ROUTING AND RESOURCE ALLOCATION FOR SOFTWARE DEFINED MOBILE NETWORKS

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ABSTRACT

ROUTING AND RESOURCE ALLOCATION FOR SOFTWARE DEFINED MOBILE NETWORKS

Since traffic diversity and volume increase with growing popularity of mobile applications, there is the strong need to manage the traffic carried by networks. Software defined networks can simplify network management while enabling new services by employing traffic management including routing whose goal is to maximize the given utility while satisfying capacity requirements. Another key concept to meet up huge data traffic is cloud-based radio access networks. By integrating cloud services to radio access networks, operators will make use of network functions virtualization which allows to host different virtualized functions on a common hardware platform. In this thesis, an efficient routing algorithm is proposed to minimize the cost based on power consumption determined by the number of active OpenFlow switches and active links in a software defined networks while satisfying throughput requirements of all flows according to constraints on link capacities in the software defined mobile network. The algorithm is also implemented in mobile network by combining resource allocation in a cloud radio access network. The performance of the proposed algorithm is evaluated based on power consumption efficiency for different network topologies with various scenarios.

ÖZET

YAZILIM TANIMLI MOBİL AĞLAR İÇİN YOL VE KAYNAK ATAMA

Mobil uygulamaların gittikçe yaygınlaşması ile artan trafik çeşitliliği ve hacmi, ağlarda taşınan trafiğin yönetilmesi ihtiyacını kuvvetlendirdi. Yazılım tanımlı ağlar, trafik yönetimini kullanarak belirlenen gereksinimleri karşılarken, verimi maksimuma çıkararak ağları yönetebilir. Artan trafik hacmi talebini karşılamak için öne çıkan bir diğer teknoloji ise bulut tabanlı radyo erişim ağlarıdır. Bulut servisleri radyo erişim ağlarına entegre edilerek, operatorler ağ fonksiyonları sanallaştırmasından faydalabileceklerdir. Böylece tek bir donanımda farklı sanallaştırılmış fonksiyonlar kullanılabilecektir. Bu tezde, ağdaki aktif anahtar ve bağlantı sayısına dayanan güç tüketimini minimuma indiren bir yol atama algoritması öneriyoruz. Bağlantı kapasitesi kısıtlamalarını göz önüne alarak, akışların veri hacmi gereksinimlerini karşılayan en iyi yolu bulmak için genetik algoritma kullanıp, düşük karmaşıklıklı yeni bir yol atama yaklaşımı öneriyoruz. Algoritmanın, bulut radyo erişim ağına sahip mobil ağ sisteminde kaynak ayırma ile birleştirilip analizi yapılmıştır. Önerilen algoritmanın verilen ağ topolojisinde çeşitli akış veri hacmi kısıtlamalarına göre performans değerlendirmelerini sunuyoruz.

TABLE OF CONTENTS

LIST OF FIGURES

Figure **Page**

LIST OF TABLES

LIST OF ABBREVIATIONS

SDN . . . . Software Defined Network
SDMN . . . . Software Defined Mobile Network
RAN . . . . Radio Access Network
C-RAN . . . . Cloud Radio Access Network
ONF . . . . Open Networking Foundation
TCAM . . . . Ternary Content-Addressable Memory
BBU . . . . Baseband Unit
RRH . . . . Remote Radio Head
LTE . . . . Long Term Evolution
GSM . . . . Global System for Mobile Communications
3G . . . . Third Generation
UMTS . . . . Universal Mobile Telecommunications System
UTRAN . . . . UMTS Terrestrial Radio Access Network
E-UTRAN . . . . Evolved-UMTS Terrestrial Radio Access Network
3GPP . . . . 3rd Generation Partnership Project
EPC . . . . Evolved Packet Core
QoS . . . . Quality of Services
GA . . . . Genetic Algorithm
OFDMA . . . . Orthogonal Frequency-Division Multiple Access

CHAPTER 1

INTRODUCTION

Software defined networking (SDN) is a network paradigm that decouples control plane from data plane. The control plane of SDN is centralized and software based. Today's routers decide the forwarding action internally by their forwarding tables. This limits the flexibility of routing policies since all network devices must follow pre-defined protocol. In SDN, the centralized controller unit is responsible for all forwarding decisions. The SDN controller has the global view of the network. The software running on controller which designed by network engineers can uniquely decide forwarding policies for every independent application. The control decisions are sent to the forwarding elements which are simple OpenFlow switches and only responsible of forwarding traffic.

Centralized control plane offers various advantages such as global network optimization, programmability, ease of configuration, reduces operation cost, fast adaptation to sudden traffic changes etc. The applications communicate with the controller via northbound communications, while controller communicates with network devices via southbound communications in SDN. It uses OpenFlow protocol to provide communication between control plane and forwarding plane since the controllers are seperated from the switches. OpenFlow is a SDN protocol that carries the message between SDN controllers and forwarding elements.

The traffic demand of mobile devices grows rapidly since the number of mobile devices and applications increases. The operators seek for solutions to able to meet this huge data demand. One of the promising solution is based on integrating cloud services to radio access networks. It is called Cloud Radio Access Networks (C-RAN). It is a centralized, cloud computing-based architecture for radio access networks for future communication standarts, and it is also backwards compatible for 2G, 3G and 4G. A C-RAN architecture will use a combination of virtualization, centralization and coordination techniques. The aim of centralization is to reduce operational expenditures while the aim of virtualization is to reduce capital expenditures by applying network function virtualization (NFV).

C-RAN is an architectural transformation of the current distributed base station system. The C-RAN architecture basically consists of three parts: the baseband processing units (BBU), remote radio heads (RRH) and optical fronthaul. The BBUs are responsible for base station functions from baseband processing to packet processing while the RRHs perform radio functions. The RRHs are connected to the BBU pool via optical fiber which is referred as fronthaul. C-RAN collects the BBUs in a data center at a central location. This makes easier to manage the network. Also, it enables resource pooling and coordination of radio resources.

In this thesis, a low complexity energy efficient routing algorithm is proposed. The proposed algorithm is compared to genetic algorithm and the shortest path algorithm. Then, the algorithm is integrated with mobile network which has C-RAN and performance evaluation of the system is obtained.

This thesis consists of 5 chapters and its outline is given as follows:

- Chapter 2 gives background information about key concepts of this thesis which are SDN, Software Defined Mobile Network (SDMN), Routing and C-RAN.
- Chapter 3 examines routing algorithms for SDN. A low complexity routing algorithm is proposed. The algorithm was designed to minimize the switch usage and put unused switches into sleep mode while satisfying the data demands of routed flows. Then, the performance of proposed algorithm is compared with the genetic algorithm and the shortest path algorithm.
- Chapter 4 examines the performance of the proposed algorithm in SDMN. The algorithm is combined with resource allocation in mobile network with C-RAN. The performance evaluation is performed in case of coexistance of SDN and C-RAN.
- Chapter 5 summarizes the final remarks.

CHAPTER 2

BACKGROUND

In this chapter, fundamental concepts related to this thesis are overviewed. In the first section, SDN concept will be introduced and explained. In the next section, SDN concept in mobile environment will be discussed. The routing concept will be given in the third section. Finally, in the last section C-RAN will be explained.

2.1. Software Defined Networking

With the increase of cloud services, server virtualization, mobile devices and applications, connectivity demands of users exceed the limits that current networks could handle. As demands on the data center rapidly increase, the current networks need to grow. However, with the addition of hundreds of network elements the network becomes more and more complex and diffucult to configure and manage. Designing and configuring the current networks are based on predictable traffic patterns. But, todays traffic patterns are getting incredibly dynamic since virtualized data centers become popular. Thus, predicting traffic pattern is not easy. Also many of the data center network infastructure was built based on a hierarchical model. Although this model provides fitting solutions to past centers, it is not suitable for dynamic computing, virtualization and high storage needs of data today's centers. In this architecture, creating or deploying a new service is takes lot of time and effort. To add or move a device multiple switches, routers, firewall, protocols must be reconfigured, access control lists, authentications, quality of service (QoS) must be updated. Protocols are developed to deliver high performance, broader connectivity and reliability. However, they provide solution to a specific problem without any fundamental abstractions. Likewise network topology, vendor switch model, and software version must be considered. The manufacturers that develop these network equipments include their own mechanisms which result non-standardized products. Also the degree of internal flexibility differs from vendor to vendor. The firmware is developed by each vendor for their own hardware. Thus, it is not possible to offer customized solutions to customers' problems. This system limits the innovations. Therefore current networks are inflexible and lack of the ability to keep up the gradually increasing demands of the new applications.

Software Defined Networking (SDN) is a new approach to networking which decouples the control plane from data plane. The control plane of SDN is centralized, independent software platform and sends the control information to the data plane. This architecture allows to software can be developed independently of the hardware. Thus, SDN has the potential to accelerate network innovation. The idea of SDN started on campus networks. While new protocols are researched, researchers came up with idea of using programmable network devices which controlled by a central element. The major advantages of SDN architecture stated by Open Networking Foundation (ONF) [ONF] are listed in the following [SDN]:

- Directly programmable: Network control is directly programmable since it is decoupled from forwarding functions.

- Agile: Abstracting control from forwarding allows administrators to dynamically arrange network-wide traffic flow to satisfy changing needs.

- Centrally managed: Network intelligence is logically centralized in software-based SDN controllers that maintain a global view of the network, which appears to applications and policy engines as a single, logical switch.

- Programmatically configured: SDN allows network managers configure, manage, secure, and optimize network resources very quickly via dynamic, automated SDN programs, which they can write themselves because the programs do not depend on proprietary software.

- Open standards-based and vendor-neutral: When implemented through open standards, SDN makes network design and operation simple because instructions are provided by SDN controllers instead of multiple, vendor-specific devices and protocols.

The SDN architecture is defined by ONF consists of three distinct layers as shown in Figure 2.1. These layers are application layer, control layer and infrastructure layer. The application layer consists of the network orchestrator which obtains topology information and request service across the network either by a customer or by an internal network process. The control layer has logically centralized network intelligence that maintains a global view of the network. It supervises the network forwarding behavior via an open interface by providing consolidated control functionality. All the control functionality is given to a centralized controller such as NOX [Gude2008], Maestro [Cai2011], Beacon [Erickson2013] and Floodlight [Floodlight2012] in the initial design and implementation of SDN because of the simplicity and flexibility. However, a single controller may not be enough to manage a network with a large number of data plane elements, as the size of the network grows. A distributed network controller such as Onix [Koponen2010], HyperFlow [Tootoonchian2010] and Kandoo [Yeganeh2012] can expand to satisfy the requirements of both small-scale and large-scale networks unlike the centralized controller. The infrastructure layer consists of the network elements and devices. These elements only responsible for packet switching and forwarding.

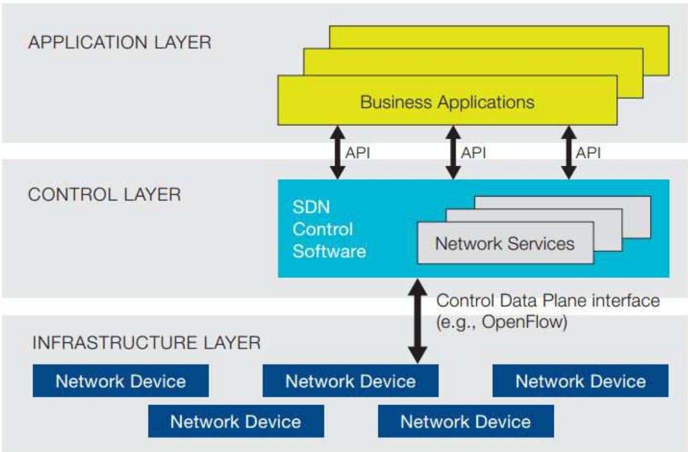

Figure 2.1. SDN architecture [ONF2012]

The infrastructure layer which contains network elements, communicates with the control layer via southbound interfaces. Application layer which includes SDN applications communicates with controller layer via northbound interfaces as shown in the Figure 2.2.

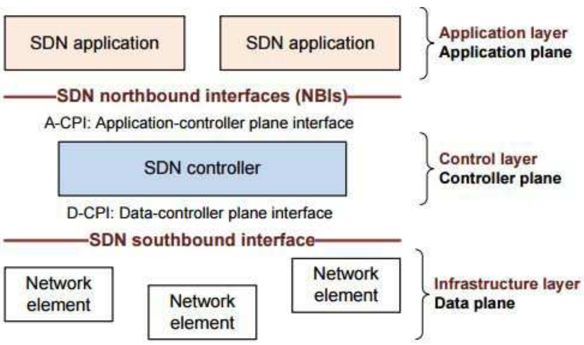

Figure 2.2. SDN components [ONF2014]

One of the potential main components of the SDN is OpenFlow switch which is the first standard transmission interface defined between the control and forwarding layers of an SDN architecture. OpenFlow, initially released by the Clean Slate Program at Stanford. ONF has been founded to expand the usage area of OpenFlow and to provide carrier grade requirements. ONF is a nonprofit organization. In order to implement data center networks, the operational capability of OpenFlow is evaluated by ONF. Members of the board of ONF are: Facebook, Deutsche Telekom, Yahoo!, Microsoft, Google, NTT Communications, Verizon, Goldman, Sachs and Co., Stanford University and Princeton University. Meanwhile ONF associated in the order of 50 members from the different areas of the industry.

