT optical switch (PLZT Switch#B) and a network manager server. As shown in Figure 3.16 and Figure 3.17, VLAN ID 100 (VLAN#100) is used for distinguishing the PSS slice network and VLAN ID 200 (VLAN#200) is used for distinguishing the CSS slice network. The PSS slice network contains a MiDOri Switch#A, and the CSS slice network contains a PLZT Switch#B. MiDOri Switch#1 and MiDOri Switch#2 are the portals of PSS and can identify their Ethernet frames from VLAN#100 and VLAN#200.

The parameter values of the actual network environment, shown in Figure 3.18, are shown as TABLE 3.1. MiDOri switches support power-on/off energy-saving modes that

Table 3.1: Parameters of E^3-DCN network environment

MiDOri switch idle power	80 watts
MiDOri switch port idle power	1.4 watts per port
MiDOri switching energy efficiency	10nJ/bit (Packet switching)
PLZT switch power	12 watts
PLZT switching energy efficiency	0.5nJ/bit (Optical switching)
Data rate of E^3-DCN node	100 Mbps ∼110 Mbps
Duration time per transmission path	120 seconds ∼180 seconds

can change the port statuses and switch them between active/idle and shutdown. The network manager server uses telnet and SCP protocols to control these switches and data transmission paths. The data transmission path is repeatedly changed between packet switching path on PSS and optical switching path on CSS, based on expected remaining duration. In order to reduce network energy consumption, when a packet switching path on PSS is used, PLZT Switch#B and connected two ports of MiDOri Switch#1 and MiDOri Switch#2 are shifted to power-off; when the optical switching path is used, the MiDOri Switch#A and the two connected ports of MiDOri Switch#1 and MiDOri Switch#2 are set to power-off.

The data transmission energy consumption and network power consumption of E^3-DCN were evaluated. Sixty minutes of camera video data was transmitted from Node#1 to Node#2 through PSS or CSS slice networks using three different transmission modes: packet switching mode (Packet Path), combination mode of packet switching and optical switching (Combination Path), and optical switching mode (Optical Path).

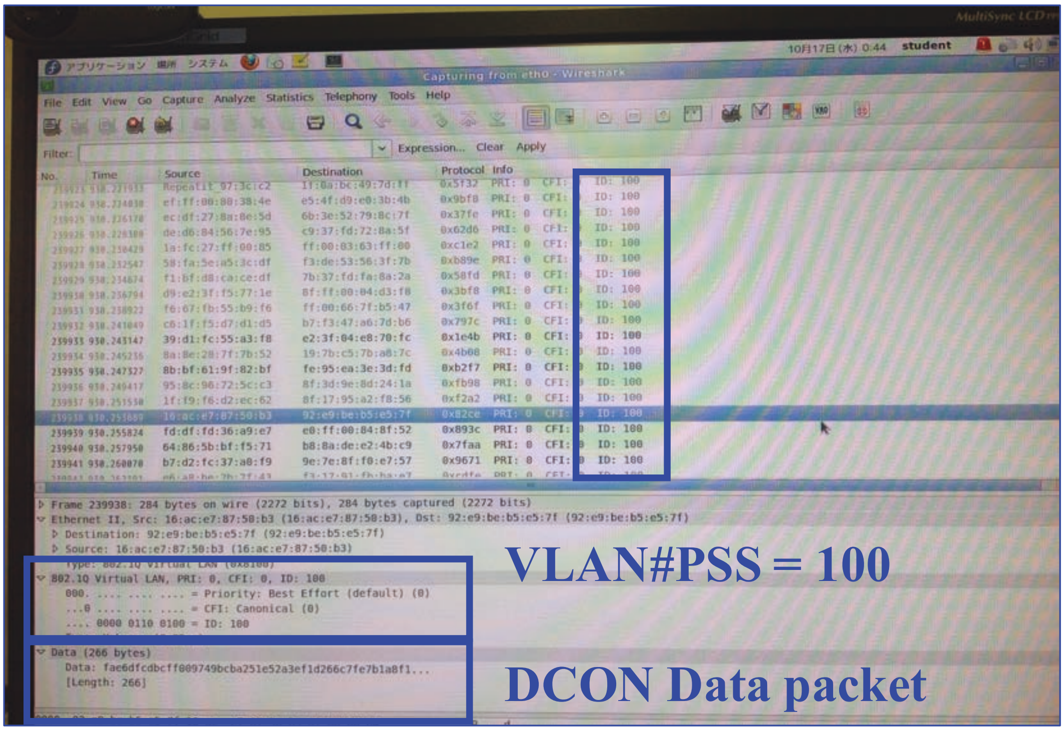


Figure 3.16: Data transmission of PSS distinguished with VLAN#100

Data switching energy consumption

As shown in Figure 3.19, over the 60 minute period, about 370 gigabits of data were transmitted from Node#1 to Node#2 by Packet Path, Combination Path, and Optical Path, i.e. the three different transmission modes. In case of Combination Path, the data switching energy consumption of E^3-DCN was reduced by about 16.2% from the Packet Path value. In the case of Optical Path, the data switching energy consumption of E^3-DCN was reduced by about 18.5% from the Combination Path value and about 31.6% from the Packet Path value. This confirms that E^3-DCN can reduce the data switching energy consumption by switching among different transmission modes: packet switching and optical switching, and moreover, optical switching can help to further reduce data switching energy consumption.

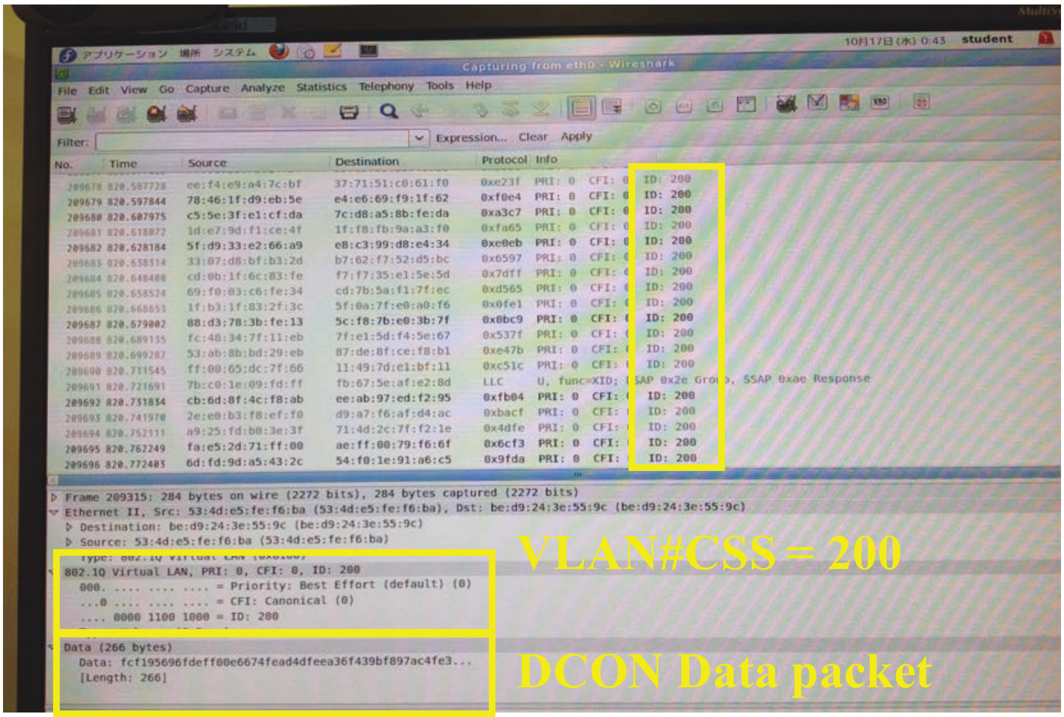


Figure 3.17: Data transmission of CSS distinguished with VLAN#200

Network power consumption

The network power consumption of E^3-DCN with the three different transmission modes over 60 minutes is shown in Figure 3.20. In the case of Packet Path, PLZT Switch#B, three MoDOri switches and eight ports were active, which created the highest power consumption. In case of Optical Path, MiDOri Switch#A and relevant four ports for packet switching were set to power-off by the network manager server; this yielded the minimum network power consumption. In case of Combination Path, when packet switching was used, PLZT Switch#B and two ports of MiDOri Switch#1 and MiDOri Switch#2 connected to PLZT Switch#B were set to power-off, and three MoDOri switches and six ports were active. When optical switching was used, MiDOri Switch#A and four associated ports were set to power-off, PLZT Switch#B, MiDOri Switch#1, MiDOri Switch#2 and four ports were active. In this way, by changing between packet switching mode

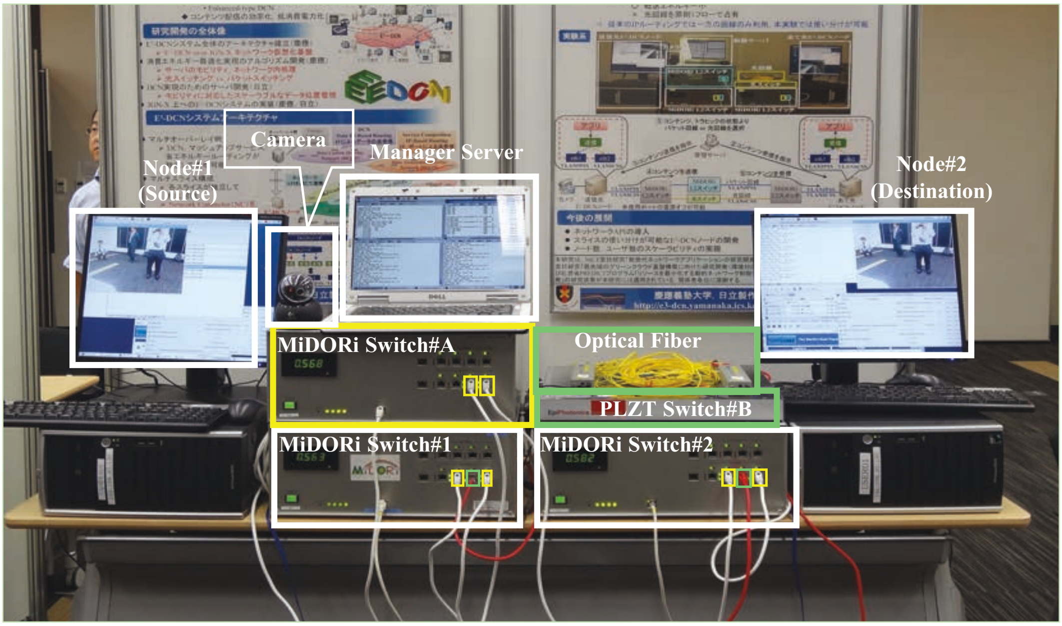


Figure 3.18: Showcase of E^3-DCN data transmission mechanism

and optical switching mode, reconfiguring the network topology of E^3-DCN can reduce network power consumption. As shown in Figure 3.20, Packet Path yields the greatest E^3-DCN power consumption. Combination Path offers 19.3% reduction in E^3-DCN power consumption from Packet Path. Optical Path reduced the E^3-DCN power consumption by about 16.5% from Combination Path and about 32.6% from Packet Path. This is because, in the case of Optical Path, the all switch ports of PSS are switched to power-off status, yielding a 32.6% reduction in network power consumption. Compared to the case of Combination Path, all switch ports of PSS are switched between power-on/off status over the 60 minute data transmission duration time, yielding a 16.5% reduction in network power consumption.

In the evaluated network environment, the electric switch amount of PSS and the optical switch of CSS is the equal. This is a typical minimum scale network design. In fact, for large-scale networks, the electric switch amount is usually more than optical switch amount. In this context, for E^3-DCN, the data switching energy consumption can be re-

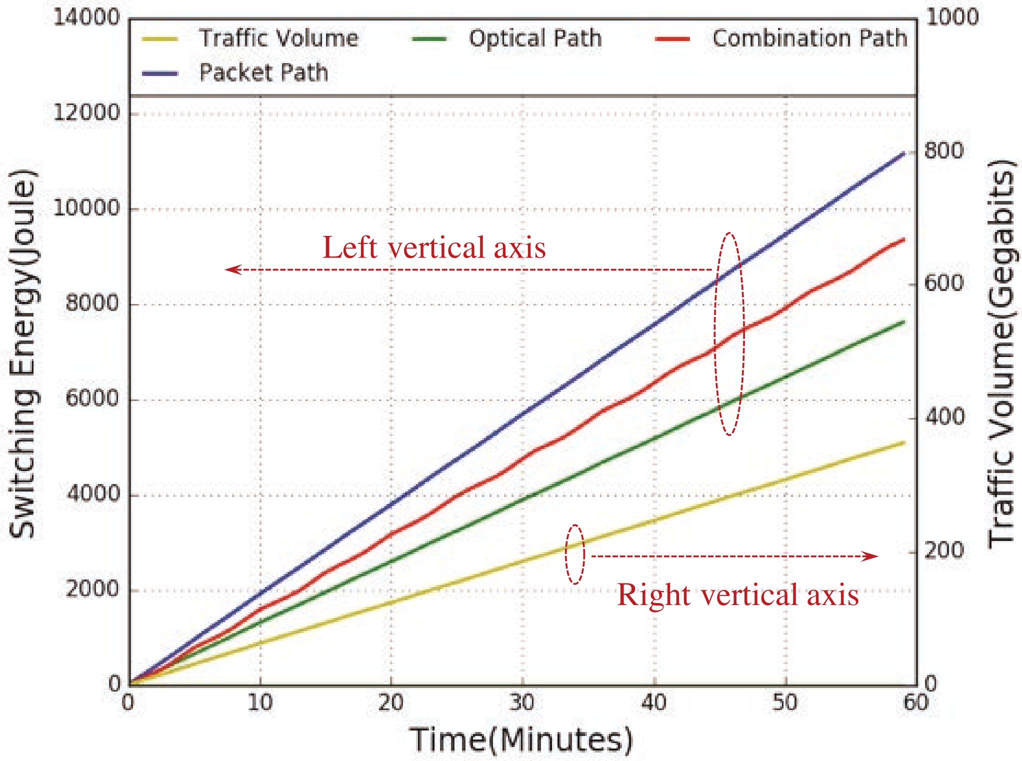


Figure 3.19: Evaluation of data transmission energy

duced by at least 16.2% by combining packet switching and optical switching, compared to just packet switching. The network power consumption can be reduced by at least 19.3% by network reconfiguration.

3.4.3 Experiment on network virtualization environment

In order to verify the feasibility of basing E^3-DCN on network virtualization, the prototype of E^3-DCN was tested on JGN-X, actual network virtualization platform. The E^3-DCN prototype included two overlay networks DCON and DGON, as the network functions, and three slice networks CPS, PSS and CSS, as the network infrastructure.

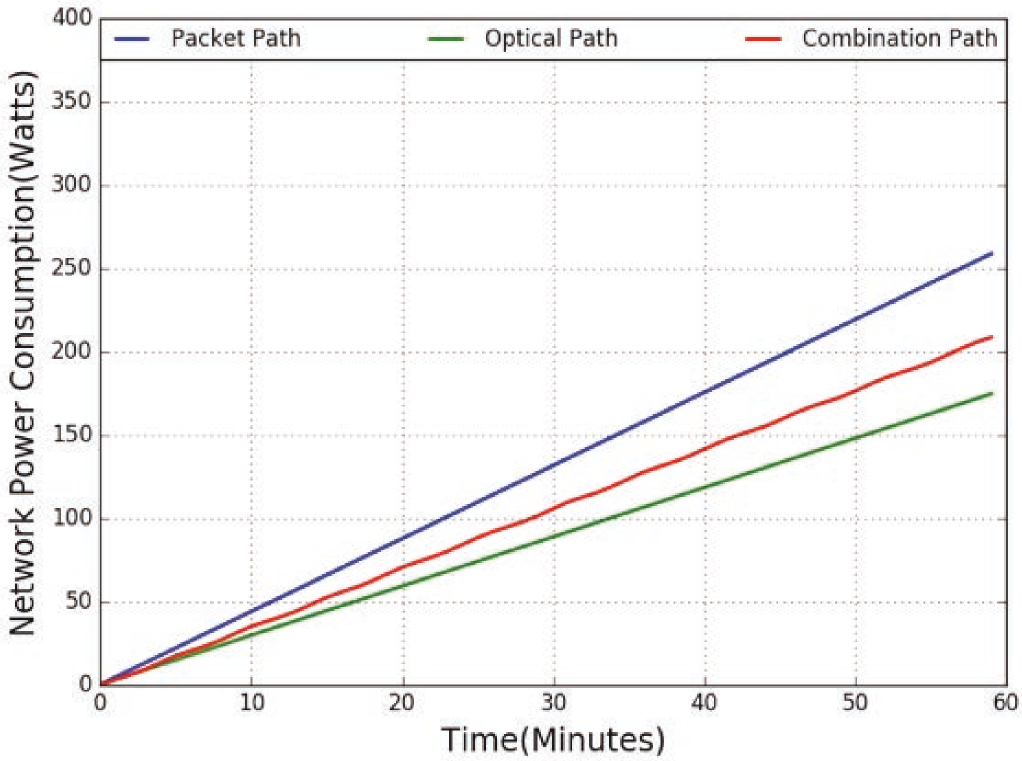


Figure 3.20: Evaluation of network power consumption

Network configuration: overlay networks

DCON and DGON were deployed as shown in Figure 3.21. DGON contains ten nodes: three nodes at Sendai data center in the Tohoku area of Japan, four nodes at Keio University in Kanagawa, Japan, and three nodes at Tokyo, Japan. The Service-Parts of these three sites can be chained and combined to generate data. DCON contains four nodes that were deployed in Tokyo, Japan. These overlay network nodes can connect to CPS, PSS and CSS of the E^3-DCN prototype on the JGN-X network virtualization platform via a VLAN and can communicate with each other. End-users can send data requests to DCON, who then either provides the requested data or requests DGON to generate the data.