In a traditional router, routing (control plane) and packet forwarding (data plane) occur on the same device. Since SDN seperates these two planes, there is a need of protocol which enables the communication of these two planes. OpenFlow is the standard communications interface defined between the control and forwarding layers which enables network controllers to determine the path of network packets towards a network. OpenFlow is based on an Ethernet switch, which has an internal flow-table, and a standardized interface. This interface is used to add and remove flow entries. An OpenFlow switch is a device that forwards packets in SDN. It can be software program or hardware device.

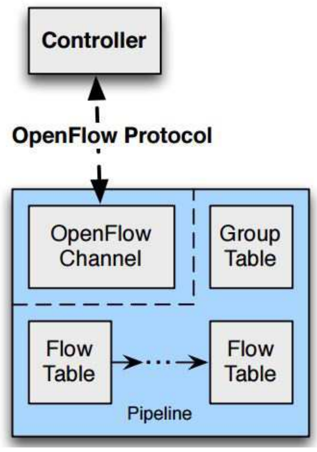

Figure 2.3. OpenFlow switch [ONF2015]

OpenFlow switch consists of three basic parts as can be seen in Figure 2.3. A Flow Table, a Secure Channel and the OpenFlow Protocol. Communication between controller and the OpenFlow switch realized via OpenFlow protocol. All packets that enters a network element passes through flow tables. A flow table consist of flow entries. Components of a flow entry in a flow table is shown in Table 2.1. A flow table entry is identified by its match fields and priority. The controller can add, update and delete flow entries in flow tables. The flow-tables typically built from ternary content-addressable memory (TCAMs). TCAM is a type of memory used mainly in high-performance network equipment. It has has three states 0, 1, and ”don't care”. TCAMs are primarily used for routing decisions.

Table 2.1. OpenFlow flow table [ONF2015]

Match Fields	Priority	Counters	Instructions	Timeouts	Cookie	Flags

Match fields is used to match against packets. They consist of the ingress port and packet headers. They can also contain metadata specified by a previous table. Priority is used for matching precedence of the flow entry. Counters' values are updated when encountering matching packets. Instructions are used to modify the action set or pipeline processing. Timeouts are defined as maximum amount of time before flow is expired by the switch. Cookies are data values chosen by the controller. They are used to filter flow statistics, flow modification and flow deletion by the controller. Flags change method of the flow entry management.

The secure channel connects the switch to the controller. OpenFlow protocol usually implemented on top of Secure Sockets Layer (SSL) or Transport Layer Security (TLS) to provide a secure OpenFlow channel. Three types of messages is supported.

- Controller-to-Device
- Asynchronous
- Symmetric

2.2. Software Defined Mobile Networking

The increasing number of smart phones and tablet computers and growing popularity of mobile applications significiantly enhanced the traffic diversity and volume. There is the strong need to manage the traffic carried by networks. SDN provides new opportunities for traffic, resource and mobility management. In [Dixon2014] detailed information has been provided about SDN, its architecture and possible applications. Authors explained SDN, gave example scenarios which SDN can be used. And they gave information about IBM's SDN approach. But there is no information regarding to mobile networks. SDN can reduce network complexity, hence it is suitable for sophisticated environments such as a mobile networks [Hyojoon2013] [Sezer2013]. In [Haw2014] and [Costa2014], SDN based LTE frameworks are examined. The aim of [Haw2014] is to provide efficient content delivery services in the mobile environment and to support easy network management. In [Costa2014], transport is simplified with SDN switches and the control plane is simplified by merging LTE network elements such as Mobility Management Entity (MME), Serving Gateway (S-GW) and PDN Gateway (P-GW) into a single network component. In [Jin2013] a new architecture called as SoftCell has been presented for the cellular core network based on inexpensive access switches, middleboxes and a centralized controller composing the data path for each user flow through a set of highly distributed middlebox functions. The architecture is shown in Figure 2.4.

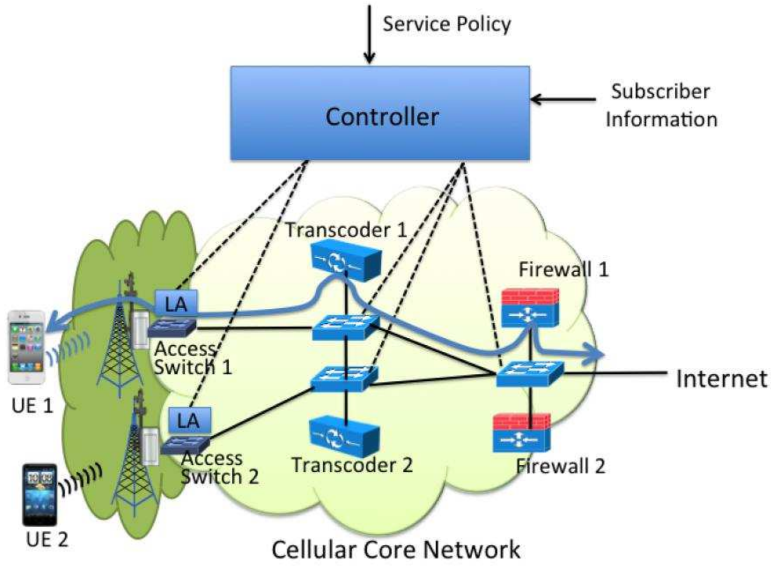

Figure 2.4. SoftCell architecture [Jin2013]

It enables operators to realize high-level service policies that direct traffic through sequences of middleboxes based on subscriber attributes and applications. SoftCell interconnects unmodified users via base stations and the Internet. It does not require specialized network elements such as S-GWs and P-GWs or point-to-point tunneling used in today's LTE networks. It uses commodity switches and middleboxes to build flexible and cost-effective cellular core networks.

SoftRAN uses SDN principles to redesign the radio access network [Aditya2013]. It is therefore complementary to SoftCell which focuses at redesigning the core network instead. In SoftRAN, all LTE networks are controlled in a centralized way. All the base stations are abstracted as a virtual element and managed by the logically central controller as shown in Figure 2.5. The controller maintains the global states of the network and makes logical decisions. There are defined APIs for the control plane to communicate with radio elements to update the global view of the network and configure every base station.

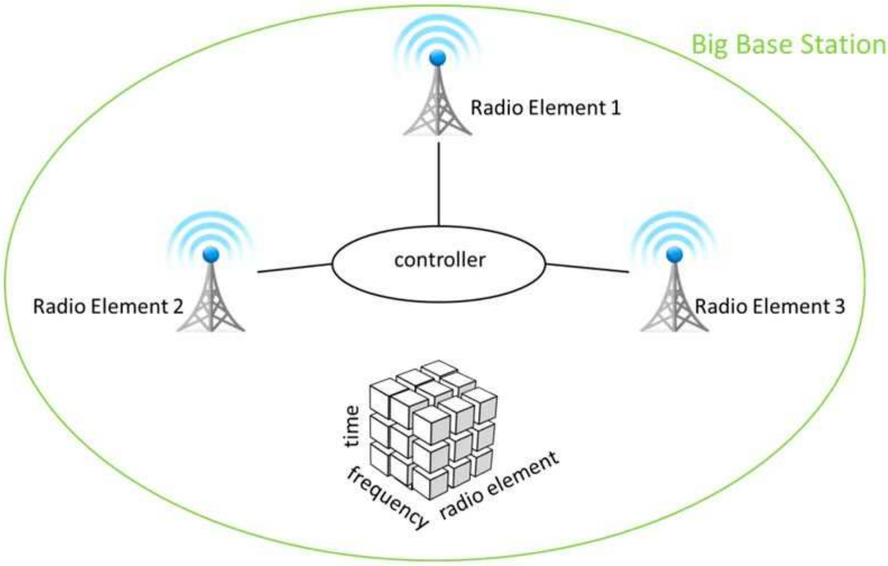

Figure 2.5. SoftRAN big base station abstraction [Aditya2013]

In SOFTRAN architecture as shown in Figure 2.6, the states of base stations are collected periodically and the global view is updated in the form of a database. The information restored in the database is utilized by the controller modules for radio resource management. The SoftRAN has two main principles for separating the control plane.

- The control decisions affected by neighbouring radio elements are made at the centralized controller, e.g. handovers, transmit powers setting.
- Decisions depending on rapidly varying parameters are made locally by the base station preferably, e.g. resource block allocation.

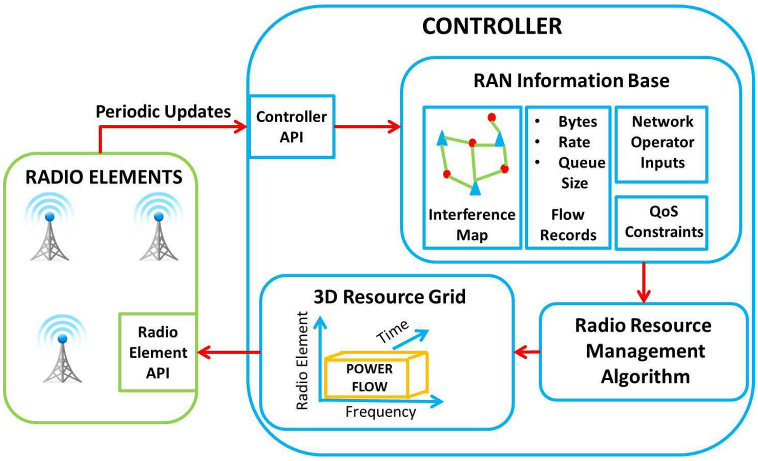

Figure 2.6. SoftRAN architecture[Aditya2013]

In [Bernardos2014] SDN-like approach has been presented for the wireless mobile networks. They stated that most of the key use cases used to present the benefits of the SDN had been limited to wired environments. Their network shown in the Figure 2.7.

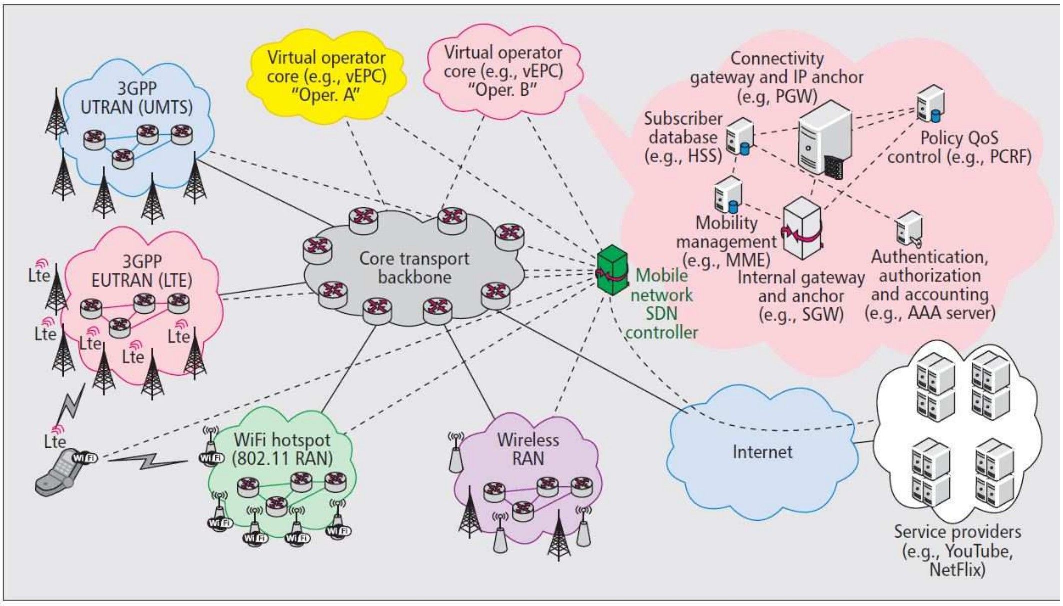

Figure 2.7. SDN-based mobile network architecture [Bernardos2014]

A mobile network consists of multiple heterogeneous radio access networks connected to a common core network. Most popular examples of RANs are: the UTRAN (for UMTS), E-UTRAN (for LTE), and a WiFi hotspot. In their architecture, RANs are supports programmability and multiple functionality levels to provide scalability. Programmable level 2 switches and level 3 routers are formed the core transport. This allows setup of unicast and multicast forwarding at the flow level. Key interfaces in their network shown in the Figure 2.8. Virtual operators connected to SDN controller with northbound interface. They share same physical network resources. This allows operators to dynamically change the share of resources. Northbound interface has authorization to influence the network behavior to the service and application providers. With use of SDN approach this interface grants access with different granularities and permissions and application providers have strong power on handling the traffic. The connection between SDN controller and the core transport backbone provided by southbound interface and it is used for implement different policies according to virtual operators. The behaviour of policies can change according to users attached to the network, and the network conditions. Another key connection is between SDN controller and RAN via southbound interface. This interface provides virtualization of the access network in other words sharing the same physical resources through different operators. The last connection authors focused is between SDN controller and mobile node via southbound interface. This interface enhance the programmability capabilities of network which can used for improve the mobility experience.

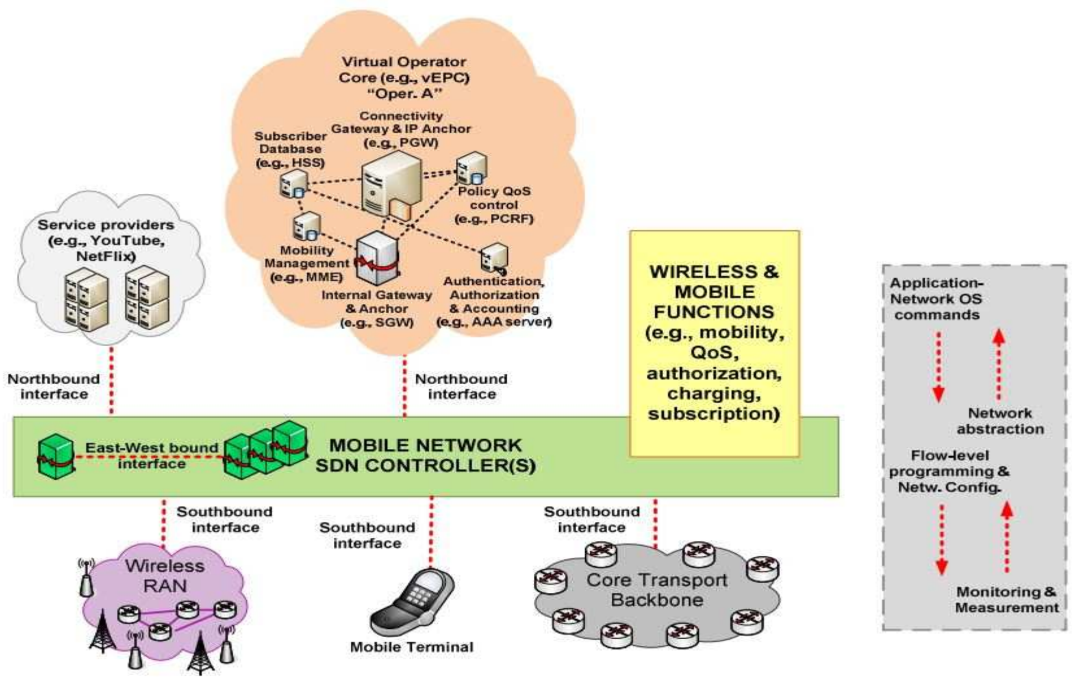

Figure 2.8. SDN-based mobile network interface architecture [Bernardos2014]

In [Zaidi2015], an integrated deployment solution for energy-efficient cellular networks combining software-defined radio access networks (SD-RANs) and beyond cellular green generation (BCG2) architecture have been studied. The integrated architecture is shown in the Figure 2.9.

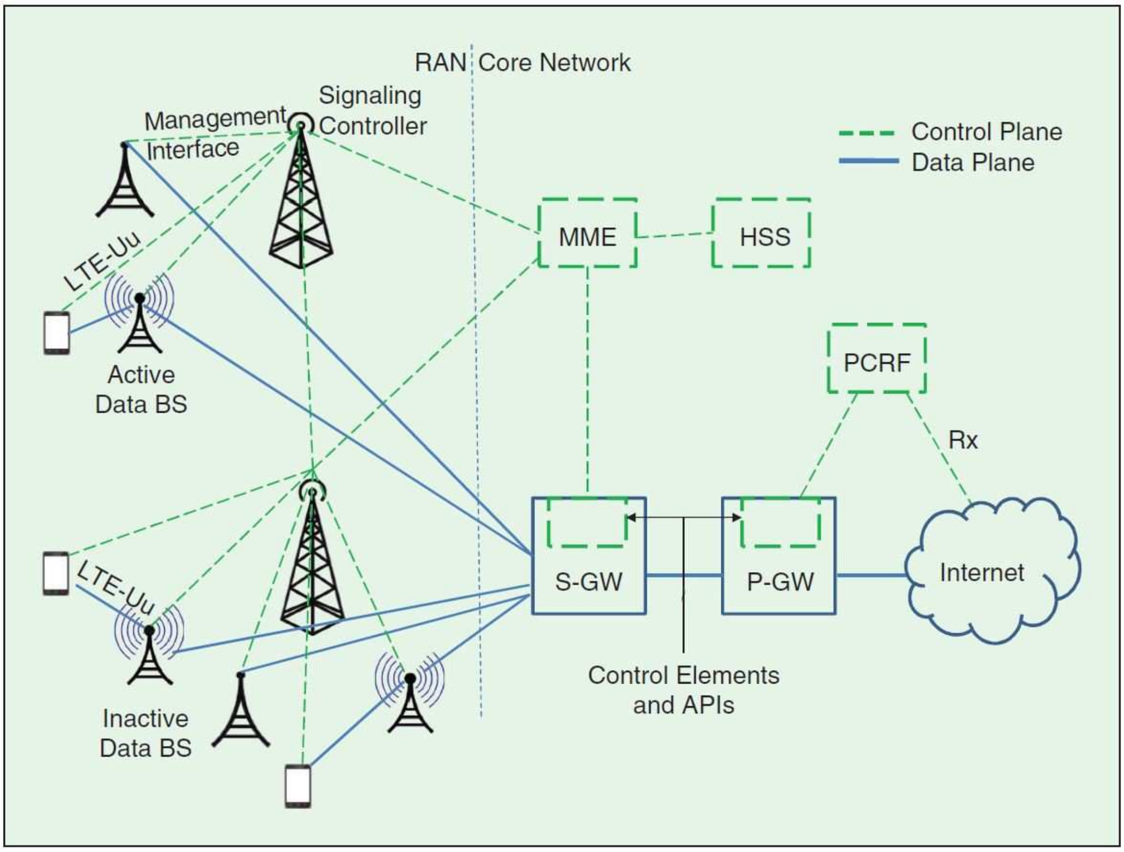

Figure 2.9. The integrated architecture [Zaidi2015]

SD-RAN provides centralized control plane and data-forwarding plane for flexible control. BCG2 architecture decouples the data transmissions and control signaling paradigm. The signaling nodes are in charge of delivering low-rate services and the coverage. The data nodes which provides high rates for small ranges can be on and off regarding to traffic. In LTE architecture base station, S-GW and the P-GW provides some control plane functions along with data forwarding. They stated SDN-based core network should contain some functional capabilities currently residing in those. Control elements which are used such as routing modification contains required APIs for control nodes and control logic for data forwarding. In a SDN domain, they will be designed as software APIs. The big towers in Figure 2.9 includes a signaling controller in their new radio access system. The signaling controller responsible for functions of a signaling node in the BCG2 architecture and functions of the centralized controller for SDN-based RAN. The eNodeB functionalities are splitted between the signaling controller and data BSs. If there is no demand data BSs are put in sleep mode. In their architecture only the signaling controller is need to have an interface with the MME of the evolved packet core (EPC). They defined the combined specifications for the signaling controller as follows.

- SDN Functions
  - It should host control logic (interference management, resource management, coordinated handover etc.) for RAN.
  - It should be programmable on general-purpose processors.
  - It should provide APIs to BSs and also to core network.
- BCG2 Functions
  - It should provide signaling for system access and paging.
  - Need to have interfaces to UE, data BSs, and core network
  - It should perform resource allocation
  - It should consume less power

They summarized advantages of the proposed architecture as: energy efficient, supports virtualization and RAN sharing and enabling technologies.

In [Wang2015], the main challanges of LTE network architecture are determined as limited system capacity, high signaling overhead, inefficient data forwarding, high cost, poor scalability and consuming less power.

SoftNet presented which is software defined decentralized mobile network architecture shown in the Figure 2.10.

Main components of the SoftNet are unified radio access network and an SDN based core network. Unified RAN is connected with access servers that are at the edge of an SDN core network. Unified RAN consists of Multi-RATs coordination function, decentralized control function and gateway control function. Multi-RATs coordination function routes the user traffic to chosen RATs according to network conditions. Decentralized control function handles mobility management. And gateway function provide access for mobile terminals to the Internet. The control plane network functions supported in the SDN based core network responsible for centralized network control like admission control, QoS control and network management. SDN controller and VNF form the network controller. They defined key working mechanisms of Softnet in the following :

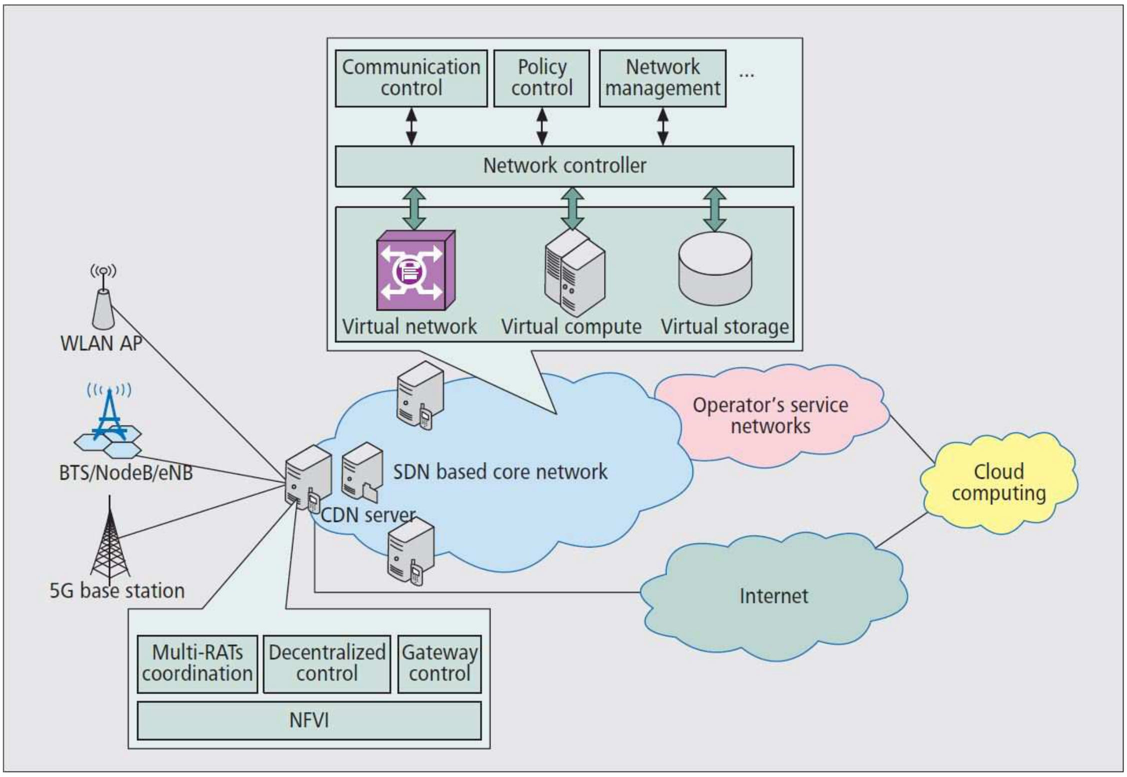

Figure 2.10. SoftNet architecture [Wang2015]

- Dynamically Defined Architecture
- Enhancing System Capacity
- Reducing Signaling Overhead
- Improving Efficiency of Data Forwarding
- Ensuring Flexibility and Scalability with Lower Cost
- RAT Independent NAS Protocol

SDN has also been integrated to the very dense heterogeneous wireless networks. These DenseNets have limitations due to constraints such as radio access network bottlenecks, control overhead, and high operational costs [Ahmad2013] [Draxler2014]. Local controllers can be used to take fast and fine-grained decisions, while regional (or global) controllers can have a broader, coarser-grained scope, i.e., that take slower but more global decisions. In such a way, designing a single integrated architecture that encompasses LTE (macro/pico/femto) and WiFi cells, while challenging, seems feasible. OpenRAN an architecture for software-defined RAN via virtualization has been presented in [Yang2013] for heterogeneous wireless networks. In [Savarase2013], a heterogeneous scenario, where Machine to Machine (M2M) and LTE interoperation has been examined. SDN has been used to make LTE cellular network much simpler to manage and reconfigure, by introducing new features, and interoperating with other technologies, in particular with M2M communications equipment. Indeed, SDN will be a key issue also in future fifth-generation cellular networks [Andrews2014].