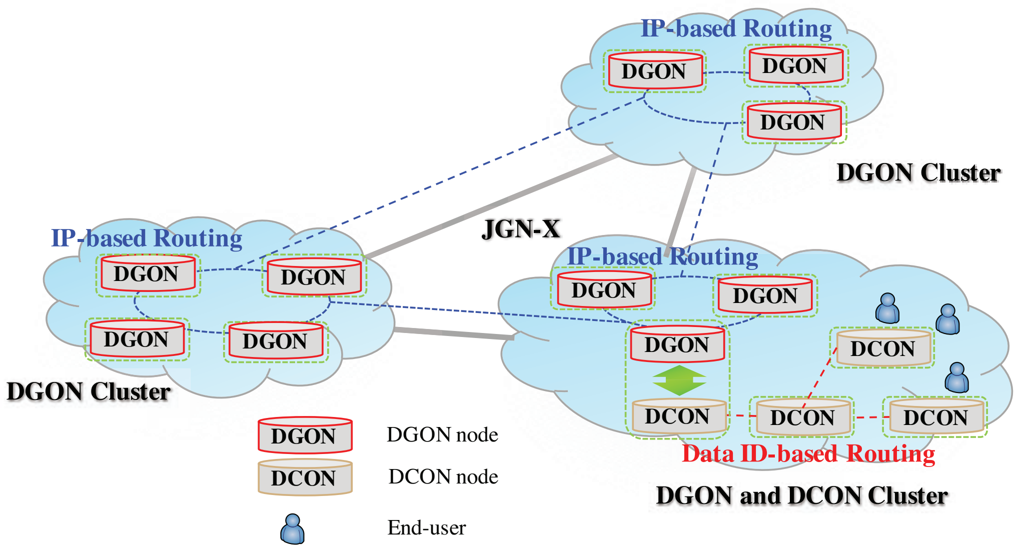


Figure 3.21: Overlay networks of E^3-DCN prototype

Network configuration: network infrastructure

The network infrastructure of E^3-DCN prototype is shown in Figure 3.22. Three slice networks, used as CPS, PSS and CSS of E^3-DCN, were created on the JGN-X network virtualization platform. The network nodes were placed at Tokyo (Otemachi), Osaka, Fukuoka and Nagoya cities of Japan. VLAN was adopted to distinguish between the different network communications; VLAN#1593 was used by JGN-X manager for gathering slice network resource information. VLAN#1594 was used for communications between E^3-DCN manager and DCON and DGON nodes. VLAN#1601, #1602 and #1603 were used for communication among CPS, PSS and CSS. VLAN#1604 was used for network services and end-users. Data routing and data transmission of DCON and DGON were performed using CPS, PSS and CSS.

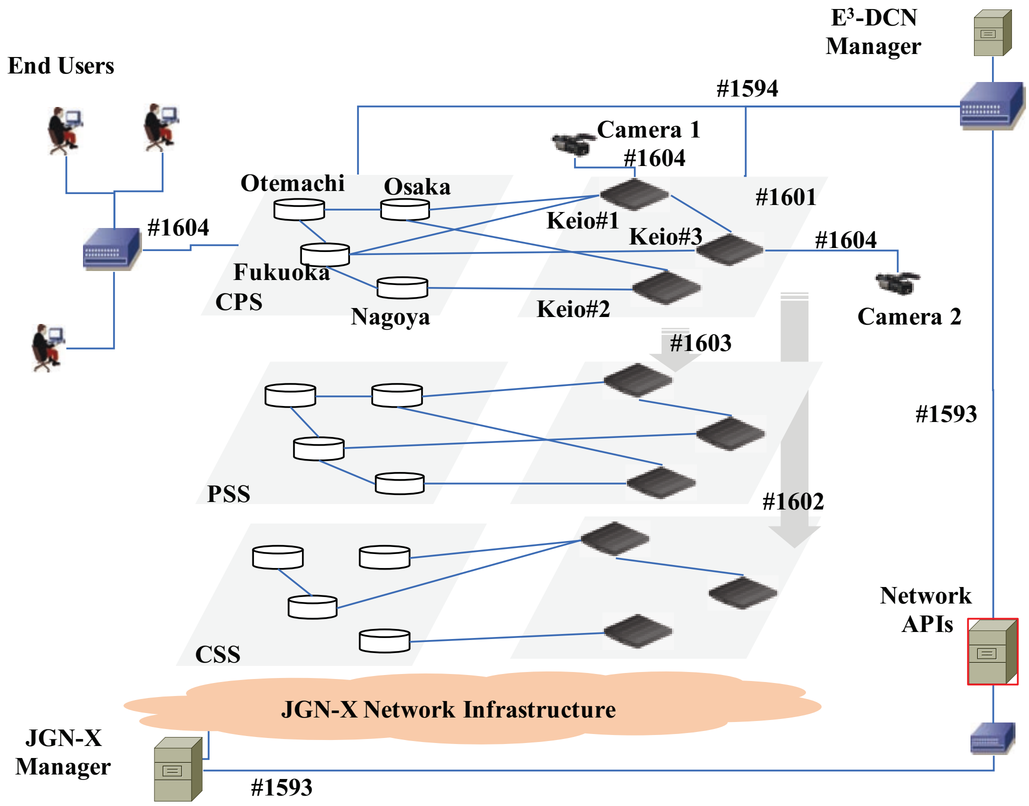


Figure 3.22: Network infrastructure of E^3-DCN prototype

E^3-DCN showcase

The prototype of E^3-DCN was exhibited at the 13th network virtualization conference of Japan 2015 [3-19]. A real-time video streaming service was implemented. Face recognition and black-and-white image functions were implemented as Service-Parts in DGON. The video pictures captured by cameras were passed through these functions for generating new services, and the output was passed to DCON. DCON provided the resulting pictures to end-users in real-time. The video data were transported using packet switching and optical switching paths on PSS and CSS.

The showcase is showed that E^3-DCN can realize an energy efficient and flexible information-centric network based on network virtualization that can satisfy the requirements of the future Internet. E^3-DCN can provide original data services and mash-up

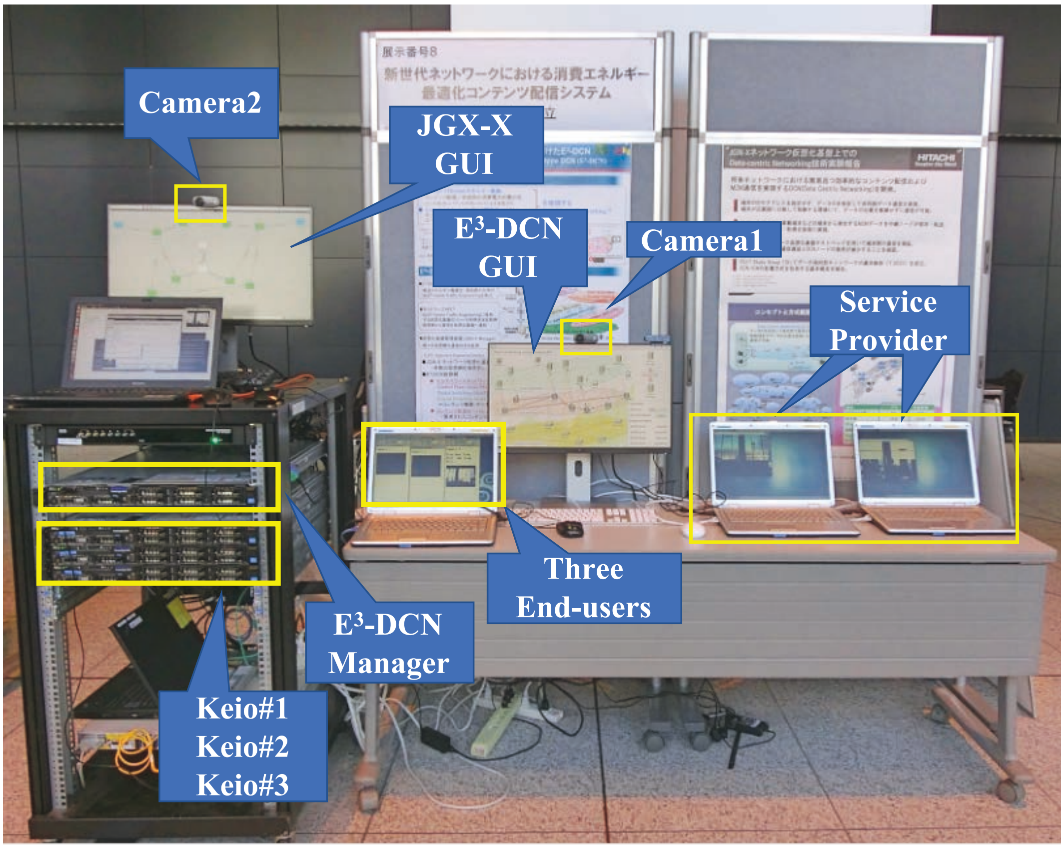


Figure 3.23: Showcase of E^3-DCN

data services by combining information-centric networking and dynamic service chaining. Moreover, E^3-DCN offers both circuit switching paths and packet switching paths to minimize data switching energy consumption, and also supports dynamic network reconfiguration to reduce network power consumption.

3.5 Chapter conclusion

This chapter proposed an energy efficient and flexible information-centric network (ICN) E^3-DCN using network virtualization that can meet the requirements of the future Internet.

E^3-DCN focuses on the ICN QoS and scalability issues for the future Internet. E^3-DCN consists of two overlay networks, DCON and DGON, and three slice/virtual networks CPS, PSS and CSS. DCON realizes information-centric networking that realizes efficient information dissemination, location-independent data communication, data security and efficient mobility support for the future Internet. DGON is a network that can generate data for DCON by chaining and combining several in-network services/processes (Service-Parts). DGON can increase network service diversity and enhances the scalability of the network in terms of service numbers. E^3-DCN combines DCON with DGON to realize an enhance-type ICN network that supports multiple data service paradigms for the future Internet. E^3-DCN can provide not only the original data services from DCON, but also the data generation services by combining DCON and DGON.

In order to realize the separation of network control plane and network data plane required by the future Internet, E^3-DCN adopted a network control plane and data plane separation design model from network architecture perspective based on network virtualization. CPS, PSS and CSS, three virtual networks as network infrastructure, are used to construct E^3-DCN. CPS is the control plane and provides control network functionality. PSS and CSS are data planes and provide data transmission. Network virtualization makes E^3-DCN network topology aware and network resource aware which helps to realize efficient strategy for high QoS and network optimization in an efficient manner.

In addition, E^3-DCN focuses on the issue of network energy consumption from data transmission to the operation of that entire network. E^3-DCN supports optical switching mode and packet switching mode and their combined use. This allows the energy consumption of every data transmission to be optimized. In order to improve network energy efficiency, like network topology reconfiguration, E^3-DCN also employs circuit switching bypass and data caching. Experiments on a prototype showed that E^3-DCN can reduce the data transmission energy consumption by about 16.2% by combining the optical switching and packet switching modes, while dynamic network reconfiguration reduces the network power consumption by about 19.3%. Furthermore, the feasibility of E^3-DCN based on network virtualization was validated by tests on the JGN-X network virtualization platform of Japan. The results showed that E^3-DCN is both energy efficient and flexible enough to support the future Internet.

There are still some issues with regard to network resource and energy optimization in E^3-DCN, such as the best dynamic network reconfiguration strategy, data caching strategy, and data transmission energy strategy. This dissertation proposes, in Chapter 4, an energy efficient data discovery and delivery method, and an energy efficient network resource allocation method will be proposed for E^3-DCN in Chapter 5.

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Chapter 4

Energy efficient data discovery and delivery method

While the network architecture of E^3-DCN was proposed in Chapter 3, data transmission energy optimization is still issue for E^3-DCN. This chapter focuses on the data transmission energy issue of E^3-DCN, and proposes an energy efficient data discovery and delivery method for E^3-DCN that can decide the optimal data source and the optimal data transmission path to reduce the data transmission energy consumption of E^3-DCN [4-1].

4.1 Introduction

Network energy consumption is an important issue for the ICN network [4-2]. Described as Section 2.4, several studies have worked on the network energy consumption issue of ICN network. They consider network energy-saving from the perspectives of hardware, network optimization, data placement, and data discovery and delivery different perspectives.

The data transmission energy of the ICN network is consumed by data discovery and delivery. For the ICN network, the data name aggregation is an efficient approach to reduce the data switching energy consumption, as described in Section 2.4.2, because it reduces the routing table space and data retrieval processing loads for data discovery and delivery. However, as described in Section 2.1.1, to realize data discovery and delivery, name-based ICN networks, such as CCN, NDN and DCN, need to create and apply Interest packets for request data, and Data packets for carrying data blocks to response to Interest packets. As shown in Figure 4.1, the traditional data discovery and delivery approach of the ICN network consists of two steps: data exploration and data response. In the data exploration step, the flooding approach releases huge numbers of Interest packets to locate the requested data. For the requested data, there may be multiple data sources in different locations in the ICN network. In the data response step, those data sources would emit huge numbers of Data packets in response to every Interest packet. Data packets are sent to the end-users along the routes of the Interest packets. Intermediate nodes process each Data packet before forwarding it out. The intermediate node check if the same Data packet has already been forwarded out, if ture, the Data packet is discarded. The intermediate node also performs complex processes to identify the optimal path according to the current conditions, such as consider the response time or the numbers of hops taken by the Data packets. In this way, the optimal path from data sources to end-users can be decided finally. As shown in Figure 4.1, the optimal path, node#6 → node#2 → node#1, is identified. Subsequent Interest packets and Data packets are forwarded along the optimal path [4-3].

Before the optimal data source is decided, this results in a lot of unnecessary traffic and wasted processing operations in intermediate nodes. It can also result in the unnecessary consumption of data switching energy, especially when there are a huge number of data requests. On the other hand, the E^3-DCN proposed in Chapter 3 ensures that only one specific DCON node can send the data generation request to DGON for data generation. This specific DCON node can be considered as a data source, and multiple such specific DCON nodes can be configured in DCON. Hence, following the traditional data discovery and delivery process of ICN, many identical generation data requests can be sent from DCON to DGON for generating the same data before the optimal request DCON node is decided in DCON. This also results in unnecessary traffic and meaningless processing,

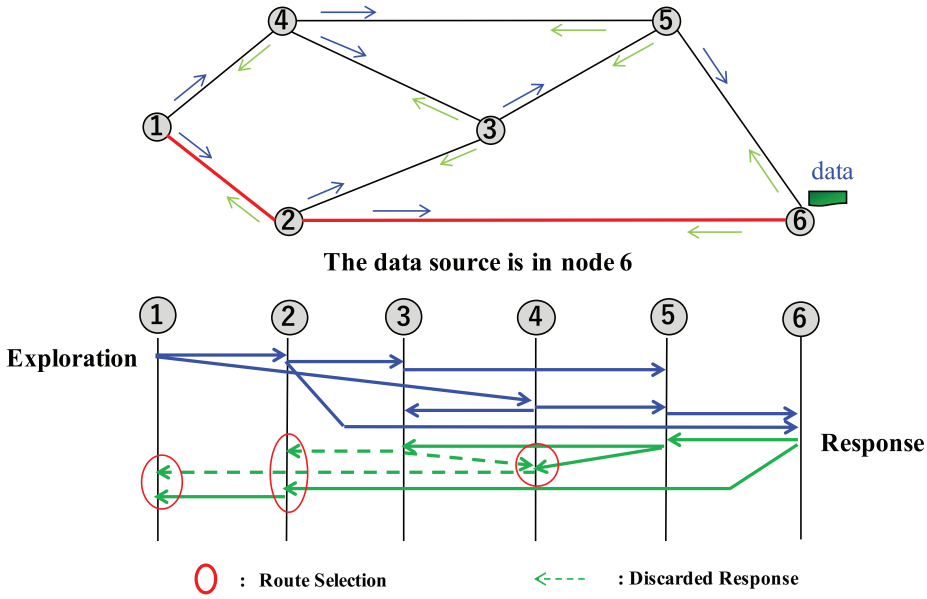

Figure 4.1: Traditional data discovery and delivery of ICN network

and increases the data switching energy consumption. Therefore, for E^3-DCN, an efficient data discovery and delivery approach is necessary.

In this context, this chapter proposes an energy efficient data discovery and delivery method for E^3-DCN. The proposed method makes DCON discover the optimal data source before responding with data, and so avoids the unnecessary traffic and meaningless processing that would otherwise occur. Note that related works on the ICN network consider only single-mode transport networks, such as electrical switching network or optical circuit switching network, and so do not consider multiple-mode transport networks like E^3-DCN for data delivery. Existing studies have analyzed the switching energy efficiency of optical circuit switching (0.5nJ/bit) and electric packet switching (10nJ/bit) modes [4-4]. E^3-DCN offers a multiple-mode transport network that supports both optical circuit switching and packet switching. The proposed method can also help E^3-DCN to establish the most energy efficient data transmission path by combining optical circuit switching and packet switching and thus save the data transmission energy.

The rest of this chapter is organized as follows: the proposed energy efficient data discovery and delivery method is introduced in Section 4.2. The results of a performance evaluation are described in Section 4.3. Finally, this chapter is concluded in Section 4.4.

4.2 Data discovery and delivery method

Routing topology

E^3-DCN is built on NVE and adopts one virtual network CPS as its network control plane, and two virtual networks, PSS and CSS as its network data planes that support packet switching and optical circuit switching, respectively. As described in Section 3.3, CPS can collect information of network resources and attributes from PSS and CSS, such as node physical location, link distance, bandwidth, delay, switching energy, and so on. Based on the collected information and network topologies, multiple routing topologies can be constructed for network optimization.

DCON, which overlies CPS, can acquire information of network resources and attributes of PSS and CSS. As shown in Figure 4.2, the routing topology of DCON can be abstracted as adjacent nodes connected with one or two links. In the case of two links, one is a PSS link and the other is a CSS link. In the case of one link, it is either a PSS or CSS link. Each link has a weight that indicates data switching energy efficiency of the link. Moreover, each PSS and CSS link is mapped to an s-path on SN which contains multiple s-nodes. Hence, the data switching energy efficiency weight graph for DCON can be calculated by examining the s-paths of PSS and CSS links.