2.3. Routing

Traffic management is an important mechanism to optimize the performance of the network by dynamically analyzing, predicting and regulating the behavior of the data to achieve routing and power saving. SDN provides great incentive for novel traffic management techniques that exploit the global network view, status, and flow patterns/characteristics. One of the goal of traffic management is to decide how to route traffic in a network in order to balance several objectives. The joint routing an resource allocation optimization problem is finding the best path by minimizing or maximizing the cost function according to given constraints.

Joint routing and resource allocation can be designed for different cost functions as in the following:

- Maximize the rate
- Maximize the fairness
- Minimizing the energy
- Maximum link utilization
- Minimize the delay

In [Feng2014], a fair model has been designed by considering the network resources based on bandwidth and flow table while minimizing the delay for multiple control applications in SDN. By definition A is the control application set, L is the link set, S is the OpenFlow switch set, P is the path set and ω_a is the price of bandwidth. With given set of parameters, optimization problem defined as:

$$\max \sum_{a:a\epsilon A} \ln \omega_a y_a(t), \forall a \in A \tag{2.1}$$

subject to

$$\sum_{p:p\epsilon P(a)} x_{ap}(t) = y_a(t), \forall a \in A \tag{2.2}$$

$$\sum_{p:p\epsilon P(u,t)} x_{ap}(t) \leq C_{u,t}, \forall (u,t) \in L \tag{2.3}$$

$$x_{ap}(t) \geq 0, y_a(t) \geq 0, \forall a \in A, p \in P \tag{2.4}$$

where

$$y_a(t) = \sum_{p\epsilon P(a)} x_{ap}(t) \tag{2.5}$$

where $y_a(t)$ is sum of flows over the link which is given in Eq.(2.5). $x_{ap}(t)$ in Eq.(2.2) is defined as individual flow rates and P(a) denotes the path sets of a giving application. P(i,j) in Eq.(2.3) denotes the path sets of a giving link and $C_{u,t}$ bandwidth of a link (u,t). Eq.(2.3) ensures the sum of flows over the link between (u,t) cannot exceed the link capacity. Since the objective function Eq.(2.1) is strictly convex function of $y_a(t)$, there is a unique optimum solution.

The distributed solution associated optimization of flow-based end-to-end Quality-of-Services (QoS) has been presented in [Egilmez2014]. The aim is minimizing the cost function subject to delay variation. P is the set of all paths. The pair (u,t) defined as the link from source node u to node t. For any path, $p \in P$, It is defined cost $f_C(p)$ and (worst case) delay variation $f_D(p)$ as,

$$f_C(p) = \sum_{(u,t)\in P} c_{ut}, \quad f_D(p) = \sum_{(u,t)\in P} d_{ut}, \tag{2.6}$$

where c_{ut} and d_{ut}, are cost and delay variation coefficients respectively for the link (u,t).

$$p^* = arg_p min\{f_C(p) | p \in P, \quad f_D(p) \leq D_{max}\} \tag{2.7}$$

This equation states that the aim is finding a path such that minimizes the cost function $f_C(r)$ subject to the delay variation $f_D(r)$ to be less than or equal to a specified value D_{max}.

A low-complexity hybrid routing scheme to achieve near-optimal load balancing for multiple traffic matrices has been given in [Zhang2014]. The aim is minimizing the maximum link utilization

$$\max_{(u,t)\in L, t=1,2...,N} (I_{ut}^t / C_{ut}) \tag{2.8}$$

where l_{ut} is the traffic load on link (u, t) and C_{ut} is its link capacity.

In [Oda2014], an energy efficient routing scheme with traffic aggregation for each flow to decrease the number of active network devices while maintaining acceptable performance has been presented. The optimization problem is defined as maximize the number of active links from several shortest path for minimization of active links in the network. In addition to hop count, active links are also used as a routing metric in this method. In their algorithm, first step is obtain shortest paths between source and destination. Then choose routes which has capacity C_p larger than demanded capacity of flow C_f as candidates for R1. If R1 set isn't empty set, then the path that maximizes the number of active links $N_{act_{link}}$ is selected from R1. If R1 set is an empty set, then the path that minimizes the maximum link utilization $max_{linkuse}$ on the path is selected. The algorithm has been shown in the Figure 2.11:

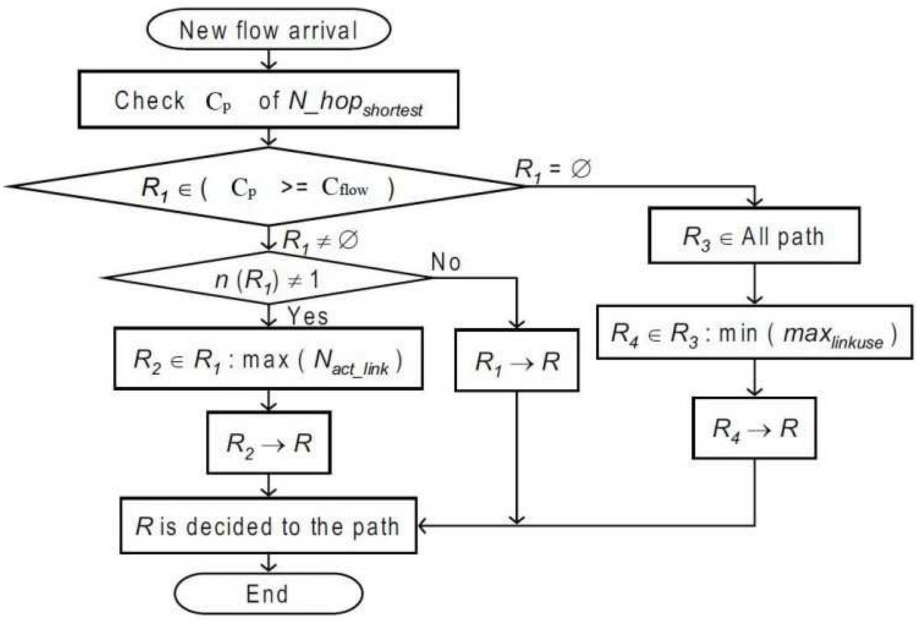

Figure 2.11. RMAD algorithm [Oda2014]

For SDN, the main resources are bandwith and flow capacity. The bandwidth refers to how much a network transmits data packets at a period of time. This kind of network ability is explicitly expressed by forwarding one which is determined by link bandwidth. More bandwidth means higher transmission rate and thus lower transmission delay.

In order to measure performance of the algorithm , the following Quality of Service (QoS) parameters can be considered.

- Response Time: Response time is the time difference between sending a request and receiving the first response by the user.
- Delay: Delay is the time difference between sending first bit of a data stream and its reception by the receiver.
- Jitter: Jitter is the deviation in the delay of received packets caused by transmission equipment.
- Data Rate: The data rate is the amount of digital data transmitted between one device to another.
- Packet Loss Rate: The packet loss rate is the number of loss packets during transmission.

There are several traffic management strategies examined for SDNs. [Agarwal2013] has considered the traffic engineering problem that is motivated by scenarios where SDNs are incrementally deployed in an existing network. In such a network, not all the traffic is controlled by a single SDN controller. There may be multiple controllers for different parts of the network and also some parts of the network may use existing network routing such as Open Shortest Path First (OSPF) which is most widely used path selection protocol that assigns weights to links and computes the shortest path across the network. They tried to answer the question if it is still possible to do effective traffic engineering when all the traffic in the network cannot be controlled centrally by a single SDN controller. They formulate the SDN controller's optimization problem for traffic engineering with partial deployment and develop fast Fully Polynomial Time Approximation Schemes (FPTAS) for solving these problems. The reason for solving the problem as an FPTAS instead of a standard linear programming problem is that the FPTAS is very simple to implement and runs significantly faster than a general linear programming solver especially on medium and large sized problems. [Arslan2013] presents a novel SDN controller that classifies the network traffic types according to the heterogeneous Quality of Service requirements that the network data is separated into the Constant Bit Rate (CBR) based realtime traffic and File Transfer Protocol (FTP) based non-real time traffic. Some crucial traffic flow parameters such as packet delivery ratio, routing overhead and delay are also considered in this classification.

In [Liao2013] propose an efficient algorithm has been presented for joint backhaul traffic engineering and physical layer interference management for a large-scale software defined radio access networks. The algorithm is a combination of two algorithms, the max-min weighted-MMSE (WMMSE) algorithm for minimum rate maximization and the Alternating Direction Method of Multipliers (ADMM) algorithm that is used to distributively solve the multi-commodity routing problem. The resulting algorithm is significantly more efficient than the subgradient-based methods. The proposed algorithm is scalable to large networks since all its steps can be computed in closed-form independently and in parallel across all nodes of the network. [Chanda2013] presents a content-centric network architecture which is based on SDN principles and implements metadata driven services, such as metadata driven traffic engineering and firewalling, with the ability to parse content metadata at the network layer. Entropy theory is exploited to analyze the feasibility of predicting traffic dynamics theoretically for software defined cellular radio access network in [Li2014]. The authors highlight in the paper that "entropy" offers a precise definition of the informational content of predictions by the corresponding probability distribution functions, and it possesses good generality because it makes minimal assumption on the model of the studied scenario. Thus, it is suitable to use the entropy approach for measuring the traffic predictability based on certain prior information from history or from neighboring cells. In [Zhang2012], a weighted multipath algorithm has been presented in which each router splits the traffic regarding to delay-sense weighted Equal-Cost Multipath split rule, so that overall network end-to-end delay is optimized. In [Li2014], the flows are scheduled separately in time domain by using exclusive routing (EXR) which guarantees that one link can occupied at most one flow at a time. In addition to that, EXR provides flexibility to define priorities to flows. The three-tier virtual machine placement algorithm which combines energy efficiency and QoS awareness has been suggested in [Shao-Wang2014].

In addition to them, the power saving strategies has been considered to perform energy efficient traffic management for SDN. In [Nguyen2013], an integrated control scheme which combines smart sleeping and power scaling algorithms has been given by testing in data center with Fat-Tree topology under low and high traffic cases. In [Giroire2014], an optimization method for rule placement considering link capacities and space constraints on routers has been suggested to reduce energy consumption for a backbone network. In [RuiWang2014-1], how to optimize power management globally at network level has been considered by re-routing traffic through different paths to adjust the load of links when the network is relatively idle. In [Markiewicz2014], the energy saving mechanism has been presented by turning on a minimal amount of network devices to carry the traffic, instead of powering on all switches at all time by formulating as an MILP problem and presenting an heuristic algorithm with four different strategies. In [Celenlioglu2014], a pre-established multi-path model has been described for energy-aware routing. In [Rivera2015], a energy efficient controller association algorithm has been given by switching off the maximum number of links by taking into account delay, link and controller load constraints.

Besides the energy efficient routing, it is possible to reduce power consumption by reducing Ternary Content Addressable Memory (TCAM) size. In [Mogul2010], a modification to OpenFlow has been suggested to reduce the number of switch-controller interactions and the number of TCAM entries. Another TCAM optimization approach has been given in [Meiners2007] to solve a multidimensional rule list optimization problem by decomposing into multiple one dimensional problems and to construct a new classifier which is semantically equal to original classifier, but requires less TCAM entries. Another approach for TCAM optimization called bit weaving has been presented in [Meiners2012]. The idea is to merge adjacent TCAM entries which has the same decision and a hamming distance of one into one entry. Compact TCAM approach which reduces the size of flow entries without changing framework of SDN has been examined in [Kannan2013]. Using this compact TCAM it becomes possible to shorten the search line size which reduce power consumption.

2.4. Cloud-Radio Access Networks

A radio access network (RAN) is a mobile communication system which provides connection between user equipments such as mobile phones, tablets and computers to the core network. Radio access network evolution from 2G to 4G is GRAN, which stands for GSM radio access network for 2G. GERAN, is the same as GRAN except addition of EDGE packet radio services. UTRAN (Universal Terrestrial Radio Access) is UMTS radio access network for 3G and E-UTRAN (Evolved Universal Terrestrial Radio Access), The Long Term Evolution (LTE) high speed and low latency radio access network. In this thesis, LTE network has been studied. The evolved UTRAN consists of eNB, providing the evolved UTRAN user plane and control plane protocol terminations towards the user equipment. The eNBs are interconnected with each other by means of the X2 interfaces. It is assumed that there always exist an X2 interface between the eNBs that need to communicate with each other. The eNBs are also connected by means of the S1 interface to the EPC (Evolved Packet Core)[3GPP]. The architecture shown in the Figure 2.12.

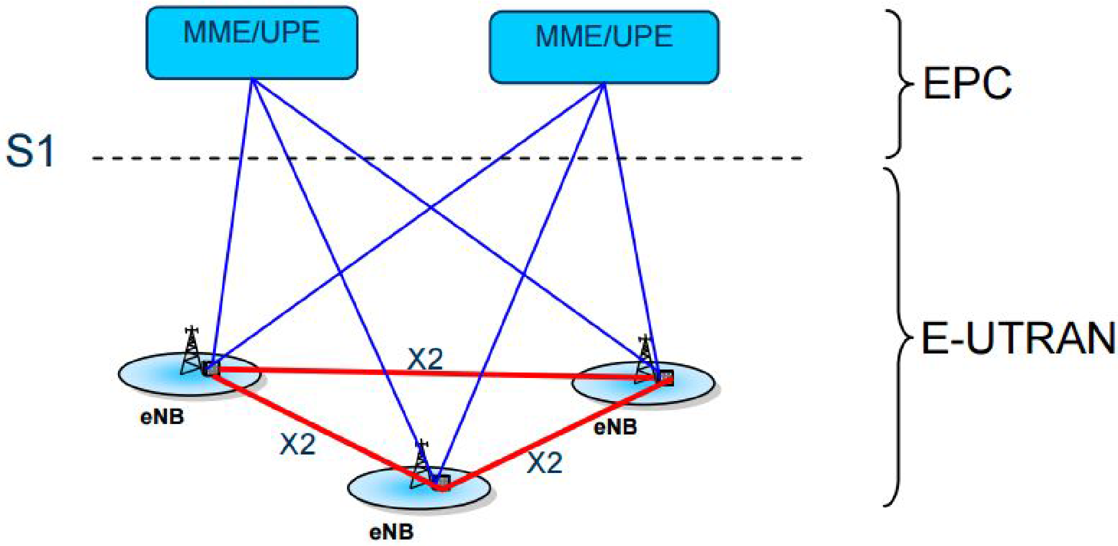

Figure 2.12. E-UTRAN architecture [3GPP]

Global mobile data traffic grew by 74 percent in 2015 and reached 3.7 exabytes per month at the end of 2015. It is awaited to be approximately 16 Exabytes per month by 2018. More than half a billion (563 million) mobile devices and connections were added in 2015. Global mobile devices and connections in 2015 grew to 7.9 billion, up from 7.3 billion in 2014 [Cisco2016]. To be able to meet this demand mobile operators are seeking new solutions for increasing network capacity and coverage. The new Radio Access Networks must provide high number of device connection, Quality of Service for different type of applications, must handle huge data traffic and it should have not only low cost but also high robustness. C-RAN is a new, centralized, cloud computing-based architecture for radio access networks which supports todays and future wireless communication standards. It is also known as Centralized RAN. It was first introduced by China Mobile Research Institute in April 2010 in Beijing, China [CMRI]. C-RAN has the potential to improve both spectral and energy efficiency by using centralized cloud principle of sharing storage and computing resources via virtualization. Conventional base stations has divided into two parts. Radio function unit, remote radio heads (RRHs), and digital function unit, baseband units (BBUs). This baseband units piled up and forms centralized BBU pool. Remote radio head(RRH) is a remote radio transceiver which connects to an operator radio control panel by using electrical or wireless interface. RRHs have great importanance since it makes multiple operation easier, increasing a base station's efficiency and facilitate easier physical location for gap coverage problems. The BBU pool communicates with RRHs via common public radio interface (CPRI) protocol.

In [Peng2016], authors stated key techniques in C-RANs which are as the fronthaul compression, large-scale collaborative processing and channel estimation in the physical layer. In the upper layer, the radio resource allocation and optimization are considered. General C-RAN system shown in the Figure 2.13. They outlined and surveyed the state-of-the-art system architecture, key technologies, and open issues in C-RANs.

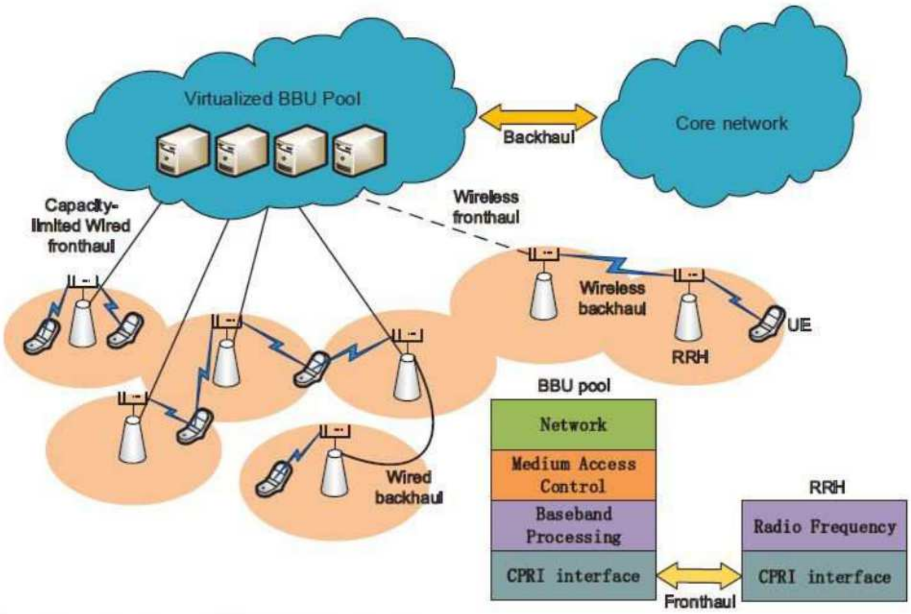

Figure 2.13. A general C-RAN system [Peng2016]

A C-RAN architecture uses combination of virtualization, centralization and coordination techniques. The use of virtualized BBU pool allows to baseband processing to adapt non-uniform traffic and handle the resources more effectively. Since the required BBUs are less than traditional architecture in C-RAN, it has also the potential to decrease the cost of network operation in terms of power and energy consumption compared to the conventional RAN architecture.

There are various work about C-RAN for improvements in the RAN. In [Cheng2015], novel software defined C-RAN (SDC-RAN) architecture for Small Cell network which provides energy consumption savings and improves radio performance has been examined. In [Arslan2015], authors studied to improve RAN performance applying both SDN to CRAN principles and presented self-organizing networking solution. In [RuiWang2014-2], authors presented 5G mobile network based on C-RAN architecture. Their main focus was coexistence of multiple radio access technologies (multi-RATs). They presented some insights about C-RAN-supporting Multi-RATs, including joint resource allocation, mobility management, trafic steering and service mapping. In [Suryaprakash2015], cost effectiveness of Cloud-Based Radio Access Networks was studied. They developed a framework and compare the deployment cost of a cloud based network against that of a traditional LTE network. They showed capital expenditure reduced with %10 to %15 per kilometer. [Dahrouj2015] gave the challenges and recent developments in heterogeneous cloud radio access networks design.

In this thesis, we consider SDMN model which employs both C-RAN and SDN compared to the existing papers in the literature. We propose a routing algorithm based on power consumption by considering the number of active OpenFlow switches and ports for different throughput constraints for various network topologies and scenarios in night-time traffic. Moreover, we present a joint routing and resource allocation in case of coexistance SDN and C-RAN in terms of power consumption.

CHAPTER 3

ENERGY AWARE ROUTING AND TRAFFIC MANAGEMENT FOR SOFTWARE DEFINED NETWORKS

In this chapter, we propose an energy efficient routing and traffic management algorithm to minimize the cost based on energy consumption determined as the number of active OpenFlow switches in the network. This goal is not always achieved by just minimizing the number of hops, which sometimes forces to power on new switches. Therefore, we propose a low complexity algorithm that achieves an efficient routing in terms of energy saving while satisfying the throughput requirement of all flows. In Section 3.1, network model and optimization problem is explained. In Section 3.2, genetic algorithm is shown to find a solution. In the next section, low complexity approach was proposed. And the last section presents performance analysis of proposed algorithm.

We design an energy efficient routing algorithm which has almost the same complexity as the shortest path algorithm to become suitable for practical applications and to achieve a better energy saving performance. We evaluate the performance of proposed algorithms on energy consumption by considering different throughput requirements of flows in various network topologies with given link capacities.

3.1. Network Model

The SDN can be modeled again as a graph $G < \mathbb{V}, \mathbb{Z} >$ where $\mathbb{V}$ is the set of switches and $\mathbb{Z}$ is the set of possible links between the switches through available ports. $N_{u,t}$ links can be established between node u and node t proportional to the number of ports in the nodes. Each link $(u_y, t_y) \in \mathbb{Z}$ has a capacity $C_{(u_y,t_y)}$ where $y = 1, \ldots, N_{u,t}$. The capacity of each link is adjusted according to the number of available ports in the switches and the maximum available capacity, $C_{(u,t)}$. The model can be seen graphically in Figure 3.1. $\mathbb{F}$ is the set of K flows and each flow $f_k \in \mathbb{F}$ has several parameters, source, s_{f_k}, destination, d_{f_k} and throughput requirement, R_{f_k}.

The aim of our solution is to find the set of routes $\mathbf{p} = \{\mathrm{p}_{f_1}, \mathrm{p}_{f_2}, ..., \mathrm{p}_{f_K}\}$ where p_{f_k} is the set of routes composed of the active links through source to destination belonging to the flow f_k. While finding the routes $\mathbf{p}$ that satisfies throughput requirements of all

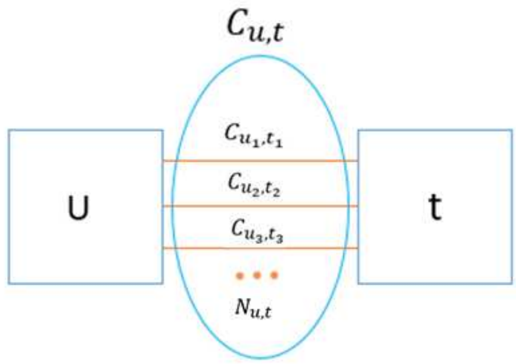

Figure 3.1. Network model

flows, we reduce the power consumption based on the number of active switches in the network. Let $x_v \in \{0, 1\}$ indicate whether the switch v is active or not. If the switch v is used through the links selected for the route $\mathbf{p}$, then its indicator, x_v, becomes 1.

The total number of active OpenFlow switches in the network is determined by

$$T(\mathbf{p}) = \sum_{v \in \mathbb{V}} x_v(\mathbf{p}) \tag{3.1}$$

In order to achieve energy awareness based on the number of active switches in the network, the optimization problem is defined as,

$$\min \quad T(\mathbf{p}) \tag{3.2}$$

subject to

$$C_{(u_y,t_y) \in \mathrm{p}_{f_k}} \geq R_{f_k} \quad \forall f_k \tag{3.3}$$

$$\sum_{y=1}^{N_{u,t}} C_{(u_y,t_y)} \leq C_{(u,t)} \quad \forall u, t \tag{3.4}$$

The first constraint states that the link capacity must be equal to or higher than throughput requirement of each assigned flow. The second constraint denotes that the total link capacity, $C_{(u,t)}$ between switch u and t must be equal to or higher than demanding rate of total established $N_{u,t}$ links.

Since we consider the nighttime traffic case in which the network load is low, the overall network capacity is higher than the rate requirements of all flows. Hence it is possible to shut down a certain number of OpenFlow switches.

3.2. Genetic Algorithm Solution

We first provide the optimal solution for $\mathbf{p}$, by minimizing $T(\mathbf{p})$ defined in Eq.(3.2) while taking into account the constraints given in Eq.(3.3) and Eq.(3.4) by performing GA which mimics the biological evolution as a search method [Goldberg1988]. GA uses techniques inspired by natural evolution like selection, crossover and mutation as shown in the Figure 3.2.