Method description

The proposed energy efficient data discovery and delivery method for DCON contains data exploration, data response, data request and data transmission, four steps, as shown

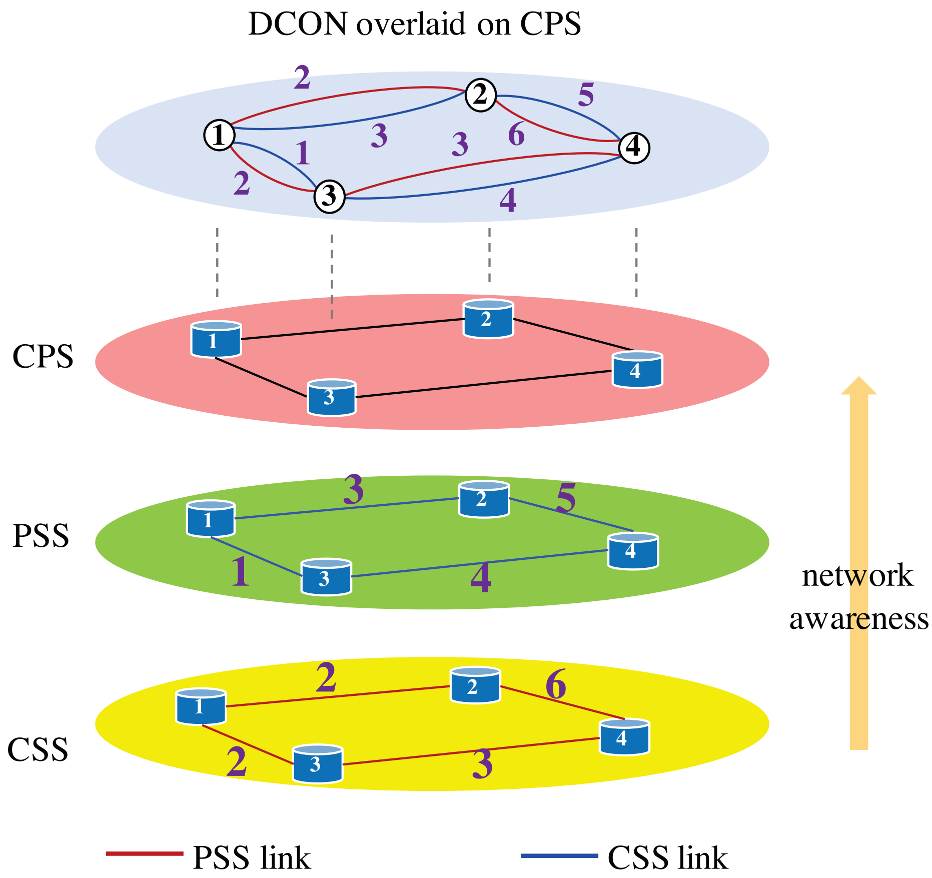

Figure 4.2: Energy aware routing topology of DCON on E^3-DCN

in Figure 4.3.

- **Data exploration** Data sources are searched by exploration messages forwarded in hop-by-hop manner from end-user.

- **Data response** When a data source receives an exploration message, the data source sends a response message along the reverse of the route track taken by the exploration message. In the data response step, the optimal data transmission path and the optimal data source can be decided in intermediate nodes by Route Selection. With regard to route selection, for example, the best data source can be decided in intermediate nodes by the first response message to be received. Finally,

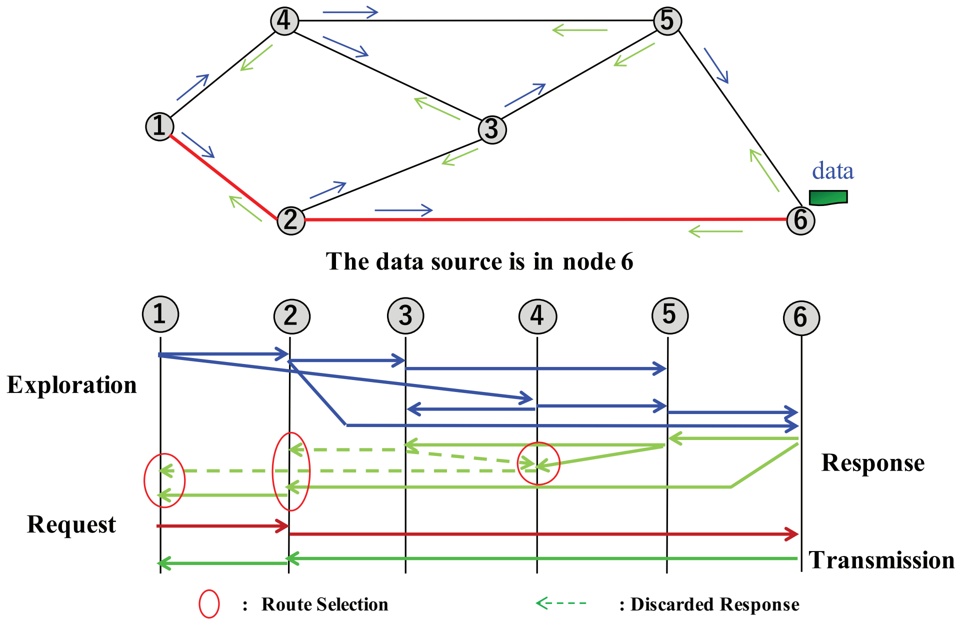

Figure 4.3: Data discovery and delivery method of DCON

the route track of the fastest response message can be used as the optimal data transmission path. As shown in Figure 4.3, the optimal data transmission path is Node#1 → Node#2 → Node#6, because it has the fewest hops. The data switching energy efficiency weight graph for DCON, as shown in Figure 4.2, is used in Route Selection to decide the optimal energy efficient data transmission path and the optimal data source.

- **Data request** Along the decided optimal energy efficient data transmission path, the huge number of Request Packets are sent to the optimal data source for data transmission.

- **Data transmission** The optimal data source sends Data Packets that carry data blocks to respond to the Request Packets. Data Packets are transferred along the decided optimal energy efficient data transmission path to the end-user.

Four packet types are defined for DCON to realize the proposed method. They are called Exploration Packet, Response Packet, Request Packet, and Data Packet. They contain common data name. Exploration Packet as exploration message is used for exploring data source. Response Packet as response message is used for responding to an exploration. And it contains a cost item that shows the minimum data transmission energy cost from data source to current intermediate node. Exploration Packet and Response Packet as routing message are routed over CPS, and are used in the Exploration and Response steps to decide the optimal energy efficient data transmission path. Request Packets as request messages are sent to the optimal data source, and Data Packets are used for carrying data blocks from the optimal data source to the end-user. One Request Packets is mapped to one Data Packet, and they are transmitted over PSS or CSS.

By the four steps of data exploration, data response, data request and data transmission, an energy efficient data transmission path consisting of packet switching links and optical switching links and the optimal data source. They avoid the unnecessary traffic, meaningless processing, and switching energy consumption compared to the traditional data discovery and delivery schemes for ICN. Moreover, the proposed method is also different from TCP's 3-way handshake communication model [4-5]. For a data service, the same multiple data sources may be configured in different locations in the same network. TCP's 3-way handshake only links to a specified host, whereas the proposed method shakes hands with the optimal data source chosen from multiple data sources.

In addition, in E^3-DCN, when the requested data cannot be directly provided by DCON, DCON redirects the data request to DGON so as to generate the requested data. If multiple DCON nodes can make multiple and identical data generation requests to DCON, how to decide the optimal request node becomes a problem. The proposed method solves this problem because the optimal request node can be decided from among the request nodes in data response step before the request is issued to DGON.

The 3D-Dijkstra method, described in Section 3.2, was proposed for energy efficient mush-up service routing [4-6]. Based on data transmission energy efficiency weight graph described in Section 4.2, the 3D-Dijkstra routing method can be also directly adopted by DGON of E^3-DCN for energy efficient data generation routing and delivery.

4.3 Evaluations

The data switching energy consumption and network performance of E^3-DCN running the proposed method were evaluated. The data plane of E^3-DCN contains PSS network for packet switching and CSS network for optical switching. The data transmission energy consumption is evaluated by comparing three cases: E^3-DCN with CSS, E^3-DCN with PSS, and E^3-DCN with PSS and CSS. The E^3-DCN with CSS and E^3-DCN with PSS are the same as the traditional CCN network in that they are single-mode transport networks. The case of E^3-DCN with CSS refers to E^3-DCN with only optical switched CSS used to transmit data. The case of E^3-DCN with PSS refers to E^3-DCN with only use packet switched PSS used to transmit data. The case of E^3-DCN with PSS and CSS refers to E^3-DCN combined with the proposed method can choose between packet switched PSS and optical switched CSS to reduce data switching energy when transmitting data.

The network performance of E^3-DCN is evaluated by comparing it with the TCP/IP-based uGrid network described in Section 3.2. Because uGrid supports the point-to-point communication model, as the number of users increases, more links will be used in the channels between two adjacent nodes. DCON of E^3-DCN realizes ICN and can aggregate the same data requests to one data request between two adjacent nodes, hence, there is only one link used between two adjacent nodes when there are multiple end-users requests for the same data. Therefore, the network performance metric is the number of links used. Network performance falls as the number of used links increases because the problems of network congestion and delay worsen.

The parameters of the network topologies used in the simulations are shown in Table

Table 4.1: Simulation parameters

Parameters of Simulations	
Topology Nodes	5000
Topology Edges	34972:Used in E^3-DCN with CSS and E^3-DCN with PSS 69944:Used in E^3-DCN with PSS and CSS
Data switching cost of CSS link	Range: 1~100
Data switching cost of PSS link	Range: 1~100
Requesting Users	From 100 to 2500
Data Source	1

4.1. Every network topology contains 5000 nodes. E^3-DCN with PSS and CSS takes into account the optimization of data switching energy consumption based on PSS and CSS, hence, there are two edges, one is PSS link and the other is CSS link, as shown in Figure 4.2. Because E^3-DCN with PSS and E^3-DCN with CSS only suit for packet switching or optical switching single-mode transport networks, there is only one PSS or CSS link between adjacent nodes. Therefore, there are 34972 network topology edges in E^3-DCN with PSS and in E^3-DCN with CSS, but 69944 in E^3-DCN with PSS and CSS. The link cost refers to the data switching energy efficiency of each link and is random positive integer between 1 and 100. One data source exists in each network. The amount of data requesting users was increased from 100 to 2500.

Evaluation of data transmission energy consumption

The data transmission energy consumption results are shown in Figure 4.4. E^3-DCN with PSS and CSS has about 40% lower data transmission energy consumption cost than E^3-DCN with PSS or E^3-DCN with CSS. This is because E^3-DCN with PSS and CSS uses the optimal energy route to transmit data unlike E^3-DCN with PSS or E^3-DCN with CSS.

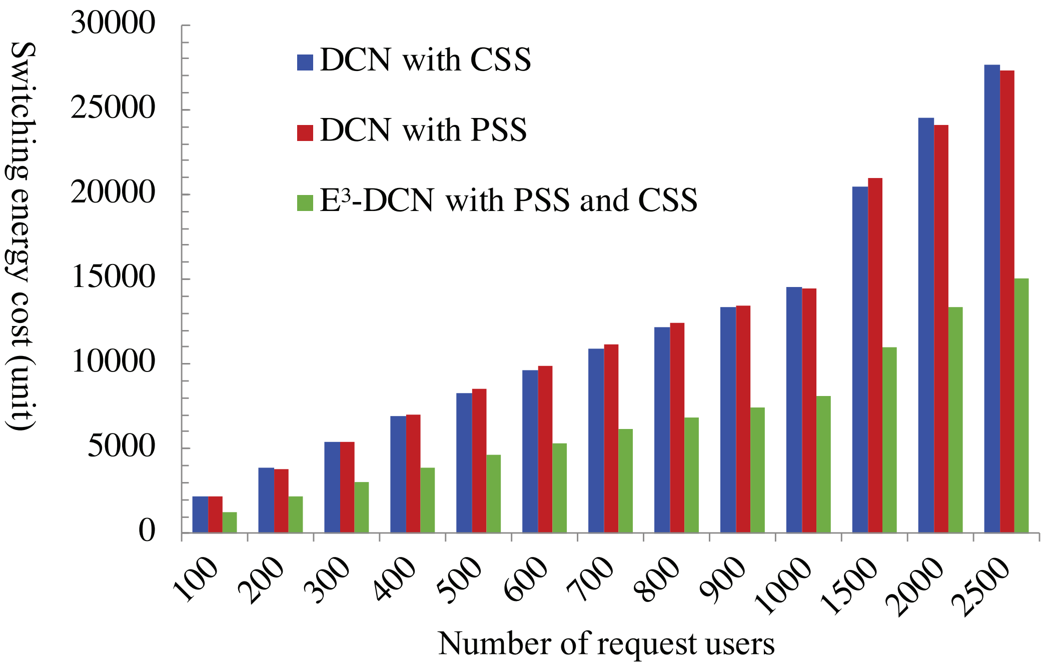

Figure 4.4: Evaluation of data transmission energy consumption

The traditional E^3-DCN with PSS and the E^3-DCN with CSS fail to take into account the data transmission energy consumption problem and only choose single data transmission route on PSS or CSS.

Evaluation of network performance

The network performance results are shown in Figure 4.5. E^3-DCN with PSS and CSS uses far fewer links than TCP/IP-based uGrid network. This is because the uGrid network uses point-to-point communication channels to transmit data, and the links of channels between two adjacent nodes are independent and cannot be aggregated into one even if all users request the same data. DCON of E^3-DCN can aggregate all user requests for the same data. Between adjacent nodes, only one channel need be established, and data packets are multicast by intermediate nodes according to aggregated the request information. The superiority E^3-DCN increases with the number of user requests.

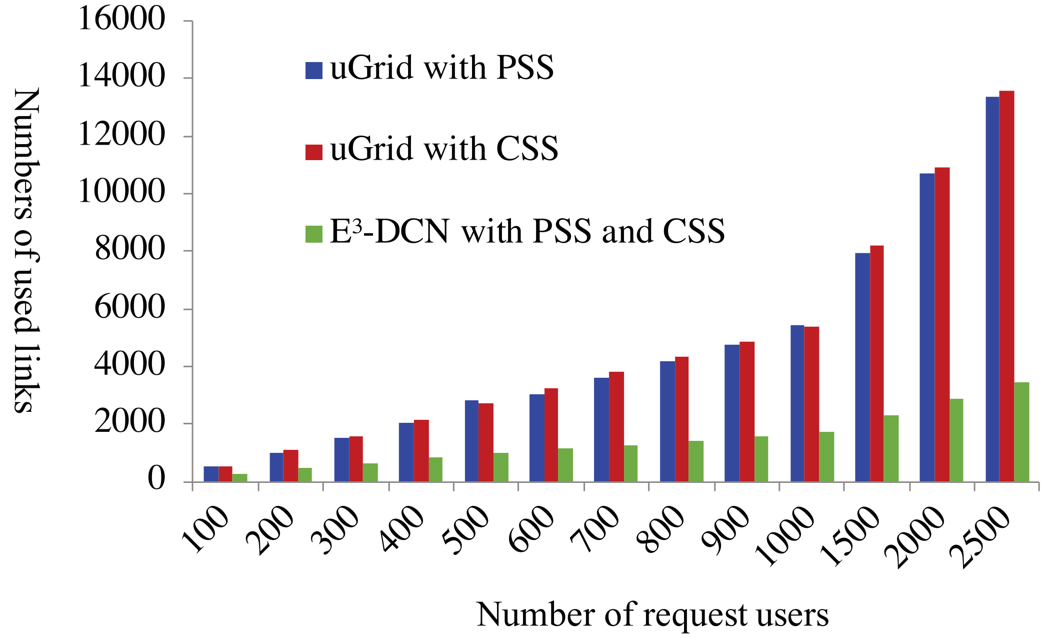

Figure 4.5: Evaluation of network performance

4.4 Chapter conclusion

This chapter focused on the data transmission energy optimization issue of E^3-DCN, and proposed an energy efficient data discovery and delivery method for E^3-DCN to save data switching energy. The proposed method establishes the four steps of data exploration, data source response, data request and data transmission. The first step, data exploration, discovers the data sources. The second step, data source response, decides the optimal data source and the optimal data transmission path. The third step, data request, sends a data request to the optimal data source along the optimal data transmission path. The final step, data transmission, sends the requested data to end-user along the optimal data transmission path. The proposed method avoids unnecessary traffic and meaningless processing operations for data transmission. It ensures that E^3-DCN can discover the optimal data source and establish the most energy efficient data transmission path by combining optical circuit switching and packet switching to reduce the data transmission energy consumption. Simulations showed that the proposed method can help E^3-DCN to use about 40% less data switching energy than the traditional E^3-DCN, and network performance is also much better than the traditional TCP/IP-based network.

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Chapter 5

Energy efficient network resource allocation method

While Chapter 5 also focuses on the data transmission energy optimization issue of E^3-DCN, it differs from Chapter 4 in that it targets the network resource perspective. Chapter 5 proposes a dynamic energy efficient network resource allocation method that ensures E^3-DCN continuously uses the most energy efficient network resources and thus minimize data transmission energy [5-1].

5.1 Introduction

E^3-DCN is built within the network virtualization environment (NVE). As descried in Chapter 3, in order to realize network control plane and network data plane separation, three virtual/slice networks are used as the network infrastructure on which E^3-DCN is constructed. In NVE, described as Section 1.3.2, multiple virtual networks (VNs) can be embedded/created on a shared substrate network (SN). Each VN consists of virtual nodes (v-nodes) connected with virtual links (v-links). As shown in Figure 5.1, each v-node is mapped to a substrate node (s-node), each v-link is mapped to a substrate transport path (s-path) on SN. Each VN has its own completely dedicated substrate resources (s-resources) on SN that are mapped to v-nodes and v-links. For NVE, how to efficiently allocate s-resources on SN to map and embed the VN is an important challenge because it can impact network energy consumption and the economic profit of Infrastructure Provider

(InP) of NVE (The details are described in Section 5.2).

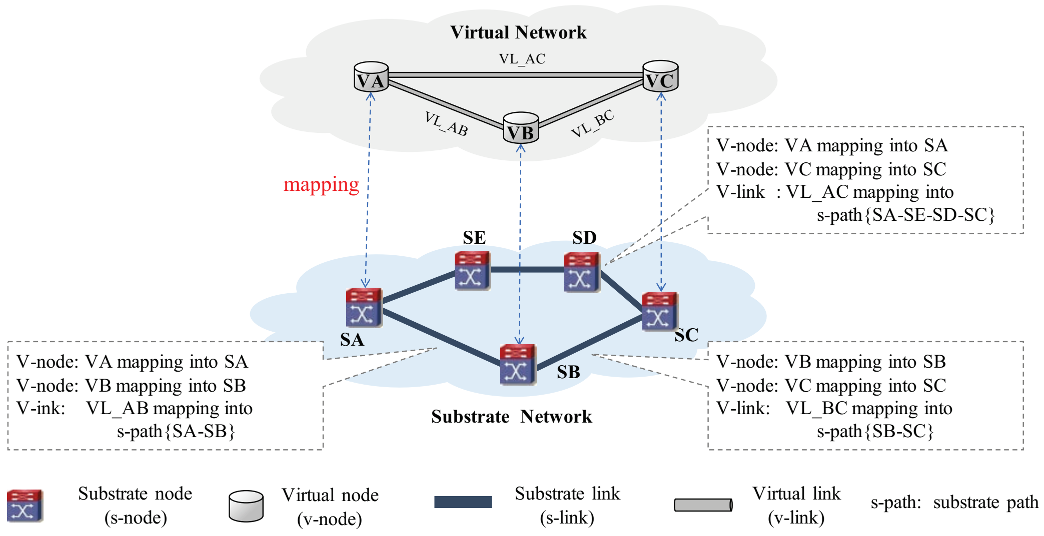

Figure 5.1: Mapping between virtual network and substrate network

Some studies have examined energy efficient s-resource allocation for NVE to reduce network energy consumption and energy cost, and increase InP profit [5-2] [5-3] [5-4] [5-5] [5-6] [5-7] [5-8] [5-9] [5-10] [5-11]. In summary, these approaches consider energy efficient s-resource allocation for embedding VNs from the initial VN embedding phase to the VN operation phase. In the VN initial embedding phase, these approaches attempt to find the most efficient subset of embeddable s-resources to embed VNs into SN [5-2] [5-3][5-4] [5-5] [5-6] [5-7] [5-8]. The energy of SN is saved by reducing the number of active s-nodes and substrate links (s-links). However, in NVE, VNs are created, modified, and removed dynamically in response to changes in requirements set by network lifetimes, topologies and resources. These requests can cause s-resource reallocation and recycling at any time resulting in dynamic changes in embeddable s-resources. Hence, these approaches in the VN initial embedding phase cannot guarantee the initial allocated s-resources of v-nodes and v-links are continuously energy efficient with dynamic changes of embeddable s-resources. Several studies adopt the approach of reconfiguring

VNs and SN in the VN operation phase for energy saving [5-9] [5-10] [5-11]. The aim is to make as many as possible currently active s-nodes and s-links enter sleep mode by dynamically optimizing the overall network resources of VNs and SN. Because network reconfiguration can interrupt traffic, VN and SN reconfiguration is usually in frequent and restricted to low traffic load conditions. Therefore, during interval period of two reconfiguration operations, these approaches cannot also guarantee the reallocated s-resources of v-nodes and v-links are continuously energy efficient with dynamic changes of embeddable s-resources in operation phase.

In this context, *how to guarantee that the allocated s-resources of v-nodes and v-links for VNs are continuously energy efficient is an important problem for NVE.* The network resources of VN include v-node resources and v-link resources. This chapter focuses on v-link resources and shows the effectiveness of dynamically reallocating energy efficient network resources of v-links to reduce the data switching energy consumption of NVE. First, the data switching energy consumption of NVE is analyzed. Then, a dynamic energy Efficient Virtual Link Resource Reallocation (*eEVLRR*) method is proposed for NVE. The idea of *eEVLRR* to take account of the dynamic changes in the characteristics of embeddable s-resources of SN, and based on the embeddable s-resources of SN and the available s-resources of v-links, *eEVLRR* dynamically reallocates energy efficient s-resources to v-links so as to ensure that the allocated s-resources of v-links remain continuously energy efficient and thus save data switching energy. In order to avoid traffic interruptions while reallocating the s-resources of v-links, a cross layer application-session-based (AS-based) forwarding model is designed for *eEVLRR* that identifies each data transmission flow forwards it along its initial specified s-path until flow completion without traffic interruptions.

The rest of this chapter is organized as follows: the virtual network s-resource allocation problem and data switching energy consumption problem of NVE are introduced in

Section 5.2. *eEVLRR* for NVE is proposed in Section 5.3. The results of performance evaluations are described in Section 5.4. Finally, this chapter is concluded in Section 5.5.

5.2 Problem descriptions

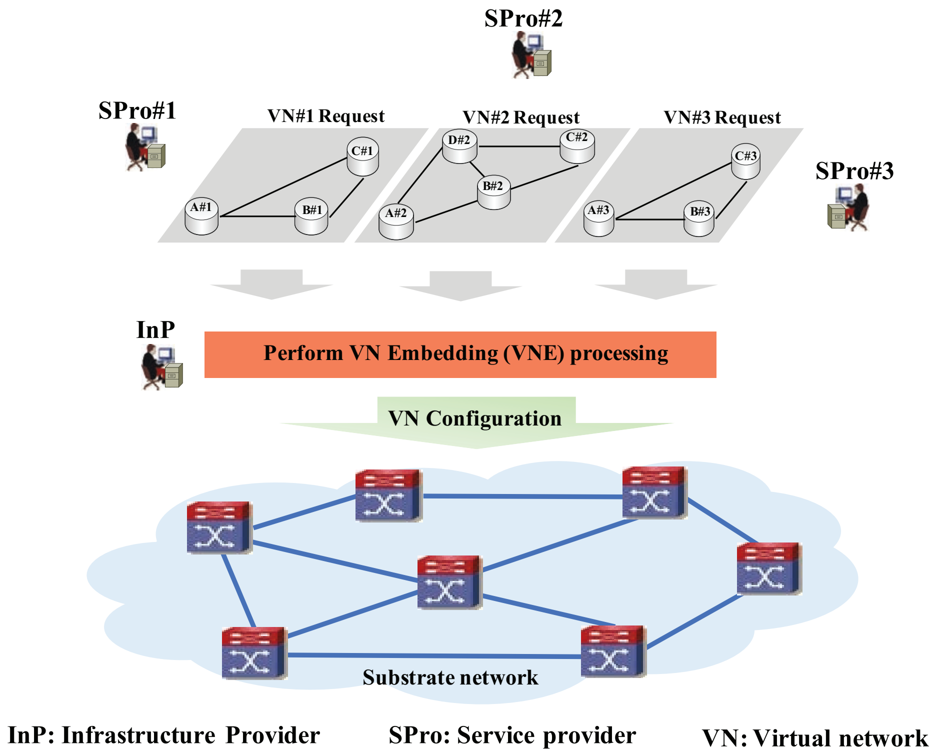

Figure 5.2: Virtual network embedding problem of InP in NVE

For NVE, efficient s-resource allocations for embedding and mapping VNs can reduce network energy consumption, improve network performance and increase the economic profit of InPs. As shown in Figure 5.2, a key challenge for InP, known as the VN Embedding (VNE) problem, is how to efficiently allocate the subset of embeddable s-resources on SN that can best map and embed VN network resources.

With the rapid growth of Internet traffic, the energy consumption of NVE has become a critical issue [5-12] [5-13]. The energy consumption of NVE can be subsumed by the VNE problem because energy efficient s-resource allocation for VN embedding can improve network energy efficiency and reduce energy cost for the InP [5-14]. This section starts by describing the VNE problem, InP profit and energy cost of NVE, and then, the data switching energy consumption of NVE and how to reduce it, is also analyzed.

5.2.1 Virtual network embedding problem

Substrate network and virtual network

SN can be represented by an undirected graph: $G_s = \left(N_s, L_s, R_s^n, R_s^l\right)$, where N_s is the set of s-nodes and L_s is the set of s-links. R_s^n and R_s^l denote the network resource attributes of s-nodes and s-links, respectively. P_s is defined as the set of all loop-free s-paths on SN. Each VN can be represented by an undirected graph: $G_v = \left(N_v, L_v, C_v^n, C_v^l\right)$, where N_v is a set of v-nodes, L_v is a set of v-links. C_v^n and C_v^l refer to the network resources capacity of v-nodes and v-links, respectively.

Virtual node mapping and virtual link mapping

VN embedding can be represented by the mapping $M : G_v = (N_v, L_v) \rightarrow G_s = \left(N_s^{'}, P_s^{'}\right)$ from G_v to G_s, where G_v is a subset of G_s, $N_s^{'} \subseteq N_s$, $P_s^{'} \subseteq P_s$. VN mapping can be decomposed into v-node mapping and v-link mapping [5-16]. V-node mapping can be modeled as: $M^n : (N_v, C_v^n) \rightarrow \left(N_s^{'}, R_s^{n'}\right)$, where $R_s^{n'}$ are the allocated s-resources of v-nodes. V-link mapping can be modeled as: $M^l : \left(L_v, C_v^l\right) \rightarrow \left(P_s^{'}, R_s^{l'}\right)$, where $R_s^{l'}$ is the allocated s-resources of v-links.

InP economic profit and energy cost

In NVE, multiple heterogeneous VNs are likely to coexist on the same SN. The ultimate objective of the VNE problem is to maximize InP economic profit by efficiently allocating the subsets of embeddable s-resources to map and embed the network resources of these VNs. The acceptance rate, revenue and substrate costs of VNs are the basic metrics often used to evaluate VNE strategies [5-15] [5-16].

InP economic profit can be defined using various economic models. In this work, InP economic profit gained from a VN is formulated as follows:

$$Pro\left(G_v\right) = Rev\left(G_v\right) - Cost\left[M^n, M^l, E_{idle}, E_{sw}\right] \tag{5.1}$$

where $Pro\left(G_v\right)$ is the InP economic profit gained from VN G_v. $Rev\left(G_v\right)$ indicates the revenue of G_v that can usually be calculated based on required network resources of the VN. The cost of G_v includes s-resources cost $Cost\left[M^n, M^l\right]$ and energy cost $Cost\left[E_{idle}, E_{sw}\right]$. The energy cost of VN includes idle energy cost E_{idle} and data switching energy cost E_{sw}. E_{idle} can be considered as a constant. E_{sw} is dependent on transmitted data volumes.

5.2.2 Data switching energy consumption

Based on Equation (5.1), decreasing the energy cost by saving data switching energy E_{sw} can increase InP profit. From the VN perspective, the switching energy of data transmission is consumed along the data transmission path on the VN which consists of v-nodes and v-links, and can be formulated as:

$$E_{sw}^{v}\left(d\right) = \left(\sum_{k=0}^{M} \eta_{sw}^{vn}\left(k\right) + \sum_{l=0}^{N} \eta_{sw}^{vl}\left(l, a, b\right)\right) \times Vol\left(d\right) \tag{5.2}$$

where $\eta_{sw}^{vn}\left(k\right)$ is the data switching energy efficiency of v-node k. $\eta_{sw}^{vn}\left(k\right)$ can be considered to be constant. $\eta_{sw}^{vl}\left(l, a, b\right)$ is the data switching energy efficiency of v-link l. l connects with two adjacent v-nodes a and b. $\eta_{sw}^{vn}\left(k\right)$ and $\eta_{sw}^{vl}\left(l, a, b\right)$ are expressed in units of J/b. M and N are the number of v-nodes and v-links along the VN data transmission path, respectively. $Vol\left(d\right)$ denotes the volume of transmitted data d. $E_{sw}^{v}\left(d\right)$ is the data switching energy consumption of d. V-link is mapped onto an s-path in SN. Therefore, the data switching energy efficiency of v-link l can be defined as:

$$\eta_{sw}^{vl}(l, a, b) = \sum_{i=0}^{D} \eta_{sw}(i) \tag{5.3}$$

where D is the number of s-nodes along the s-path of the v-link l. $\eta_{sw}(i)$ is the data switching energy efficiency of s-node i which can be measured as shown in [5-17] [5-18] [5-19].

Data transmission with lower switching energy consumption is one of the network energy saving strategies [5-20]. According to Equation (5.2) and (5.3), the data switching energy of NVE can be saved by increasing the data switching energy efficiency of the v-link. The proposed method reduces the data switching energy consumption of NVE by dynamic reallocation of the s-resources of v-link to increase v-link data switching energy efficiency. In the next section, the proposal is introduced in detail.

5.3 Energy efficient virtual link resource allocation

5.3.1 Overview

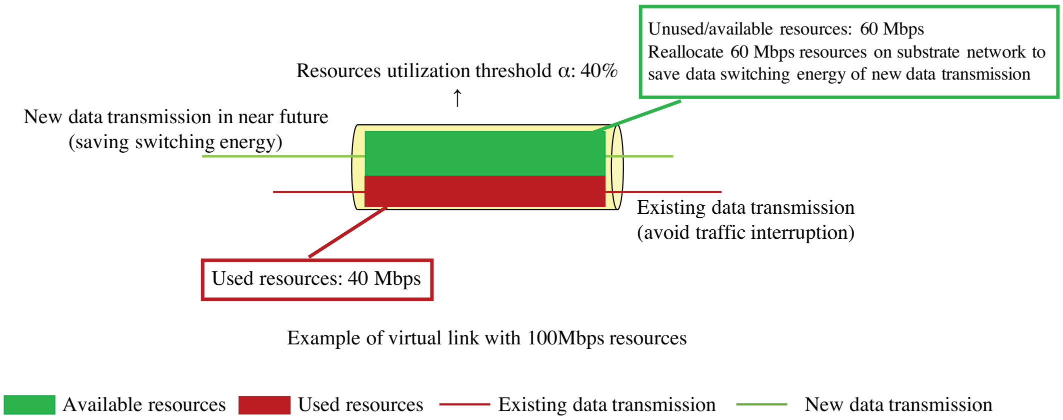

Figure 5.3: Overview of virtual link resources reallocation with *eEVLRR*

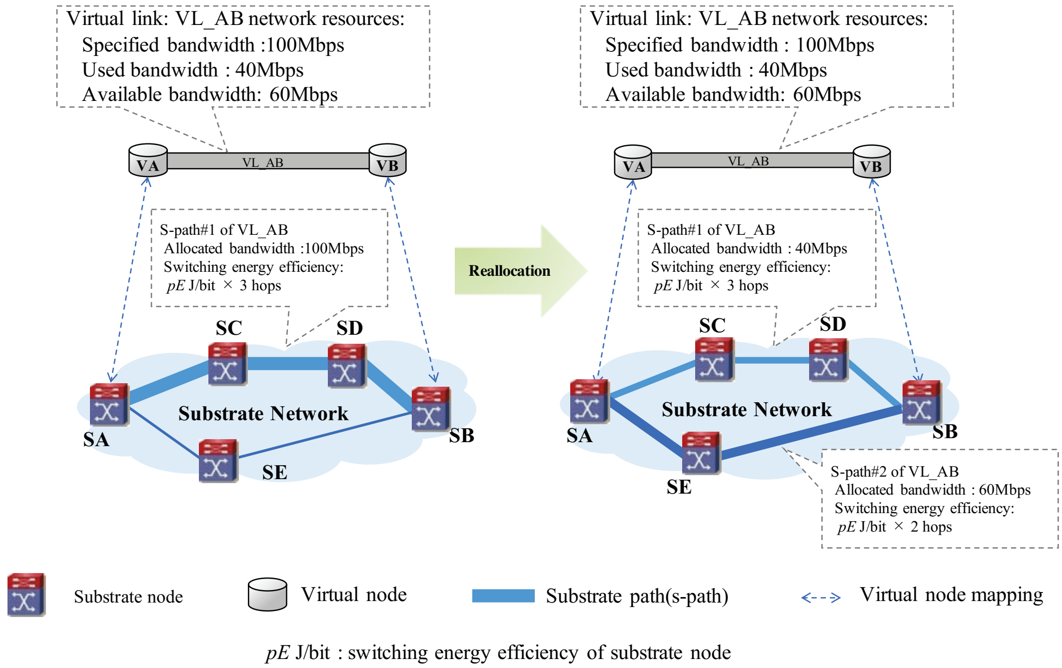

Figure 5.4: Example of substrate resources reallocation for virtual link

In order to guarantee that the allocated s-resources of v-links are always energy efficient, and thus save data switching energy, the proposed energy Efficient Virtual Link Resource Reallocation (*eEVLRR*) method dynamically reallocates energy efficient s-resources for v-links to meet the dynamic changes in embeddable s-resources on SN.

eEVLRR allows a v-link to map one or two s-paths on SN and distinguishes the s-resources of a v-link into available/unused s-resources and used s-resources. In order to avoid traffic interruptions while reallocating and reconfiguring the s-resources of v-links, *eEVLRR* keeps currently used s-resources and existing s-path of a v-link when the v-link is mapped to one s-path. Based on the embeddable s-resources of SN and the available s-resources of v-link, *eEVLRR* calculates and allocates a new s-path for the v-link that has higher data switching energy efficiency than the existing one. The new allocated s-path of v-link is used to support new data transmission on the VN in the near future to save data switching energy. The existing s-path of the v-link is kept active in carrying the current data transmissions on VN until they end. A v-link resource utilization threshold is defined, and when the resource utilization of a v-link exceeds the threshold, the v-link is deemed to be busy with heavy traffic load; in this case, *eEVLRR* is triggered to reallocate the s-resources of v-link to increase the data switching energy efficiency of the v-link. As shown in Figure 5.3, given the v-link bandwidth resource of 100Mbps, when its resource utilization exceeds the threshold of 40%, the available/unused resource 60 Mbps will be reallocated on SN to save data transmission energy of new data transmission in near future, the used resources 40 Mbps of v-link is still kept for avoiding traffic interruption on existing data transmission. As shown in Figure 5.4, the data switching energy efficiency of v-link is increased by *eEVLRR*. When a v-link is mapped to two s-paths, *eEVLRR* adjusts the available s-resources between the two s-paths so that more available s-resources of v-link become energy efficient on data switching. In this way, *eEVLRR* can guarantee that the allocated s-resources of v-links are continuously efficient to save data switching energy in the operation phase without traffic interruptions.

For *eEVLRR*, it is also necessary to identify each data transmission and transmit each data transmission along its initial specified data transmission path on SN. Therefore, we design an application-session-based forwarding model for *eEVLRR* that identifies each data transmission and forwards the data along its specified data transmission path until completion.

In the next subsections, the energy efficient s-resources reallocation algorithms and application-session-based forwarding model of *eEVLRR* are described in detail.