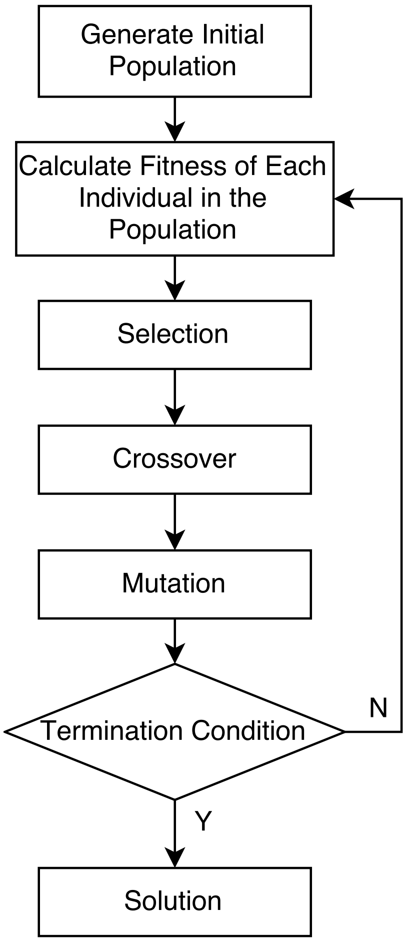

Figure 3.2. Genetic algorithm

We perform the optimal solution as described in the following:

- *Construct initial population:* We generate randomly M parents. Each parent includes K routes, each of which corresponds to a candidate route considering all flows. Besides, each parent has to satisfy the constraints given in Eq.(3.3) and Eq.(3.4).

- *Apply selection criterion:* We select the best $M/2$ parents in terms of the total number of demanding active switches as defined in Eq.(3.2).
- *Apply crossover:* We apply one point crossover which is chosen as a midpoint of the corresponding routes of each flow. A single crossover point on two parents is selected and then all values beyond that point are swapped between these two parent values. The resulting ones are added to the population as the new children.
- *Apply mutation:* We apply uniform mutation method by choosing the value randomly and replacing it by randomly generated value in the range of the route-specified upper and lower bounds.
- *Convergence:* The convergence criterion is selected as unchanged value on the number of total active switches for a certain number of iteration.

In order to prevent GAs converging to a local optima, adaptive techniques can be applied by adjusting crossover probability, P_c, mutation probability, P_m and population size, M. Besides that, depending on the initialization, GA may have a tendency to converge towards local optima than global optima of the problem. Therefore, we implement mutation phase, increase diversity in the population by different initial population and then provide the average results.

Since the complexity of GA increases depending on the number of flows, switches and links in the network, it can not be suitable for real applications.

3.3. Low Complexity Approach

In order to reduce the complexity of the GA, we propose an efficient routing algorithm with simplified complexity [Ozbek16] [Aydogmus16]. In order to implement the proposed flow based energy efficient routing in SDN, we present the architecture illustrated in Figure 3.3.

The efficient routing module (referred to as ”Proposed Routing” in the architecture) which is connected to a North Bound agent implementing the application programming interface (API), receives the initial topology and the capacity of the links from the SDN Controller. When a request for a path between two nodes is received, the controller relays this request to the application and the proposed algorithm that will be explained below finds the route and returns back to the controller to set up the route (via OpenFlow or any suitable south bound protocol). The proposed algorithm also communicates with

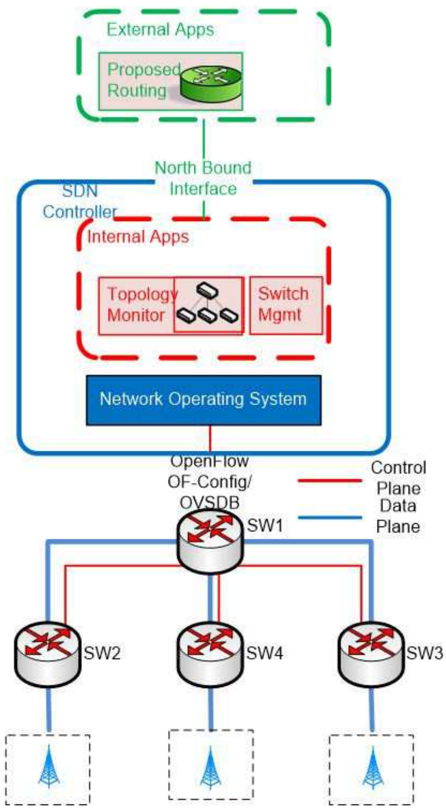

Figure 3.3. The proposed architecture

the switch management module (referred to as Switch Mgmt) to shut down and turn on switches to reduce power consumption.

We formulate the problem as an energy routing with bare-metal switches and we determine the gain on power saving based on the number of active switches which is directly corresponding to power consumption. Besides that the problem also has roots on the NFV side where enabling/disabling switches correspond to instantiating (or allocating servers) for virtual machines (therefore also leading to power consumption) which will act as virtual switches.

In the proposed low complexity approach, the flows are routed sequentially in a random manner instead of routing simultaneously as in the optimal solution. This method also allows for real-time operation where flow requests are arrived and then are released.

In the proposed algorithm, the optimization problem is defined for each flow $f_k \in \mathbb{F}$ by,

$$\min \quad T(\mathrm{p}_{f_k}) \tag{3.5}$$

subject to

$$C_{(u_k,t_k)\in \mathrm{p}_{f_k}} \geq R_{f_k} \tag{3.6}$$

where $T(\mathrm{p}_{f_k}) = \sum_{v\in\mathbb{V}} x_v(\mathrm{p}_{f_k})$.

After routing the flow f_k, the total available link capacity belonging to all links is updated by,

$$C_{(u,t)} = C_{(u,t)\in \mathrm{p}_{f_k}} - R_{f_k} \tag{3.7}$$

In order to solve this problem given in Eq.(3.5), we propose a low complexity routing algorithm. Figure 3.4 depicts the flow chart of the proposed approach.

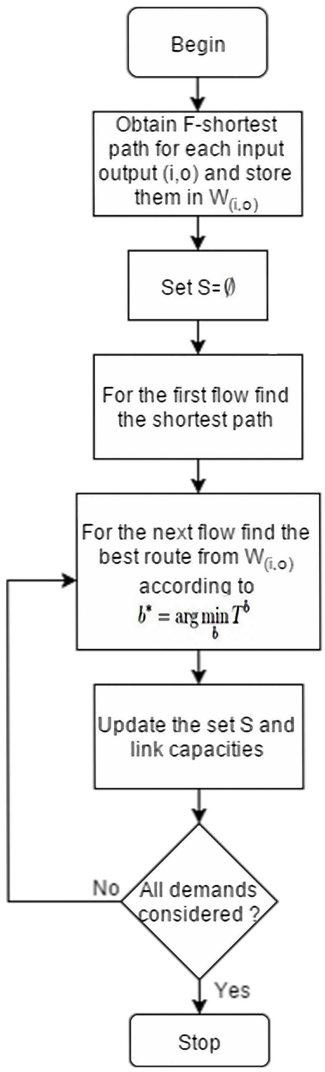

Figure 3.4. The flowchart of proposed routing algorithm

The proposed low complexity routing algorithm is explained in detail as follows:

- *Initialization*: The sets of input OpenFlow switches, $\mathbb{I}$, which are connected to SDN controller and the output OpenFlow switches, $\mathbb{O}$, which are connected to such as base stations for the wireless networks are determined in a given network topology. Then, F-shortest paths [Yen1971] for each input and output pair (i, o) are computed and stored in the set $W_{(i,o)}$ for $\forall i \in \mathbb{I}$ and $\forall o \in \mathbb{O}$. The set of all routes is initialized by $S = \emptyset$.

- *For the first flow*, f_1:

  - For the flow f_1 with source s_{f_1} and destination d_{f_1}, chose the optimum route p_{f_1} from the set $W_{(\mathrm{s}_{f_1},\mathrm{d}_{f_1})}$ according to Eq.(3.5) while satisfying Eq.(3.6). This optimal route corresponds to the shortest path solution for flow f_1 among all possible routes in the set $W_{(\mathrm{s}_{f_1},\mathrm{d}_{f_1})}$ since it is the first flow to be routed in the network.
  - Update $S = S \cup \mathrm{p}_{f_1}$.
  - Update the available link capacities in the network by using Eq.(3.7).

- For $k = 2, \cdots, K$

  - For flow f_k, find the $B \leq F$ routes having shortest paths as $\mathrm{W}^b_{(\mathrm{s}_{f_k},\mathrm{d}_{f_k})}$; $b = 1, \ldots, B$ while satisfying Eq.(3.6).
  - Select the best route for flow f_k in terms of total number of active switches while maximizing the switch usage:

    $$b^* = \arg\min_b T^b \tag{3.8}$$

    where $S^b = S \cup \mathrm{W}^b_{f_k}$ and $T^b = \sum_{v \in \mathbb{V}} x_v(S^b)$ with $b = 1, \ldots, B$.
  - Update $S = S \cup \mathrm{p}^{b^*}_{f_k}$ by adding the new switches that become active for flow f_k to the set S.
  - Update the available link capacities in the network by Eq.(3.7).

- End.

In any step, if there are more than one route that satisfies the constraints while giving the same number of switches on the cost function, we select the one which has the highest remaining available link capacity. The reason is that we will follow this route for the remaining flows in order to avoid to increase the number of active switches.

3.4. Performance Evaluation

In the thesis, we consider nighttime traffic in which the network load is low and consequently the number of flows is low. Then, we show that it is possible to shut down a certain number of OpenFlow switches by considering four different network topologies and various scenarios.

3.4.1. First Topology

We have 20 switches in the network topology as illustrated in Figure 3.5. The link capacities vary between 0.1 Gbps, 0.2 Gbps, 0.5 Gbps and 1 Gbps. The initial population size is selected as 1024 for genetic algorithm and 128 for low complexity approach. The probability of crossover and mutation are chosen respectively as $P_c = 0.9$ and $P_m = 0.1$.

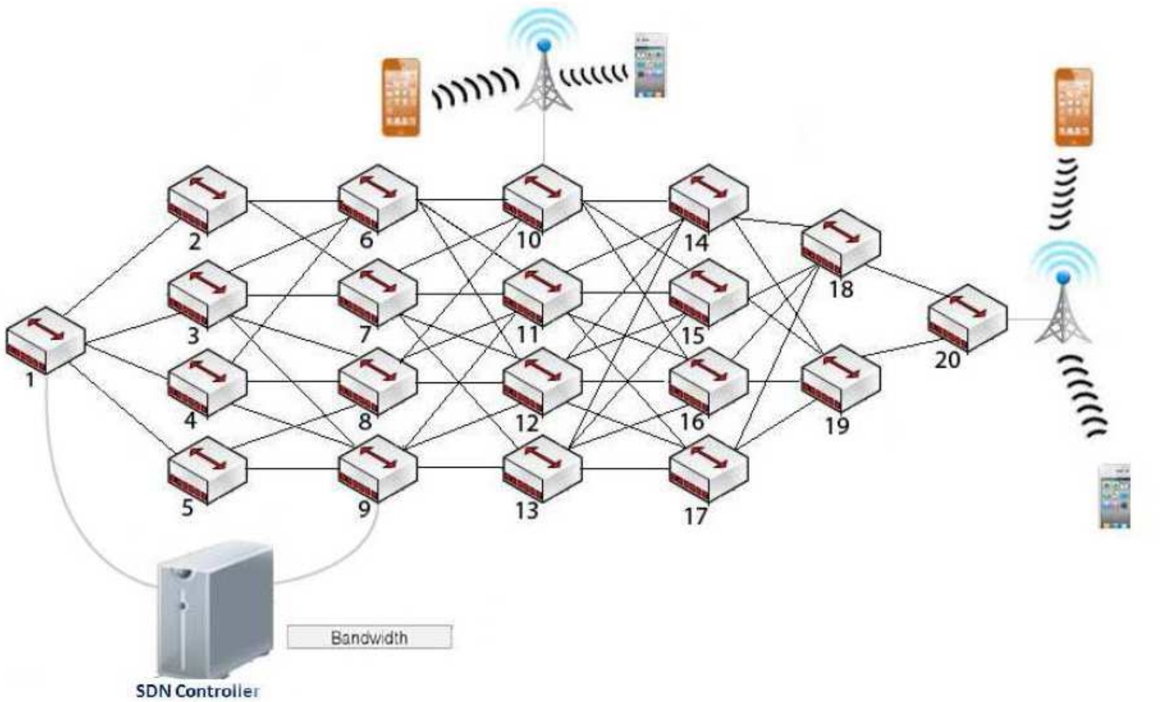

Figure 3.5. First network topology

By assuming that the network load is low (nighttime traffic), we obtain performance results according to the following scenarios:

- Scenario 1 (S1): All flows are routed from 1st node to 20th node with the same throughput requirements. Throughput requirements are equal to 100 Mbps.
- Scenario 2 (S2): Half of the flows are routed from 1st node to 20th node and the remaining ones are routed from 9th node to 20th node. The throughput requirements of all flows are the same. Throughput requirements are equal to 100 Mbps.
- Scenario 3 (S3): All flows are routed from 1st node to 20th node. Throughput requirements of 50$\%$ of the flows are 50 Mbps, 25$\%$ of the flows are 75 Mbps and 25$\%$ of the flows are 100 Mbps.
- Scenario 4 (S4): Half of the flows are routed from 1st node to 20th node and the remaining ones are from 9th node to 20th node. Throughput requirements of 50$\%$ of the flows are 50 Mbps, 25$\%$ of the flows are 75 Mbps and 25$\%$ of the flows are 100 Mbps.