5.3.2 Algorithms

There are two common v-link mapping patterns are adopted by NVE [5-21] [5-22]: (1) a v-link is mapped onto an s-path; (2) a v-link is mapped onto two s-paths. As shown in Figure 5.5, *eEVLRR* supports both patterns. When a v-link is mapped onto an s-path,

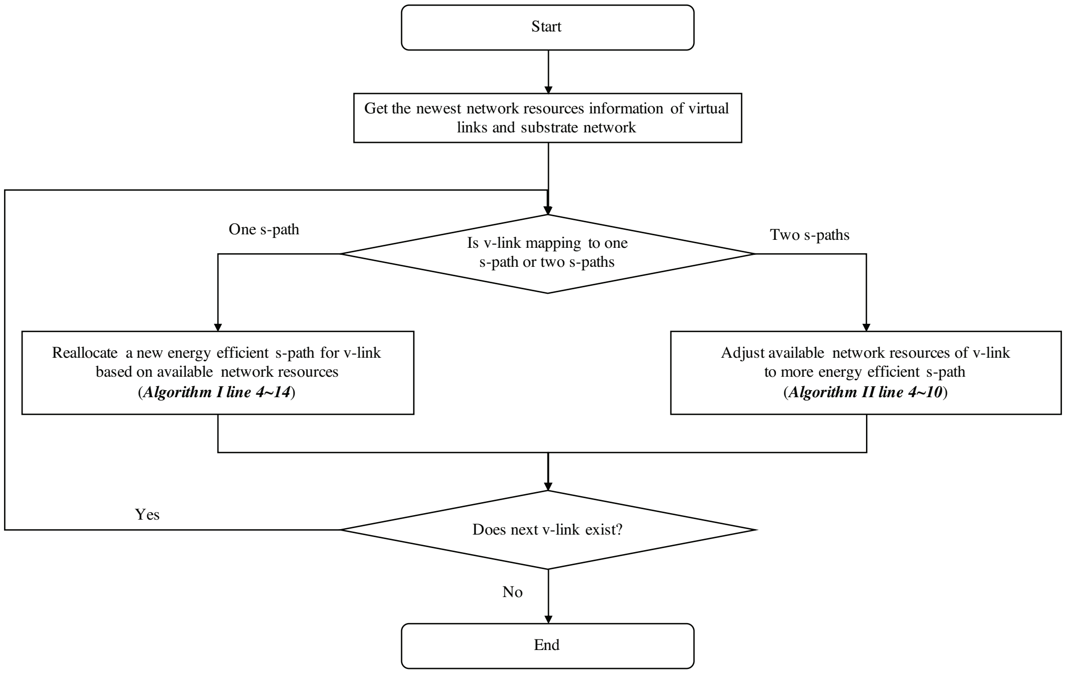

Figure 5.5: Flowchart of *eEVLRR* processing

based on the available s-resources of the v-link, *eEVLRR* allocates a new energy efficient s-path for the v-link. When a v-link is mapped onto two s-paths, *eEVLRR* adjusts the available s-resources of the v-link for the two s-paths and makes more available s-resources of v-link assign to energy efficient s-path. In order to handle the two patterns, two algorithms are implemented as Algorithm I and Algorithm II, respectively. Key variables are defined in Table 5.1.

eEVLRR adopts the event-driven model. A v-link resource utilization threshold is defined. If the resource utilization of v-link l_v^i is greater than its threshold γ_{vl}^i, *eEVLRR* is triggered to take into account the reallocation of available s-resources for l_v^i. Otherwise, do nothing (Algorithm I and Algorithm II: Line: 03).

The pattern of l_v^i mapped onto a s-path: $M^{l_v^i} : l_v^i \to \left\{P_{s_1}^{l_v^i}\right\}$, is described as Algorithm I, *eEVLRR* calculates a new s-path $P_{s_2}^{l_v^i}$ for l_v^i that has higher data switching energy efficiency than current $P_{s_1}^{l_v^i}$. A weighted shortest path algorithm is designed to find $P_{s_2}^{l_v^i}$. Firstly,

Algorithm I: allocate available virtual link resources

input: VN: G_v, SN: G_s, VN mapping: $M : G_v \rightarrow G_s$

output: The newest v-link mapping

sort v-links by available s-resources $aRes(L_v)$ in ascending order

for each v-link $l_v^i \in L_v$ **do**

  if $Res_{vl}^i \times \gamma_{vl}^i < uRes\left(l_v^i\right)$ **then**

    if $M^{l_v^i} : l_v^i \rightarrow \left\{P_{s_1}^{l_v^i}\right\}$ **then**

      obtain the subset of SN: $G_s' = \left(N_s', L_s', R_s^{l'}\right), R_s^{l'} \geq aRes\left(l_v^i\right)$

      calculate new s-path $P_{s_2}^{l_v^i}$ based on:

      $G_s' : swE\left(P_{s_2}^{l_v^i}\right) < swE\left(P_{s_1}^{l_v^i}\right), hops\left(P_{s_2}^{l_v^i}\right) \leq hops\left(P_{s_1}^{l_v^i}\right)$

      if new s-path $P_{s_2}^{l_v^i}$ exists **then**

        establish $P_{s_2}^{l_v^i}$ for l_v^i: $M^{l_v^i} : l_v^i \rightarrow \left\{P_{s_1}^{l_v^i}, P_{s_2}^{l_v^i}\right\}$

        adjust the s-resources of $P_{s_1}^{l_v^i}$: $res\left(P_{s_1}^{l_v^i}\right) = Res_{vl}^i - aRes\left(l_v^i\right)$

        allocate the s-resources of $P_{s_2}^{l_v^i}$: $res\left(P_{s_2}^{l_v^i}\right) = aRes\left(l_v^i\right)$

        update the v-link mapping: $M^{l_v^i} : l_v^i \rightarrow \left\{P_{s_1}^{l_v^i}, P_{s_2}^{l_v^i}\right\}$ to $M^l : \left(L_v, C_v^l\right) \rightarrow \left(P_s', R_s^l\right)$

      else

        continue: next v-link: l_v^{i+1}

      end if

    end if

  end if

  continue: next v-link: l_v^{i+1}

end for

Return v-link mapping: $M^l : \left(L_v, C_v^l\right) \rightarrow \left(P_s', R_s^l\right)$

Table 5.1: Notations

Notation	Explanation
l_v^i	virtual link i
γ_{vl}^i	resource utilization threshold of l_v^i
Res_{vl}^i	resourcecapability of l_v^i
$uRes\,()$	used s-resources of l_v^i
$aRes\,()$	available/unused s-resources of l_v^i
$res\,()$	resources capability of path
$swE\,()$	data switching energy efficiency of path
$hops\,()$	number of hops along path

which yields the subgraph of SN whose embeddable resources of s-links are greater than or equal to the available s-resources of l_v^i (Algorithm I: Line:05). The data switching energy efficiency of s-node (described at subsection 3.3) is taken to be the link weight of the subgraph. Based on the subgraph, the new s-paths are calculated with the k-shortest path algorithm. As constraint conditions, the data switching energy efficiencies of these new s-paths are less than that of $P_{s_1}^{l_v^i}$. Meanwhile, in order to limit the s-resources cost and delay of l_v^i increases, the number of hops of these new s-paths are also less than or equal to that of $P_{s_1}^{l_v^i}$. If there are multiple such new s-paths, *eEVLRR* attempts to decrease the s-resources cost and delay of l_v^i. In order to minimize network resource fragments and maintain fair network resource allocation as far as possible [5-15], the calculated s-path whose hop number is the nearest or equal to that of the existing $P_{s_1}^{l_v^i}$ is finally selected as new s-path $P_{s_2}^{l_v^i}$ (Algorithm I: Line: 06). If $P_{s_2}^{l_v^i}$ exists on the subgraph, it will be configured for l_v^i. Meanwhile, the available s-resources of l_v^i are also assigned to $P_{s_2}^{l_v^i}$. The embeddable s-resources are also updated (Algorithm I: Line: 07-10).

The pattern of l_v^i mapped onto two s-paths: $M^{l_v^i} : l_v^i \rightarrow \left\{P_{s_1}^{l_v^i}, P_{s_2}^{l_v^i}\right\}$, is described as Algorithm II. *eEVLRR* dynamically adjusts the available s-resources of l_v^i between $P_{s_1}^{l_v^i}$ and $P_{s_2}^{l_v^i}$

Algorithm II: adjust available virtual link resources

input: VN: G_v, SN: G_s, VN mapping: $M : G_v \rightarrow G_s$

output: The newest v-link mapping

sort v-links by available s-resources $aRes\,(L_v)$ in ascending order

for each v-link $l_v^i \in L_v$ **do**

  if $Res_{vl}^i \times \gamma_{vl}^i < uRes\left(l_v^i\right)$ **then**

    if $M^{l_v^i} : l_v^i \rightarrow \left\{P_{s_1}^{l_v^i}, P_{s_2}^{l_v^i}\right\}$ **then**

      if $aRes\left(P_{s_1}^{l_v^i}\right)$ can be migrated to $P_{s_2}^{l_v^i}$ **then**

        adjust the s-resources of $P_{s_1}^{l_v^i}$ and $P_{s_2}^{l_v^i}$:

        $res\left(P_{s_2}^{l_v^i}\right) = res\left(P_{s_2}^{l_v^i}\right) + aRes\left(P_{s_1}^{l_v^i}\right)$, $res\left(P_{s_1}^{l_v^i}\right) = Res_{vl}^i - res\left(P_{s_2}^{l_v^i}\right)$

        update the v-link mapping:

        $M^{l_v^i} : l_v^i \rightarrow \left\{P_{s_1}^{l_v^i}, P_{s_2}^{l_v^i}\right\}$ to $M^l : \left(L_v, C_v^l\right) \rightarrow \left(P'_s, R_s^l\right)$

      else

        continue: next v-link: l_v^{i+1}

      end if

    end if

  end if

  continue: next v-link: l_v^{i+1}

end for

Return v-link mapping: $M^l : \left(L_v, C_v^l\right) \rightarrow \left(P'_s, R_s^l\right)$

and makes more available s-resources of l_v^i assign to energy efficient s-path that has higher data switching energy efficiency than another one. If the embeddable s-resources along the energy efficient s-path are greater than or equal to the available s-resources capacity that will be adjusted, *eEVLRR* adjusts the available s-resources for l_v^i to the energy efficient s-path. The embeddable s-resources are also updated. (Algorithm II: Line: 05-07).

In line 1 of Algorithm I and Algorithm II, the insertion sort algorithm is used to sort the v-links by available s-resources in ascending order. The running time of the insertion sort algorithm is $O\left(l^2\right)$, the l is the number of virtual links. From line 2 of Algorithm I and Algorithm II, each v-links is traversed and processed for available s-resource allocation or adjustment. Hence, the running time of these processes is $O\left(l\right)$. In line 6 of Algorithm I, the K shortest path algorithm is performed to get the new s-path for v-link. The running time of the insertion sort algorithm is $O\left(k \times v\left(v + e \times \log\left(e\right)\right)\right)$, the k is the number of shortest paths, the v is the number of substrate nodes of SN, the e is the number of substrate links of SN [5-23].

Hence, the running time of Algorithm I can be defined as follows:

$$O\left(l^2\right) + O\left(l \times \left(k \times v\left(v + e \times \log\left(e\right)\right)\right)\right) \tag{5.4}$$

The running time of Algorithm II can be defined as follows:

$$O\left(l^2\right) + O\left(l\right) \tag{5.5}$$

5.3.3 Application-session-based forwarding

eEVLRR allows a v-link to map one or two s-paths, and moreover, dynamically reallocates and reconfigures these s-paths to reduce data switching energy consumption. In *eEVLRR*, when a v-link is mapped onto two s-paths, in order to avoid traffic interruptions during resource reallocation and reconfiguration, the energy efficient s-path is preferentially used for near-term new data transmissions, and the other s-path still is used for maintain the existing data transmission until completion. Hence, as a challenge, it is necessary to identify and forward each data transmission flow along its initial specified s-path until completion. Some existing technologies can identify and split traffic across multiple transport paths, such as deep-packet-inspection [5-24], load-balancing [5-25] and multi-path-routing protocols [5-26] [5-27]. However, there are some drawbacks with regard to dynamic configuration, flexible control and processing speed. Moreover, they make it difficult to identify the data transmission flows of VNs on SN. OpenFlow supports network flexible, programmable and extendable control [5-28], and has been widely applied into NVE and even multi-layer NVE [5-29] [5-30]. Therefore, to solve this problem, this work establishes an application-session-based (AS-based) forwarding model based on OpenFlow extension mechanism.

Cross-layer-solution

The AS-based forwarding model is based on a cross-layer design paradigm that can help to realize effective solution on complex network behavior and optimization [5-31]. In NVE, a data is transmitted through the application/service layer, VN layer and SN layer. In order to identify each data transmission flow on SN, it is necessary to share data-transmission-property-information from application/service layer to SN layer. In the AS-based forwarding model, a session is considered as the application response to an end-user request. Each data transmission is identified by a pair of application identifier (APP_ID) and session identifier (S_ID). The APP_ID is a unique identifier and is predetermined. The S_ID is a continuous sequential number. Here, we assume that the S_IDs are a series of continuous natural numbers that helps to perform data forwarding policy on SN and reduce the flow table entries at each switch. Each pair of APP_ID and S_ID as data-transmission-property-information is unique. While responding to an end-user data request, the newest pair of APP_ID and S_ID is attached to the rear of all data chunks

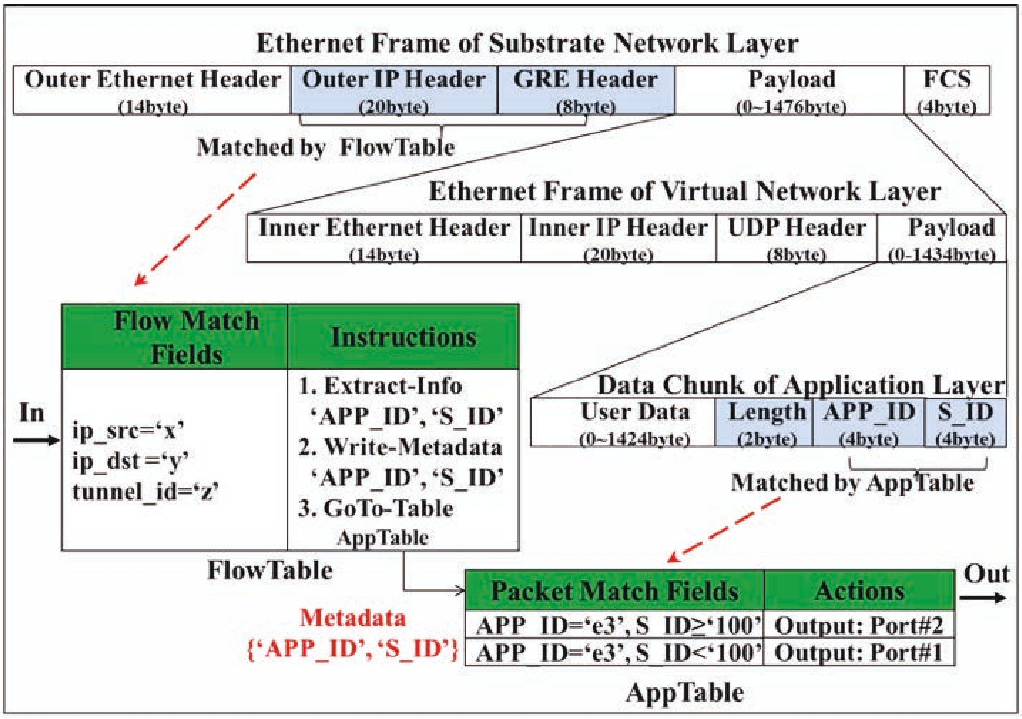

Figure 5.6: Example of application-session-based forwarding model for NVE

before being sent out, as shown in Figure 5.6. In the SN layer, the pair of APP_ID and S_ID is extracted and used for packet forwarding.

OpenFlow extensions

OpenFlow allows one or more flow tables in pipeline processing to achieve policy-based data forwarding [5-28]. In the AS-based forwarding model, flow tables are classified into two categories: FlowTable and AppTable. FlowTable and AppTable record flow entries. As shown in Figure 5.6, the Generic Routing Encapsulation technique (GRE) is used for isolating VNs [5-32]. FlowTable matches v-link with GRE header. AppTable matches application data packets with APP_ID and S_ID. For FlowTable, a flow entry contains flow match field and instructions field. Each v-link as a flow entry is configured into FlowTable by InP to match the data packets of VN. Sequential instructions are configured into the instruction field to process matched data packets. There are three standard instructions of OpenFlow that can be configured into the instruction field: Apply-Action, Write-Metadata and GoTo-Table. Based on the extendable experimenter action mechanism of OpenFlow, we create the new Extract-Info action to extract the pair of APP_ID and S_ID from each data packet. When a data packet is matched by flow match field, Apply-Action executes Extract-Info action to extract the pair of APP_ID and S_ID. Metadata enables to pass information to be passed between flow tables in a pipeline processing. The extracted APP_ID and S_ID are written into Metadata by Write-Metadata, then, GoTo-Table delivers the data packet with Metadata to AppTable. AppTable forwards the data packet. AppTable's flow entry contains packet match field and action field. Data forwarding rule is determined and configured into packet match field by InP. In order to reduce the number and size of flow entries, we create the logical match mode for AppTable based on flexibility OpenFlow Extensible Match (OXM) mechanism. Logical match allows logical expressions to be used in matching APP_ID and S_ID, such as '<': less than, '>': greater than, '=': equal to. The standard action of OpenFlow Output is configured into the action field. When APP_ID and S_ID are matched by packet match field, the data packet is forwarded from the port specified by Output action. As shown by the example of the application (APP_ID = 'e3') data packet in Figure 5.6, if the value of attached S_ID is less than 100 (S_ID < '100'), the data packet is forwarded from Port#1, otherwise (S_ID ≥ '100'), and thus forwarded from Port#2. When *eEVLRR* successfully reallocates the new energy efficient s-resources for v-links (described in Section 5.3.2), InP also updates the flow entries of AppTable.

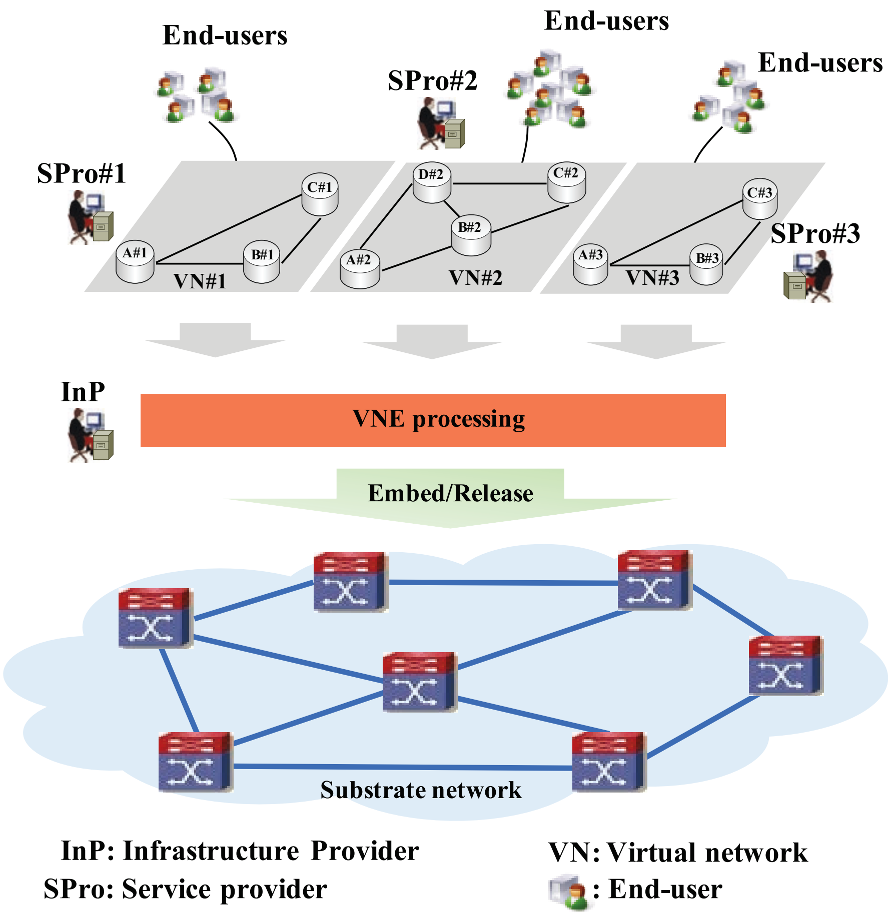

Figure 5.7: Overview of simulated network virtualization environment

5.4 Evaluations

Simulation environment

The NVE simulator, implemented as a C++ program as shown in Figure 5.7, can construct SN layer for InP, VN layer, and end-user service layer for Service Providers (SPs), such as E^3-DCN. The Brite network topology generator was used to generate Waxman network topologies for SN and VNs [5-34]. The SN layer includes a SN consisting of 50 s-nodes and 150 s-links. Each of s-nodes has the same computing resources of 50 units. The average latency of each s-node is 4.1 microseconds [5-33]. The average data switching energy efficiency of each s-node is 10 nJ/b [5-18]. Each of s-links has the same bandwidth resource of 1024 Mbps. The VN layer consists of embedded VNs. The number of VN nodes is uniformly distributed between 3 and 10. Each v-node is connected with up to three v-nodes and has the same computing resource of 1 unit. For a VN, each v-link has the same bandwidth resource is uniformly distributed between 30 and 100 Mbps. The VN lifetime is uniformly distributed between 1000 and 1500 seconds (time units). When a VN request arrives, the s-resources of SN are allocated to the VN. The well-known method Greedy v-node mapping method with k-shortest path algorithm for v-link mapping is used for embedding the VN. The s-path of a v-link is average between four and ten hops. At the end of VN, the s-resources allocated to the VN are recycled. For data transmission, the simulation assumes an end-user service like YouTube streaming on each of embedded VNs [5-35]. The rate of data transmission is distributed between 200 and 400 kbps according to a Poisson process with a mean of 320. The duration of data transmission is uniformly distributed between 100 and 200 seconds. The bandwidth resources occupied by of data transmission are reflected on VN and SN along the data transport path from the beginning to end.

eEVLRR was evaluated by comparing it with conventional NVEs such as those in [5-2] [5-3] [5-4] [5-5] [5-6] [5-7] [5-8] [5-9] [5-10] [5-11]. There are two v-link mapping patterns adopted into conventional NVEs [5-21] [5-22]: (1) a v-link is mapped onto an s-path; (2) a v-link is mapped onto two s-paths whose total equals the average bandwidth resources of the v-link. We call such conventional NVEs as NVE#1:1 and NVE#1:2, respectively. *eEVLRR* was adopted and extended to yield NVE#1:1 and NVE#1:2, called NVE#1:1+eE+γ and NVE#1:2+eE+γ, respectively. γ means the v-link resource utilization threshold for *eEVLRR*. *eEVLRR* was evaluated by comparing NVE#1:1 and NVE#1:1+eE+γ, NVE#1:2 and NVE#1:2+eE+γ. Furthermore, different v-link resource utilization thresholds γ ($\gamma \in$ 20%, 30%, 40%, 50%) were set for *eEVLRR* to observe the impact of the change.

Each NVE experienced the same VN request arrivals, modeled as a Poisson process with an average of 4 request arrivals every 100 seconds. All details of each VN request such as network topologies and network resources were also the same for an arrival. In an arrival, if these same VN requests were all successfully accepted and embedded into each of NVEs, and moreover, the s-resources configurations of these VNs in each of NVEs are also the same, we call them completely the same VNs (SameVNs). If the s-resources configurations of these VNs in each of NVEs are different in an arrival, we call them common VNs (CommonVNs). When VN is embedded into NVE successfully, the data switching energy efficiency of each v-link is calculated based on its s-path to construct the data switching energy efficiency weight graph for the VN. The arrivals and details of end-user requests are also the same for each VN in each of NVEs; modeled as a Poisson process with an average of 2 request arrivals per second. The receiver and sender of data transmission were connected by two uniformly distributed distinct v-nodes. The data transmission path on a VN was calculated by energy-aware routing algorithm created by extending the Dijkstra-shortest-path algorithm using the data switching energy efficiency weight graph and the available network resources of the VN. For SameVNs embedded in each of NVEs, the end-user requests are the same, and the total transmitted data volume of each SameVN is also the same over the communication lifetime.

Each simulated run was was performed 8 times on an Ubuntu16.04 Server with 32 Cores CPU, 450GB Memory and 500GB Disk.

Performance metrics

The following NVE metrics was measured to analyze the performance of *eEVLRR*:

- **Data switching energy**

  The data switching energy of NVE contains the data switching energy of all VNs and the data switching energy of SameVNs.

- **Virtual network acceptance rate**

  The acceptance rate of NVE taken to be the number of accepted VN requests for all arrived VN requests that arrived in a time interval.

- **Revenue to cost ratio**

  The revenue of NVE is considered to be the total required network resources of all VNs including all v-nodes and links network resources. The cost of NVE is considered to be the total allocated s-resources for all VNs as calculated based on substrate configurations.

- **S-resources utilization**

  The s-resource utilization is calculated by summing the allocated s-resources of all VNs and the total s-resources of SN.

- **Average virtual link delay**

  Virtual link delay is the sum of the latency of each s-node along s-path of a v-link. The average delay of a virtual link, calculated as the sum of delay of all virtual links and the number of virtual links, is used for evaluating the QoS of NVE.

In general, acceptance rate, revenue to cost ratio and s-resources utilization are common basic metrics used for evaluating VNE strategies. This thesis adds data switching energy and average delay of v-links as new metrics to evaluate *eEVLRR*.

Evaluation of data switching energy consumption

The available VNs of NVE#1:1 and NVE#1:1+eE+γ ($\gamma \in$ 20%, 30%, 40%, 50%) are shown in Figure 5.8. The data switching energy consumption of NVE#1:1 and NVE#1:1+eE+γ are shown in Figure 5.9 and Figure 5.10. As shown in Figure 5.8, in the time period between 0 and 1750, there are 8 SameVNs embedded into each of NVEs. Figure 5.9 shows the data switching energy of all SameVNs. Under the same traffic volume condition, the

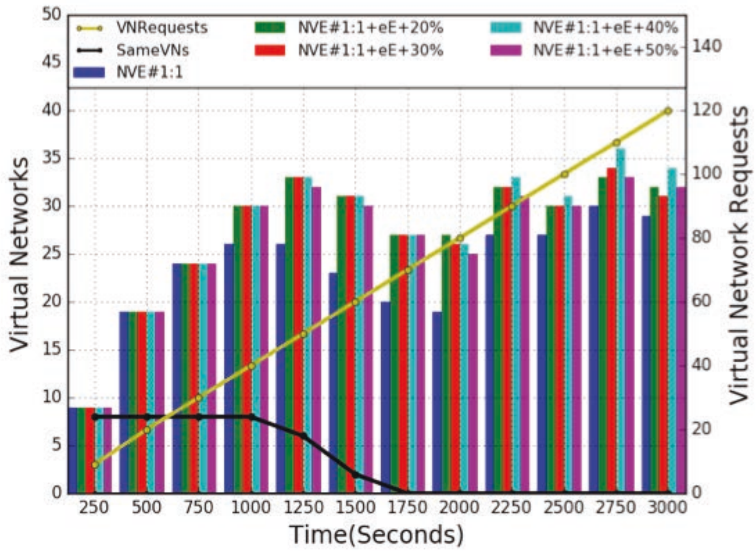

Figure 5.8: Evaluation of available embedded virtual networks

data switching energy consumption of NVE#1:1+eE+ γ is less, overall, than NVE#1:1; the greatest reduction is about 30% in time period between 400 and 1000. In the time period between 0 and 400, with the increase in traffic volume, the data switching energy consumption of NVE#1:1+eE+ γ gradually becomes less than NVE#1:1. This shows that *eEVLRR* could reallocate and adjust the energy efficient s-resources for v-links because the resource utilization of some v-links were greater than their thresholds γ . In the time period between 1000 and 1750, as the end of SameVNs, the data switching energy consumption of NVEs gradually fell. However, the data switching energy consumption of NVE#1:1+eE+ γ remained less than that of NVE#1:1. This shows that *eEVLRR* continuously reallocated and adjusted the energy efficient s-resources for v-links so as to save data switching energy. Figure 5.10 shows the total data switching energy consumption of all available VNs. Except for the time period between 1500 and 2250, NVE#1:1+eE+ γ consumed less data switching energy than NVE#1:1; the reduction was at least 15% from the time period of 700. As shown in Figure 5.8 and Figure 5.10, in the time period between 1500 and 2250, there were eight more available VNs on NVE#1:1+eE+ γ than on

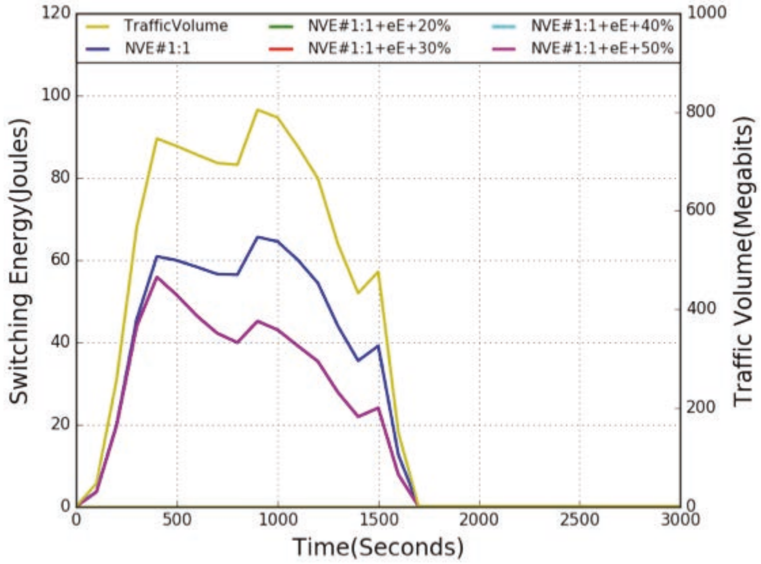

Figure 5.9: Evaluation of data switching energy on same virtual networks

NVE#1:1, but the data switching energy of NVE#1:1+eE+ γ was only a little more than that of NVE#1:1. In the time period from 2250 and 3000, there were three more available VNs on NVE#1:1+eE+ γ than on NVE#1:1, but NVE#1:1+eE+ γ consumed less data switching energy than NVE#1:1. This shows that *eEVLRR* continuously reallocated energy efficient s-resources to v-links to save the data switching energy of NVE. These results prove that the proposal, *eEVLRR*, guarantees that the s-resources of v-link remain continuously energy efficient in terms of data switching by dynamically reallocating v-links's-resources under the influence of the dynamic changes in embeddable s-resources.

Evaluation of average virtual link delay

The average virtual link delay values of NVE#1:1 and NVE#1:1+eE+ γ ($\gamma \in$ 20%, 30%, 40%, 50%) are shown in Figure 5.11. Each NVE had, at first, almost the same average virtual link delay, and then that of NVE#1:1+eE+ γ 's gradually become smaller than that of conventional NVE#1:1; the reduction ranged from 18% to 30%. The reason is that *eEVLRR* attempted to reduce the s-path delay while reallocating the available s-resources

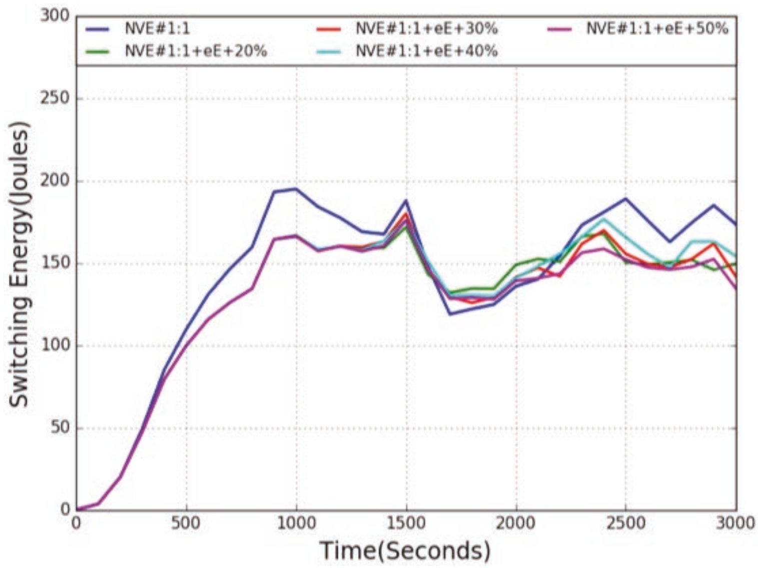

Figure 5.10: Evaluation of total data switching energy

of v-links whose resource utilization exceeded their thresholds γ . In combination with Figrue 5.9 and Figure 5.10, these results prove *eEVLRR* can reduce not only the data switching energy of NVE, but also the delay of v-links to improve the QoS of NVE.

Evaluation of virtual network acceptance rate

The available VNs and acceptance rate of NVE#1:1 and NVE#1:1+eE+ γ are shown in Figure 5.8 and Figure 5.12, respectively. In the time period between 0 and 750, as the number of VN requests accepted in each of NVEs increased, the numbers of available VNs all increased from 0 to 24, and the acceptance rates fell from 100% to 50%. However, for the time period beyond 750, NVE#1:1+eE+ γ attained more available VNs than NVE#1:1, NVE#1:1+eE+ γ also had higher acceptance rate than NVE#1:1. The reason is that *eEVLRR* dynamically reallocated and adjusted the available s-resources for v-links in response to the dynamic changes in the embeddable s-resources. This reduced the frequency and duration of network resource fragmentation and promoted fair s-resource allocations and higher acceptance rates [5-15]. Another reason is that *eEVLRR*

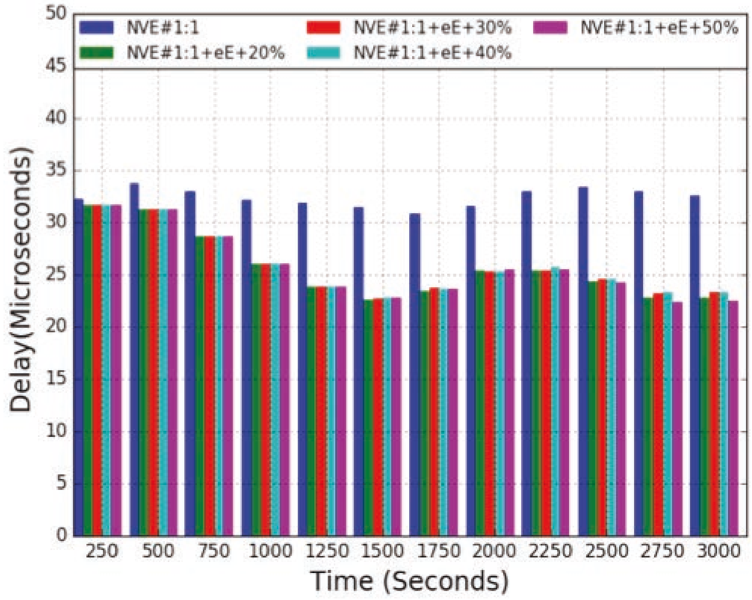

Figure 5.11: Evaluation of average virtual link delay

also considered possible reductions in the s-resource cost of v-links in each reallocation. This increased the embeddable s-resources of SN and thus raised the probability of VN request acceptance.