First of all, we compare the complexity of genetic algorithm and the proposed approach for different number of flows in the network. The number of required iterations of genetic algorithm for Scenario 1 and Scenario 2 are illustrated in Figure 3.6. The complexity of the proposed approach is only $\%5$ of the genetic algorithm for $K = 6$ by taking into account the number of required iterations and the number of generated parents in the initial population. The number of required iterations for genetic algorithm for Scenario 1 and Scenario 2 with throughput requirement of 100 Mbps and convergence comparison for source node is 1, destination node is 20 and throughput requirement for 100 Mbps is given in Figure 3.6 and 3.7 respectively. The low complexity approach gives between $\%5 - 10$ less performance on power consumption depending on scenario and the number of flows while reducing the complexity significantly.

As a result of low complexity routing approach for Scenario 1 with 8 flows, the active switches in the network are shown in Figure 3.8. The other switches are shut down to reduce power consumption following the procedure explained in the proposed architecture.

The power saving performances of the low complexity approach for different traffic load for four scenarios in Figure 3.9 and Figure 3.10. The percentage of power reduction is changed between $\%50$ to $\%70$ by applying the proposed low complexity routing algorithm.

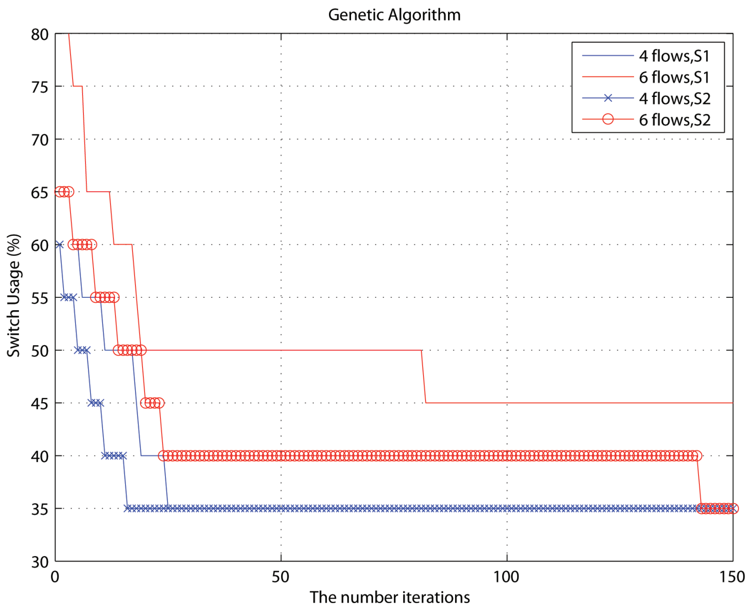

Figure 3.6. The number of required iterations for optimal solution for Scenario 1 and Scenario 2 with throughput requirement of 100 Mbps.

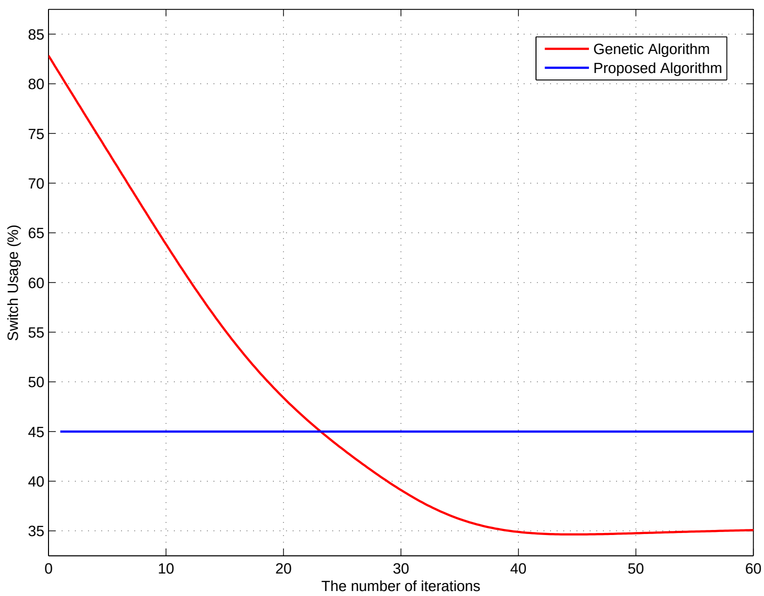

Figure 3.7. Convergence comparison for source node is 1, destination node is 20 and throughput requirement is 100 Mbps

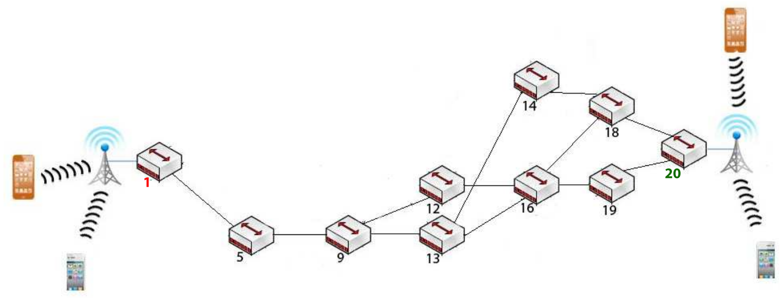

Figure 3.8. Demonstration of network after proposed routing for 8 flows, Scenario 1 with throughput requirement of 100 Mbps.

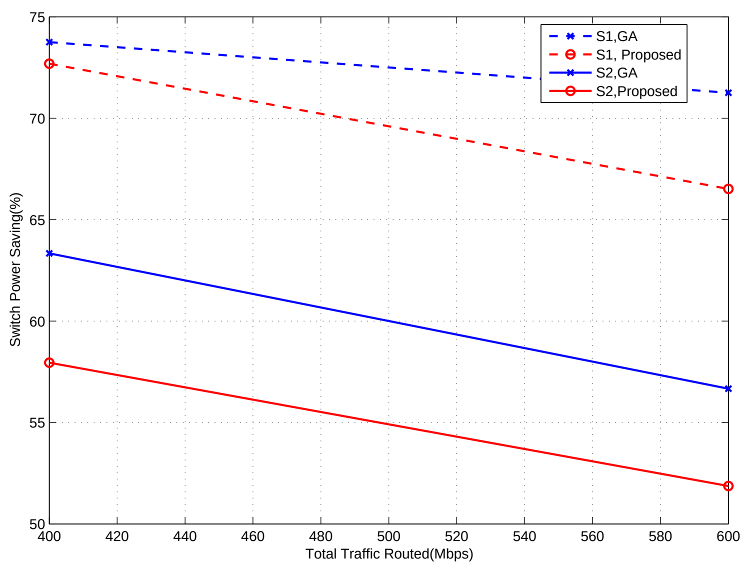

Figure 3.9. Performance results of low complexity approach for Scenario 1 and Scenario 2 .

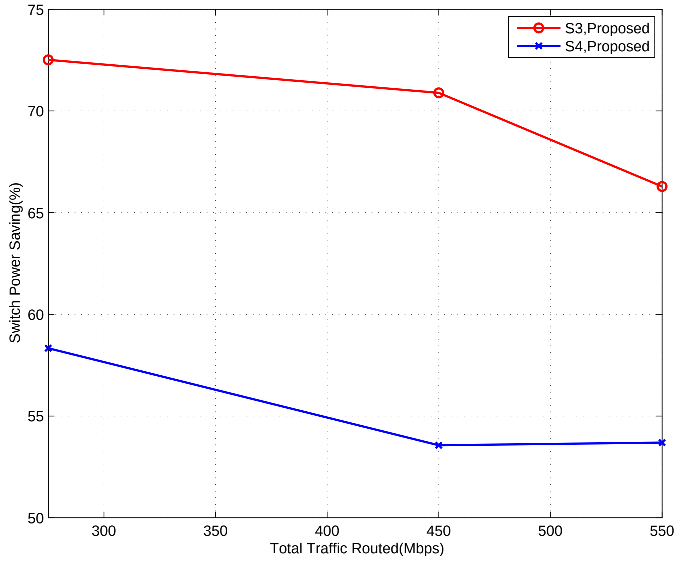

Figure 3.10. Performance results of low complexity approach for Scenario 3 and Scenario 4.

3.4.2. Second Topology

The second topology as shown in Figure 3.11, there are 20 OpenFlow switches with given total link capacities by varying between 0.1 Gbps, 0.2 Gbps, 0.5 Gbps and 1 Gbps. Then, the number of total ports per switch is determined for each OpenFlow switch depending on the capacity per port defined in each scenario.

For the second and third topology, we obtain the performance results according to the following scenarios:

- Scenario 1 (S1): All flows have the same destination and source nodes. The throughput requirements of all flows are the same with 100 Mbps. The capacity per port is equal to 100 Mbps.
- Scenario 2 (S2): Half of the flows have different source and destination nodes. The throughput requirements of all flows are the same with 100 Mbps. The capacity per port is equal to 100 Mbps.
- Scenario 3 (S3): All flows have the same destination and source nodes. The throughput requirements of all flows are the same with 200 Mbps. The capacity per port is

set 200 Mbps.

- Scenario 4 (S4): Half of the flows have different source and destination nodes. The throughput requirements of all flows are the same with 200 Mbps. The capacity per port is equal to 200 Mbps.

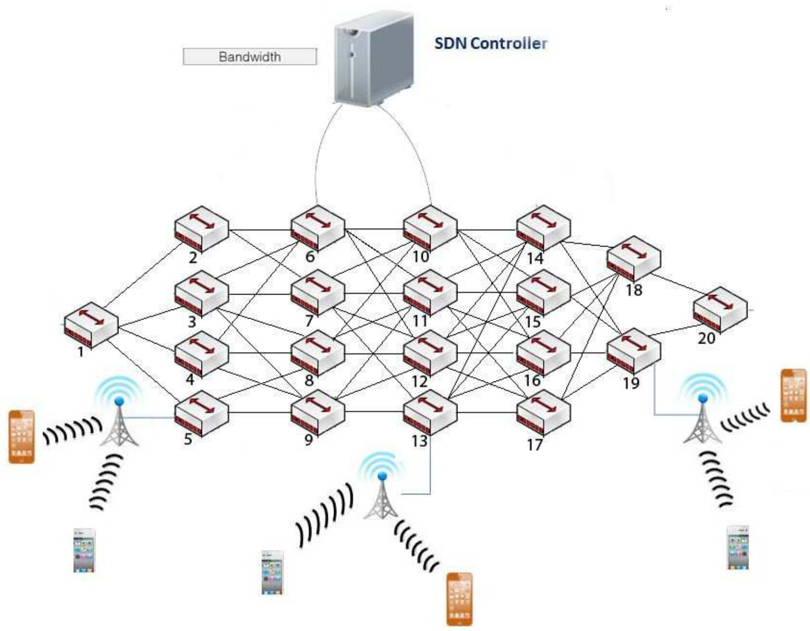

Figure 3.11. Second network topology

In Figure 3.12 and Figure 3.13, we demonstrate the network including only the active OpenFlow switches as a result of the proposed low complexity routing approach considering the throughput requirements of 100 Mbps for capacity per port of 100 Mbps and throughput requirements of 200 Mbps for capacity per port of 200 Mbps, respectively. In the Figure 3.12, there are 8 flows which are the same source and the destination as node 6 and node 19. For Figure 3.13, there are also 8 flows. The source and destination of half of flows are node 10 and node 5 and the source and destination nodes of remaining flows are node 6 and node 19. The other switches are shut down to reduce power consumption following the procedure explained in the proposed algorithm.

Firstly, we obtain the comparison results for the proposed and the genetic algorithm. In order to provide optimal solution using GA, the initial population size is selected as 1024 and the probability of crossover and mutation are chosen respectively as $P_c = 0.9$ and $P_m = 0.1$ respectively. The complexity comparison between GA and the proposed algorithm is determined in terms of required iterations. The number of iterations required

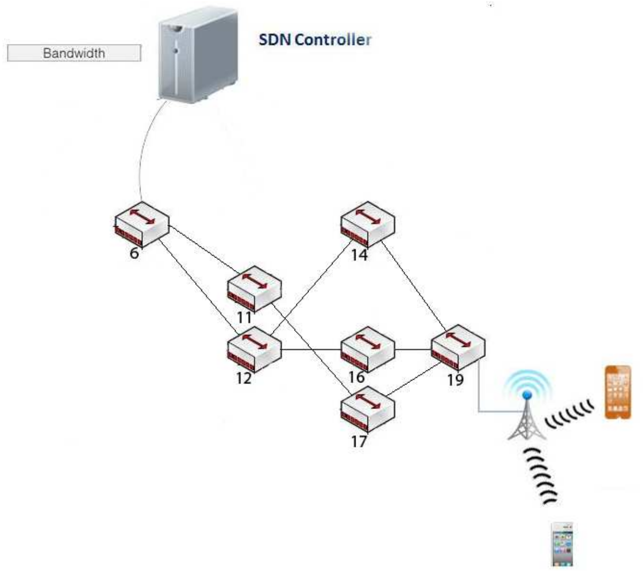

Figure 3.12. Demonstration of the second network with capacity per port of 100 Mbps after proposed routing for 8 flows with throughput requirements of 100 Mbps for the same source and destination nodes.