Evaluation of revenue to cost ratio and substrate resource utilization

The evaluations of the revenue to cost ratio and s-resource utilization of NVE#1:1 and NVE#1:1+eE+ γ are shown in Figure 5.13 and Figure 5.14, respectively. As shown in Figure 5.13, NVE#1:1+eE+ γ had higher revenue to cost ratio than NVE#1:1 overall; the maximum discrepancy was about 4%. As shown in Figure 5.14, in the time period between 0 and 750, for the same number of available VNs shown in Figure 5.8, NVE#1:1+eE+ γ had lower s-resource utilization than NVE#1:1. The reason is that *eEVLRR* attempts to chooses the energy efficient s-path with lower s-resources cost while reallocating the available s-resources of v-link. Starting the time period of 1000, as the number of accepted VN requests increased, NVE#1:1+eE+ γ had higher available VNs

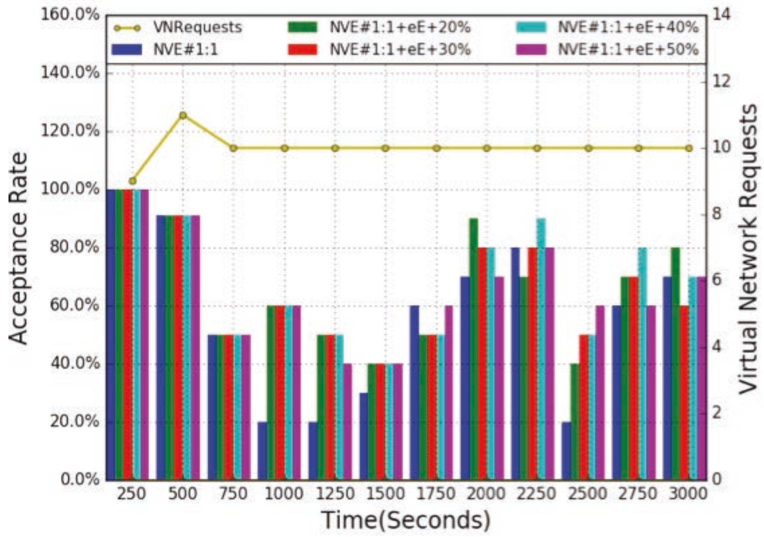

Figure 5.12: Evaluation of virtual network acceptance rate

and revenue to cost ratio than NVE#1:1, see Figure 5.8 and Figure 5.13. As shown in Figure 5.14, *eEVLRR* continuously attempts to reduce the s-resources cost of available VNs, however, the reduced s-resources cost of available VNs is sometimes less than the allocated s-resources cost for new embedded VNs. Hence, NVE#1:1+eE+ γ sometimes had higher s-resource utilization than NVE#1:1. This confirms that *eEVLRR* can promote to new VN accepted simultaneously and attempts to reduce the s-resources cost of VNs as far as possible.

The performance evaluation results yielded by comparing NVE#1:2+eE+ γ with traditional NVE#1:2, in which a v-link is mapped onto two s-paths, are shown in Appendix B, from Figure B.1 to Figure B.6. Similarly, *eEVLRR* can also guarantee that the s-resources allocated to v-links are continuously energy efficient in terms of data switching even with the dynamic changes in embeddable s-resources, and can strengthen the increase InP profit and the QoS.

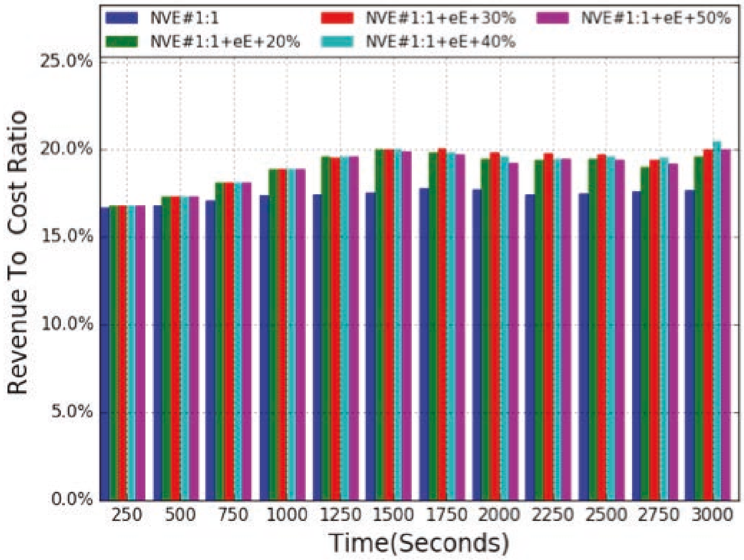

Figure 5.13: Evaluation of revenue to substrate cost

5.5 Chapter conclusion

This chapter focused on the data switching energy consumption issue of E^3-DCN. E^3-DCN is built on NVE and adopts three VNs as its network infrastructure. For NVE, efficient s-resource allocation to VNs can reduce network data switching energy consumption. There is an important problem with regard to existing works on energy efficient s-resource allocation; they cannot guarantee that the s-resources allocated to VNs remain energy efficient under dynamic changes in the embeddable s-resources of SN.

This chapter proposed *eEVLRR*, a dynamic energy Efficient Virtual Link Resource Reallocation method for NVE that can help E^3-DCN to reduce the data switching energy consumption. Based on the embeddable s-resources of SN and available s-resources of v-links, *eEVLRR* dynamically reallocates energy efficient s-resources for v-links to ensure that the s-resources allocated to v-links remain energy efficient. In order to guarantee QoS and avoid traffic interruptions while reallocating the s-resources of v-links, a cross layer application-session-based (AS-based) forwarding model was designed for *eEVLRR* that

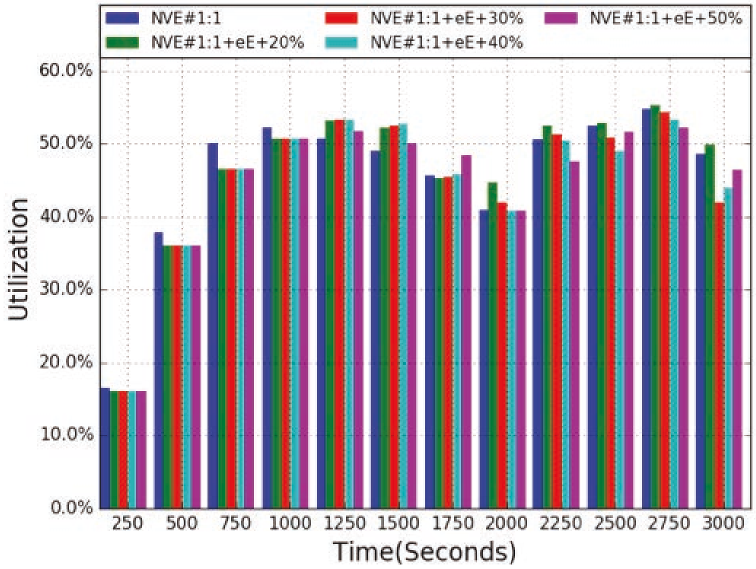

Figure 5.14: Evaluation of substrate resources utilization

identifies each data transmission flow and forwards it along its initially specified s-path until completion without traffic interruptions.

Data switching energy consumption, average virtual link delay, virtual network acceptance rate, revenue to cost ratio and s-resources utilization as performance metrics were used as performance evaluations. Comparisons of *eEVLRR* to traditional NVEs, showed that the former could reduce network data switching energy by up to 30% and improve NVE acceptance rate. In the NVE saturated state, *eEVLRR* increased the number of embedded VNs by 5 to 8 over the traditional NVEs, while reducing the network data switching energy by at least 15%. The revenue to cost ratio of *eEVLRR* exceeded that of traditional NVEs by about 4%. The average virtual link delay was reduced by 18% and 30%.

These results prove that *eEVLRR* can not only guarantee that the s-resources allocated to v-links remain energy efficient in terms of data switching under the dynamical changes in embeddable s-resources expected, but can also increase InP profit and improve QoS. The reason is that *eEVLRR* considers the network resources fragmentation issue and allocation fairness while reallocating energy efficient s-resources of v-links. *eEVLRR* limits the increase in s-resource cost of v-links while trying to gradually reduce the s-resource cost and delay of v-links.

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Chapter 6

Overall conclusion

Researchers are actively exploring the information-centric networking (ICN) communication model as the most attractive networking paradigm for the future Internet. This dissertation focused on ICN and realized an energy efficient and flexible ICN for the future Internet.

Chapter 3 proposed an Energy Efficient and Enhanced-type Data-centric Network (E^3-DCN) based on network virtualization. Network virtualization can create multiple virtual/slice networks (VNs) on a substrate/physical network and can allocate dedicated network resources to each VN. E^3-DCN is built on three VNs, one is used as the network control plane, the other two provide the network data plane. These three VNs realize network awareness and satisfy the control plane and data plane separation requirements of the future Internet. The thesis then introduced the data-centric overlay network (DCON) and data generation overlay network (DGON), as network functions that overlay the network control plane to realize location-independent ICN network and multiple service paradigms to ensure the future Internet has adequate scalability. One of the two network data plane VNs supports packet switching while the other supports optical circuit switching. By combining packet switching and optical circuit switching in a flexible manner, data transmission energy consumption can be reduced. E^3-DCN also supports other energy efficiency enhancements, such as in-network caching, network reconfiguration and circuit switching bypass. A prototype of E^3-DCN was implemented on the JGN-X network virtualization platform, and data switching energy consumption and network energy consumption were measured. The data switching energy consumption can be reduced by at least 16.2% by combining packet switching and optical switching compared to single packet switching. The network power consumption can be reduced by at least 19.3% by network reconfiguration.

Data transmission energy optimization remains one of the key issues with E^3-DCN. Chapter 4 focused on this issue, and proposed an energy efficient data discovery and delivery method for E^3-DCN to reduce its data switching energy consumption. The proposed method obtains the requested data in four steps: data exploration, data source response, data request and data transmission. Concurrently, the proposed method avoids the transmission of unnecessary traffic, and ensures that DCON of E^3-DCN can discover the optimal data source and the most energy efficient data transmission path by combining optical circuit switching and packet switching to reduce data transmission energy consumption. Simulation results showed that the proposed method can help E^3-DCN to reduce data switching energy by about 40% compared with traditional ICN networks, and achieve network performance is superior to that of the current TCP/IP-based networks.

Chapter 5 also focused on the data transmission energy optimization issue, and proposed an energy efficient network resource allocation method for E^3-DCN that helps to further reduce the data switching energy consumption of E^3-DCN. The proposed method dynamically identifies and selects energy efficient network resources of the data plane on the network virtualization environment that ensures that the allocated network resources remain energy efficient and thus save data switching energy. Simulation results show that the proposed method can reduce the network data switching energy consumption of E^3-DCN by 15% on average and up to 30% at maximum, and can also reduce network delay by 18% to 30% for enhancing QoS.

To reach an overall conclusion, this dissertation contributes to the realization of truly energy efficient and flexible ICN network E^3-DCN for the future Internet. E^3-DCN meets the requirements of the future Internet, such as location-independent communication, network awareness, network control plane and data plane separation, multiple service paradigms, easy network reconfiguration and high energy efficiency. This dissertation focused on data transmission energy optimization of E^3-DCN in Chapter 4 and Chapter 5. There are still unsolved issues with E^3-DCN that need to be studied, such as network resource optimization, data caching optimization, and network reconfiguration optimization. Resolving these issues will help E^3-DCN to further improve QoS, scalability and energy efficiency.

Appendix A

Internet Protocol Suite

[1]Reference documents can be accessed at https://tools.ietf.org/html/

Table A.1: Common protocols of TCP/IP-based Internet

Protocol Name	**TCP/IP Layer**	**Time**	**Reference**[1]
Teletype Network(Telnet)	Application layer	1969	RFC15
Network Control,Program (NCP)	Transport layer	1969	RFC36
File Transfer Protocol(FTP)	Application layer	1971	RFC114
Host.file	Internet layer	1974	RFC608
Transmission Control Protocol (TCP)	Transport layer	1974	RFC675
User Datagram Protocol (UDP)	Transport layer	1980	RFC768
Internet Protocol version 4 (IPv4)	Internet layer	1981	RFC791
Internet Control Message Protocol (ICMP)	Internet layer	1981	RFC792
Simple Mail Transfer Protocol(SMTP)	Application layer	1982	RFC821
Gateway-To-Gateway Protocol (GGP)	Internet layer	1982	RFC823
Address Resolution Protocol (ARP)	Link layer	1982	RFC826
Exterior Gateway Protocol (EGP)	Application layer	1982	RFC827
Reverse Address Resolution Protocol(RARP)	Link layer	1984	RFC903
Domain Name System (DNS)	Application layer	1985	RFC882
Routing Information Protocol (RIP)	Application layer	1988	RFC1058
Internet Group Management Protocol (IGMP)	Internet layer	1989	RFC1112
Intermediate System to Intermediate System (IS-IS)	Link layer	1990	RFC1142
Dynamic Host Configuration Protocol (DHCP)	Application layer	1993	RFC1533
Open Shortest Path First (OSPF)	Link layer	1994	RFC1583
Integrated Services(IntServ)	Internet layer	1994	RFC1633
Point-to-Point Protocol (PPP)	Link layer	1994	RFC1661
Generic Routing Encapsulation (GRE)	Internet layer	1994	RFC1701
Uniform Resource Locator (URL)	Application layer	1994	RFC1738
Secure Sockets Layer (SSL)	Application layer	1994	RFC6101
Border Gateway Protocol (BGP)	Application layer	1995	RFC1771
Internet Protocol Security (IPsec)	Internet layer	1995	RFC1825
Internet Protocol version 6 (IPv6)	Internet layer	1995	RFC1883
Secure Shell (SSH)	Application layer	1995	RFC4250
Multipurpose Internet Mail Extensions (MIME)	Application layer	1996	RFC2045
Hypertext Transfer Protocol (HTTP)	Application layer	1997	RFC2068
Resource Reservation Protocol (RSVP)	Transport layer	1997	RFC2205
Protocol-Independent Multicast (PIM)	Internet layer	1998	RFC2117
Differentiated Services (DiffServ)	Internet layer	1998	RFC2474
Network Address Translation (NAT)	Internet layer	1999	RFC2663
HTTPS (HTTP Secure)	Application layer	2000	RFC 2818
Explicit Congestion Notification (ECN)	Internet layer	2001	RFC3168
Datagram Congestion Control Protocol (DCCP)	Transport layer	2006	RFC4336
Mobile IP (MIP)	Internet layer	2007	RFC4721
Stream Control Transmission Protocol (SCTP)	Transport layer	2007	RFC4960
Multicast DNS (mDNS)	Application layer	2013	RFC6762
Multipath TCP(MPTCP)	Transport layer	2013	RFC6824
Locator/ID Separation Protocol (LISP)	Internet,layer	2013	RFC6830
Hypertext Transfer Protocol Version 2 (HTTP/2)	Application layer	2015	RFC7540

Appendix B

Additional Performance Evaluations

There are two common virtual link (v-link) mapping patterns adopted into the network virtualization environment (NVE) [B-1] [B-2]: (1) a v-link is mapped onto one substrate path (s-path); (2) a v-link is mapped onto two s-paths whose total capacity equal the average bandwidth resources of the v-link. The performance evaluation results of NVE#1:1+eE+ γ ($\gamma \in$ 20%, 30%, 40%, 50%) combined with our proposal of Chapter 5 and traditional NVE#1:1 in pattern (1) have been introduced in Section 5.4. The performance evaluation results for NVE#1:2+eE+ γ and traditional NVE#1:2 with pattern (2) are described in Appendix B. The simulation parameters of NVE#1:2+eE+ γ and traditional NVE#1:2 are the same as NVE#1:1+eE+ γ and traditional NVE#1:1 and have been described in Section 5.4. The performance evaluation results by comparing NVE#1:2+eE+ γ with traditional NVE#1:2 are shown from Figure B.1 to Figure B.6.

The available VNs of NVE#1:2 and NVE#1:2+eE+ γ ($\gamma \in$ 20%, 30%, 40%, 50%) are shown in Figure B.1. The data switching energy consumption of NVE#1:2 and NVE#1:2+eE+ γ are shown in Figure B.2 and Figure B.3. As shown in Figure B.1, in the time period between 0 to 1750, there are 8 to 12 SameVNs in each of NVEs. Similarly, Figure B.2 and Figure B.3 all show that proposed *eEVLRR* continuously reallocates and adjusts the energy efficient substrate resources (s-resources) for v-links to save data switching energy. These results can prove our proposal *eEVLRR* guarantees the s-resources of v-link is continuously energy efficient on data switching by reallocating v-links's-resources with dynamic changes of embeddable s-resources.

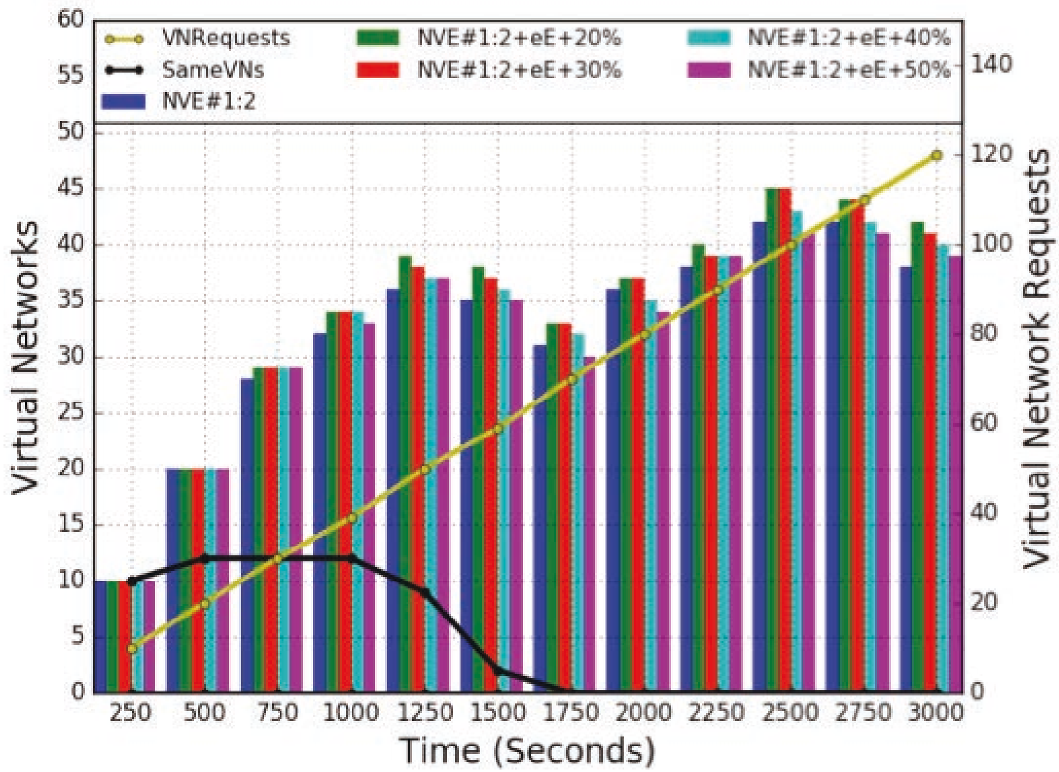

Figure B.1: Evaluation of available embedded virtual networks

The average virtual link delay of NVE#1:2 and NVE#1:2+eE+ γ ($\gamma \in$ 20%, 30%, 40%, 50%) are shown in Figure B.4. The average virtual link delay of each NVE is nearly the same, firstly, and then, NVE#1:2+eE+ γ 's become smaller gradually than conventional NVE#1:2. The reason is that *eEVLRR* attempted to reduce the delay of s-path if possible while reallocating the available s-resources of v-links whose resources utilization were greater than their thresholds γ . With Figrue B.2 and Figure B.3, these results can prove *eEVLRR* can not only reduce data switching energy of NVE, but also reduce the delay of v-links to improve QoS for NVE.

The revenue to cost ratio and s-resource utilization of NVE#1:2 and NVE#1:2+eE+ γ are shown in Figure B.5 and Figure B.6. Similarly, they also all proves the effectiveness of the proposal on the revenue to cost ratio and s-resource utilization is better than those of NVE#1:2.

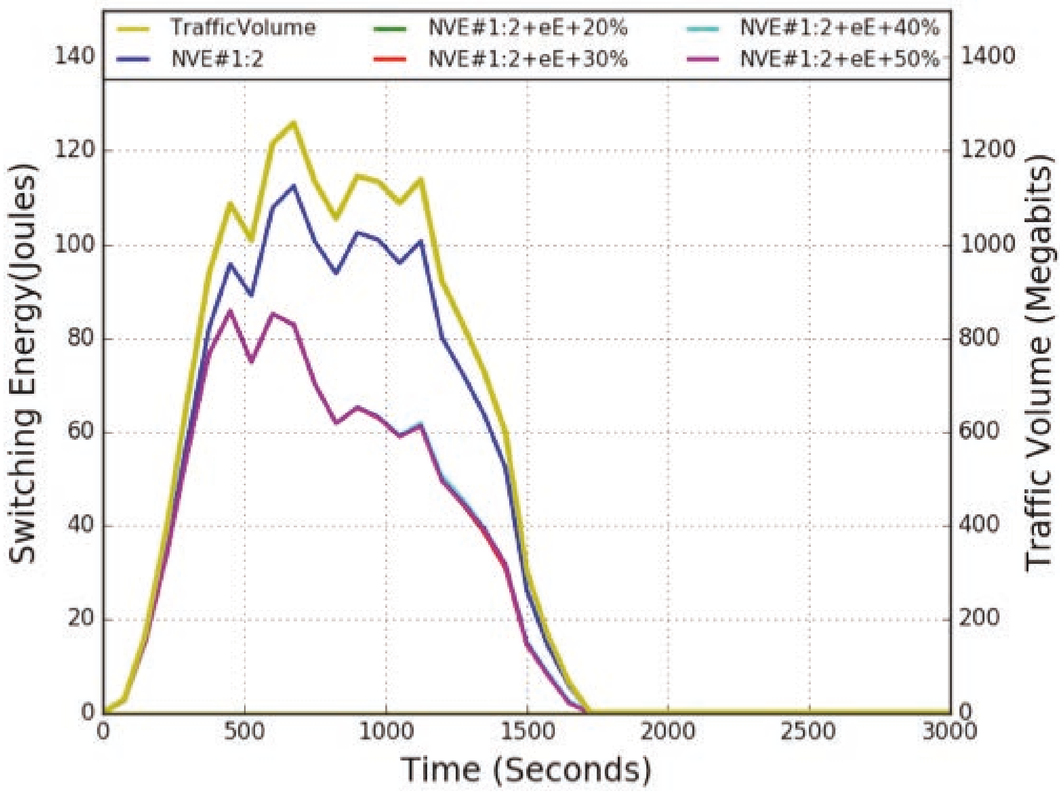

Figure B.2: Evaluation of data switching energy of the same virtual networks

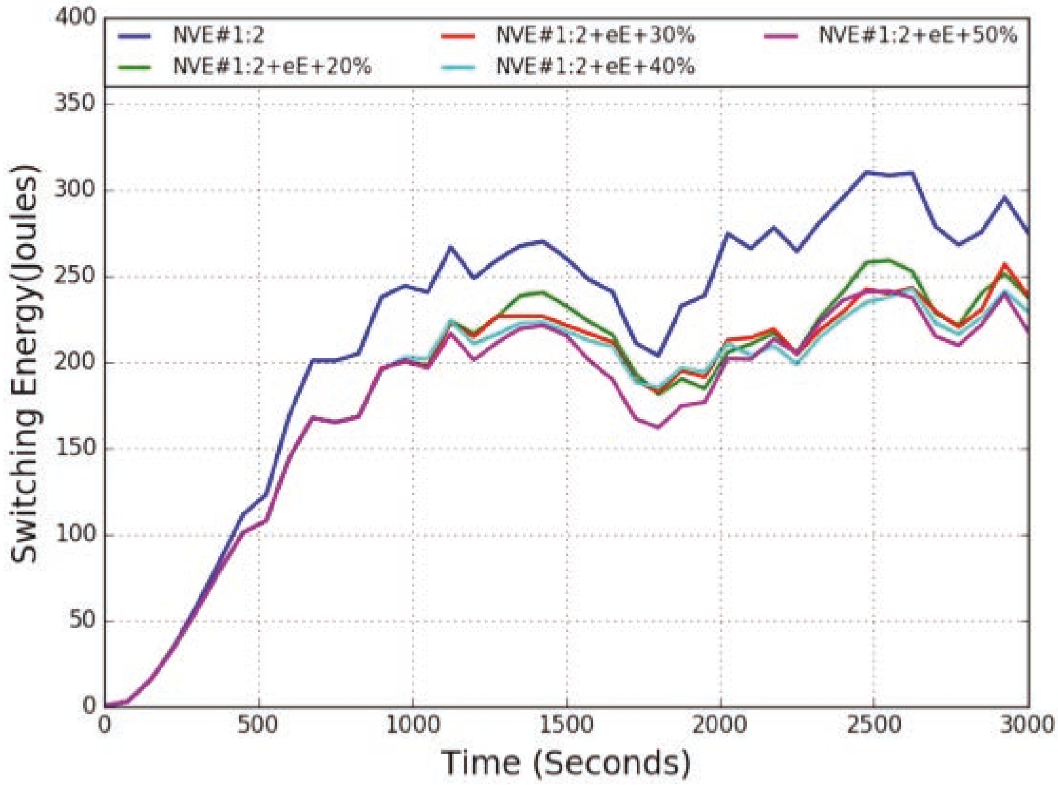

Figure B.3: Evaluation of total data switching energy

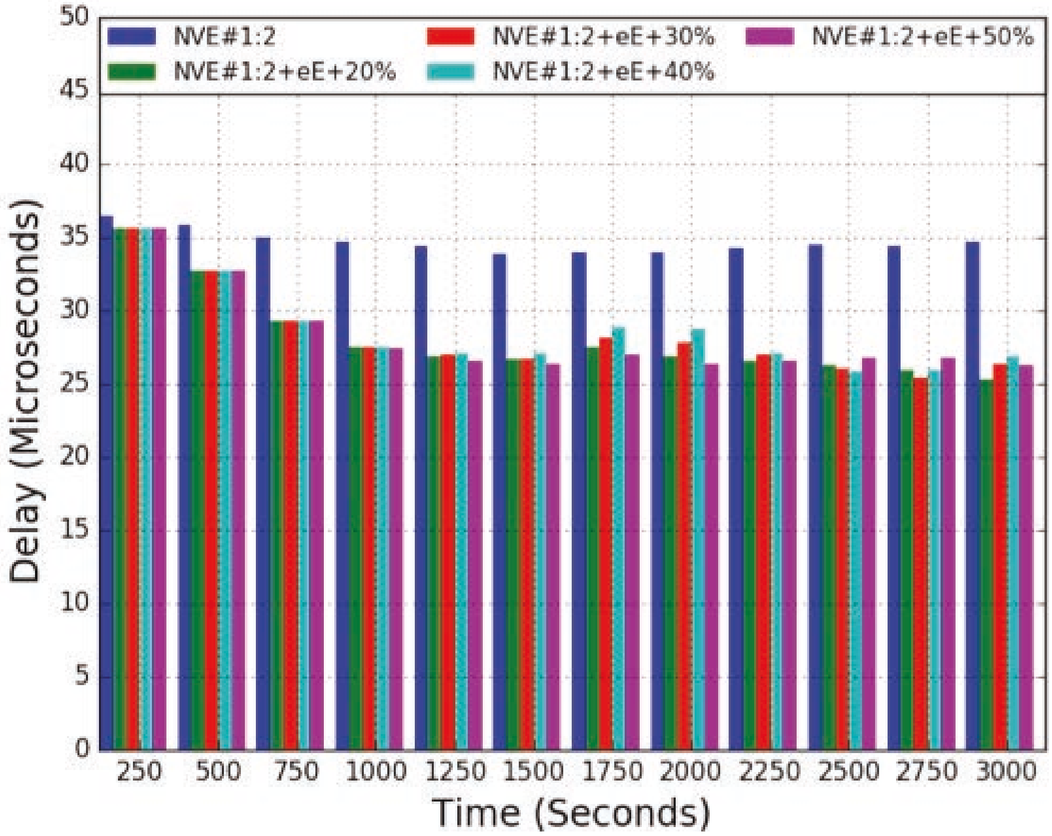

Figure B.4: Evaluation of virtual link delay

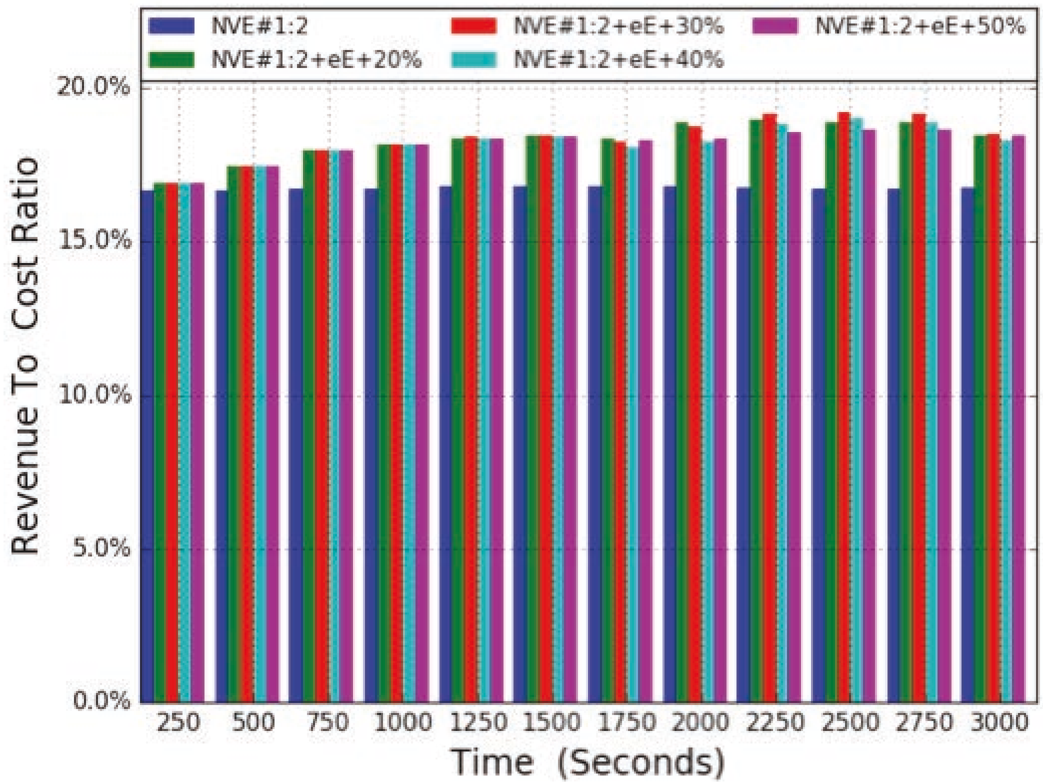

Figure B.5: Evaluation of revenue to substrate cost

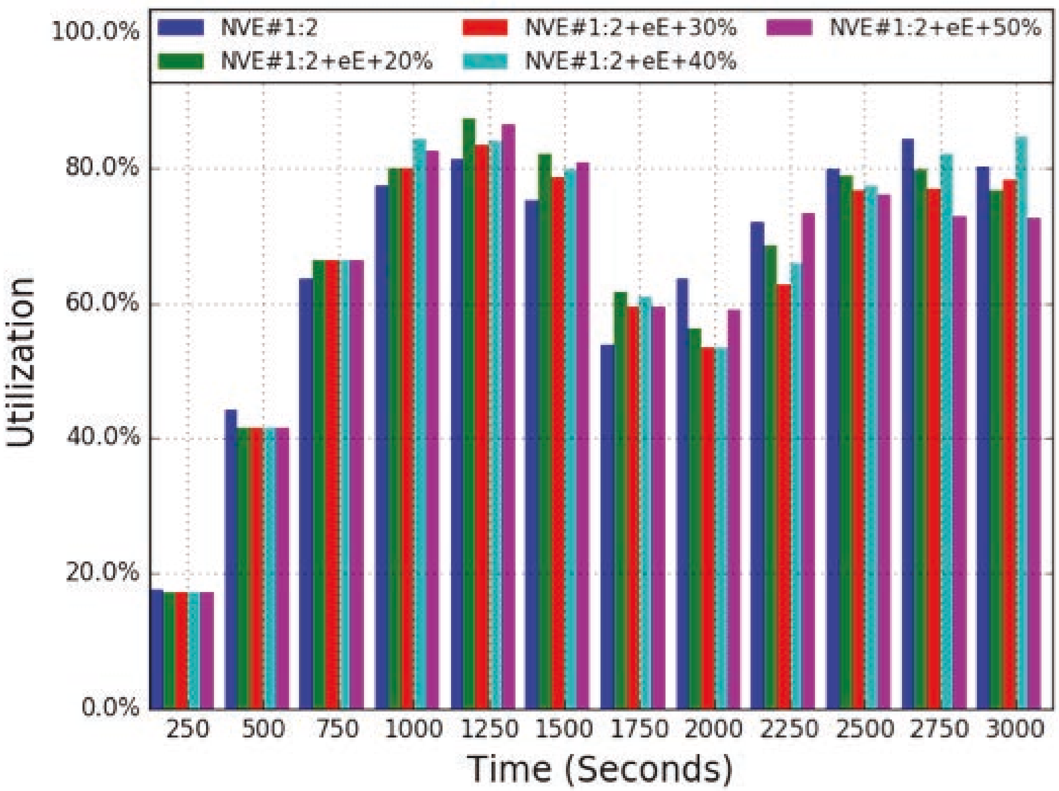

Figure B.6: Evaluation of substrate resource utilization

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List of the related papers

Journal papers

Papers related to this dissertation

(1) **Shanming Zhang**, Takehiro Sato, Satoru Okamoto, Naoaki Yamanaka, "Dynamic Energy Efficient Virtual Link Resource Reallocation Approach for Network Virtualization Environment," IEICE Transactions on Communications, Vol. E101-B, No. 7, pp. 1675-1683, July 2018.

(2) **Shanming Zhang**, Hidetoshi Takeshita, Satoru Okamoto, Naoaki Yamanaka, "Energy Efficient and Enhanced-type Data-centric Network Architecture," International Journal of Computer and Information Science (IJCIS), Vol. 16, No. 1, pp. 60-70, March 2015.

International conference papers

(1) Shoichi Nagata, Mirai Chino, Tetsuhiro Uchida, **Shanming Zhang**,
Hidetoshi Takeshita, Satoru Okamoto, and Naoaki Yamanaka, "Network API for Energy-Aware Routing in Energy Efficient and Enhanced-type Data- centric Networking," The 21st Asia-Pacific Conference on Communications (APCC 2015) Latest Results Workshop, No. 16-AM2-D-1, pp. 485-490, October 2015.
(Presented by Shoichi Nagata)

(2) Satoru Okamoto, **Shanming Zhang**, and Naoaki Yamanaka, “Energy Efficient Data-centric Network on the Optical Network Virtualization Platform,” 12th International Conference on Optical Internet (COIN2014), No. FB2-1, August 2014.
(Presented by Satoru Okamoto)

(3) Naoaki Yamanaka, Hidetoshi Takeshita, Satoru Okamoto, Takehiro Sato, and **Shanming Zhang**, “Energy Efficiency of Future Central and/or Linked Distributed Function Network Using Optical Technologies,” 19th European Conference on Networks and Optical Communications (NOC 2014), No. 5-1, pp. 97-101, June 2014.
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Technical reports

(1) Naoaki YAMANAKA, Daisuke MATSUBARA, **Shanming ZHANG**, Hidetoshi TAKESHITA, Satoru OKAMOTO, “Data-centric Networking (DCN) and Energy-Efficient and Enhanced type DCN (E^3-DCN),” The 13th domestic conference of IEICE Technical Committee on Network Virtualization (NV), Tokyo, March 2015.
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(2) Naoaki YAMANAKA, Satoru OKAMOTO, **Shanming ZHANG**, Hirofumi YAMAZAKI, Takashi KURIMOTO, “Beyond the SDN and Virtualization,” 2014 IEICE General Conference, No. BP-1-3, March 2014.
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(3) **Shanming ZHANG**, Hidetoshi TAKESHITA, Takashi KURIMOTO, Satoru OKAMOTO, Naoaki YAMANAKA, “Optimal Multiple Multicast Trees for Many-to-Many Multicasting Communication,” Technical Report of IEICE, Vol.

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(4) Naoaki Yamanaka, Satoru Okamoto, Naohiko Shibuta, **Shanming ZHANG**, Takuro Okano, and Takashi Kurimoto, "Energy Efficient and Enhanced-type Data Centric Network (E^3-DCN) using Network Virtualization Techniques : Network virtualization, Smart (Photonic/Energy) Network," Technical Report of IEICE, Vol. 113, No. 7, IN2013-4, pp. 19-24, April 2013.
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(5) **Shanming ZHANG**, Naohiko SHIBUTA, Hidetoshi TAKESHITA, Satoru OKAMOTO, and Naoaki YAMANAKA, "A Novel Architecture of Energy Efficient and Enhanced-type Data-centric Network (E^3-DCN)," Technical Report of IEICE, Vol. 112, No. 230, IN2012-78, pp. 25-30, October 2012.
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