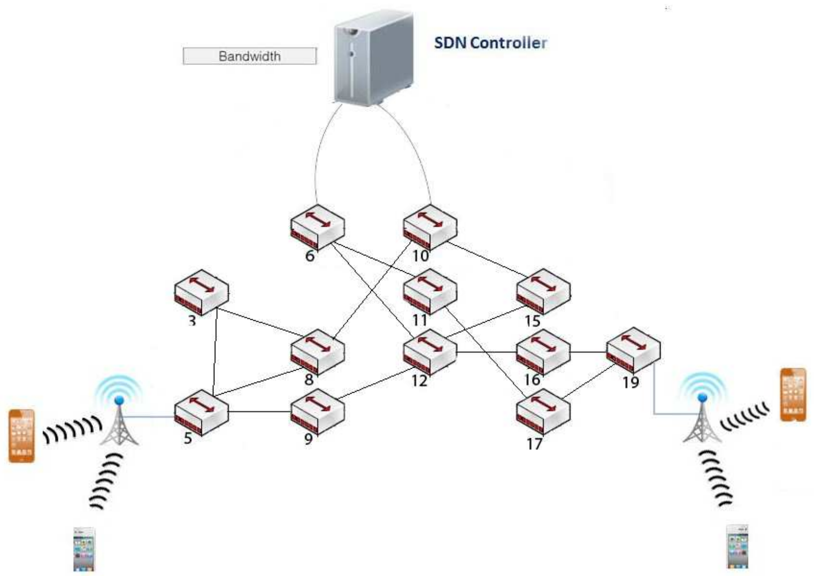

Figure 3.13. Demonstration of the second network with capacity per port of 200 Mbps after proposed routing for 8 flows with throughput requirements of 200 Mbps for the different source and destination nodes.

by GA is approximately 100 to reach convergence while the proposed algorithm is implemented in one iteration. In Figure 3.14, it is shown that the proposed approach gives approximately $\%5$ less performance on power consumption than the genetic algorithm while having only $\%1$ computational complexity of the genetic algorithm.

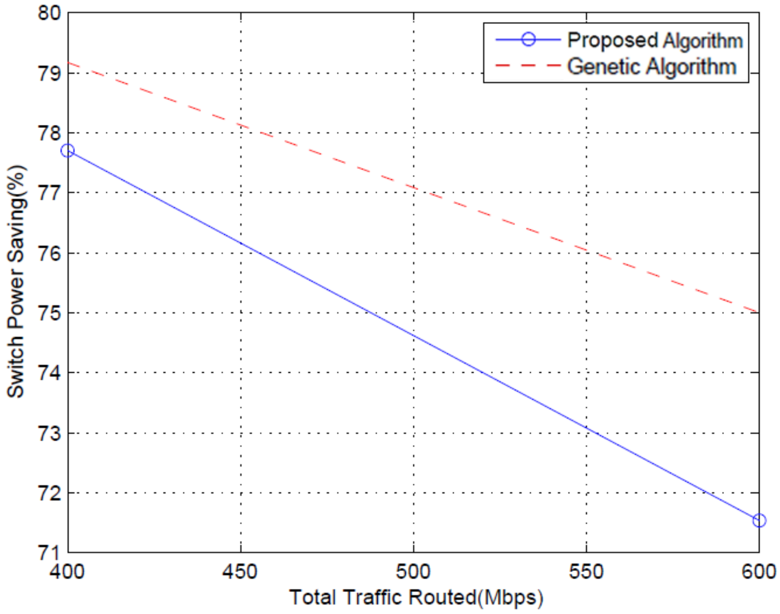

Figure 3.14. Performance comparison for optimal solution and proposed algorithm for Scenario 1 in the second network topology.

The power saving performances of the proposed low complexity approach for different traffic loads and four scenarios as illustrated in Figure 3.15 and Figure 3.16. The power saving ratio is determined as $(T_{ShortestPath} - T_{Proposed})/T_{ShortestPath}$ where $T_{ShortestPath}$ is the required number of switches for the shortest path algorithm and $T_{Proposed}$ is the required number of switches for the proposed algorithm. As a result of proposed routing algorithm, the achievable percentage of power saving that can reach up to $\%8$ depending on the traffic load compared to the shortest path algorithm in the second network topology.

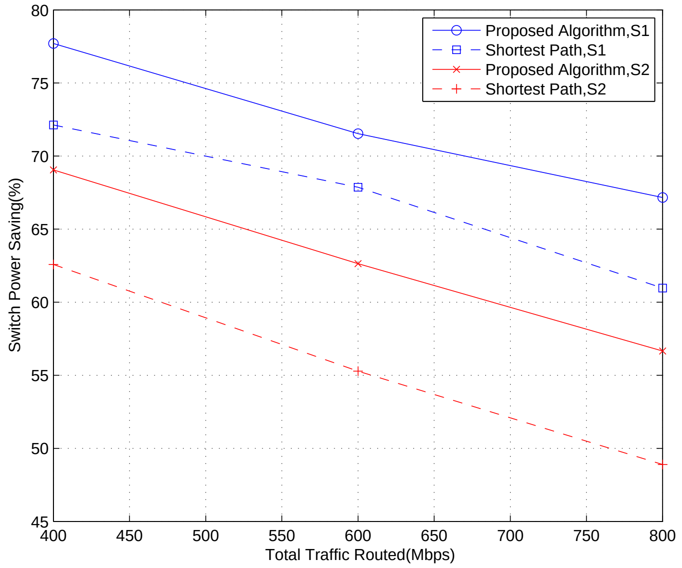

Figure 3.15. Performance results of the proposed algorithm for Scenario 1 and Scenario 2 in the second network topology.

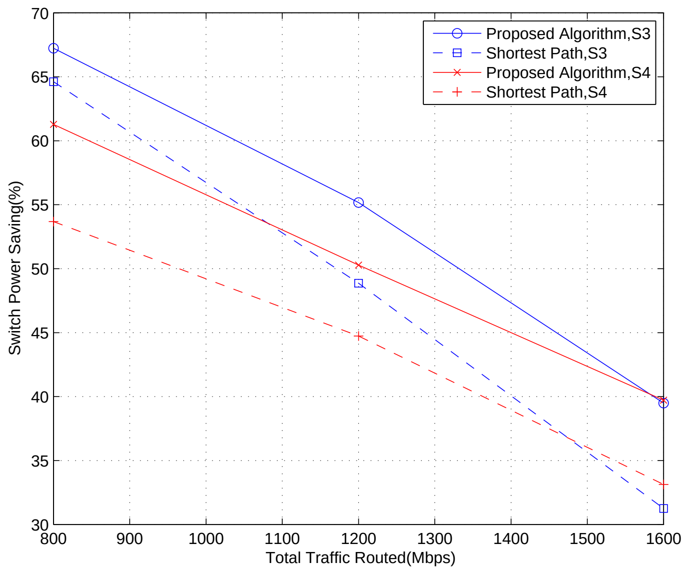

Figure 3.16. Performance results of the proposed algorithm for Scenario 3 and Scenario 4 in the second network topology.

3.4.3. Third Topology

The third topology as shown in Figure 3.17, there are 28 OpenFlow switches with the ports by varying between 2, 6, 8 and 14. Port capacities are fixed and the total link capacities between two OpenFlow switches are determined depending on the link capacity per port defined in each scenario.

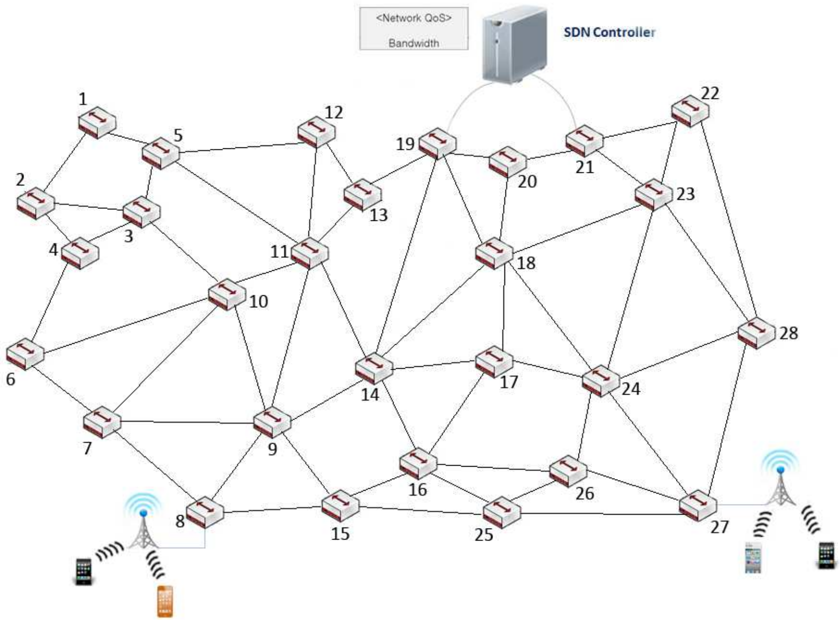

Figure 3.17. Third network topology

As shown in Figure 3.18, the achievable percentage of power reduction of the proposed routing algorithm is also up to $\%8$ compared to the shortest path algorithm in the third network topology.

3.4.4. Waxman Topologies

We also generate various topologies based on Waxman [Waxman1988] to illustrate the performance of the proposed algorithm. All links between any two nodes have the capacity of 1 Gbps. In the topology, the network nodes are uniformly placed in the plane and edges defined according to distances between nodes. The probability to have an edge between nodes u and t is given by

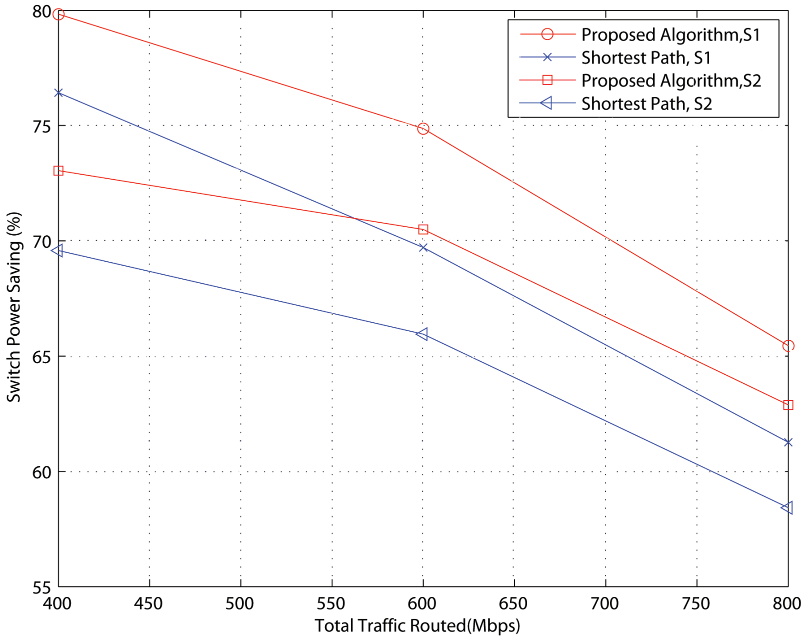

Figure 3.18. Performance results of the proposed algorithm for Scenario 1 and Scenario 2 in the third topology.

$$Pr(u,t) = \alpha e^{\frac{d^l}{\beta L}} \tag{3.9}$$

where α determines the maximal link probability and β controls the length of edges d^l is the distance between the node u and t, and L is the maximum distance between any two nodes. The parameters are given in Table 3.1.

Topology	node count	α	β
First Waxman Network	20	50	0.1
Second Waxman Network	40	50	0.1

Table 3.1. Parameters for generation of Waxman networks

In the first Waxman topology shown in the Figure 3.19, node 12 and node 19 are chosen as the possible sources and node 11, node 17 and node 18 are selected as the possible destination. The requirements of flows have generated as uniformly distributed demands by 100 Mbps, 200 Mbps and 300 Mbps.

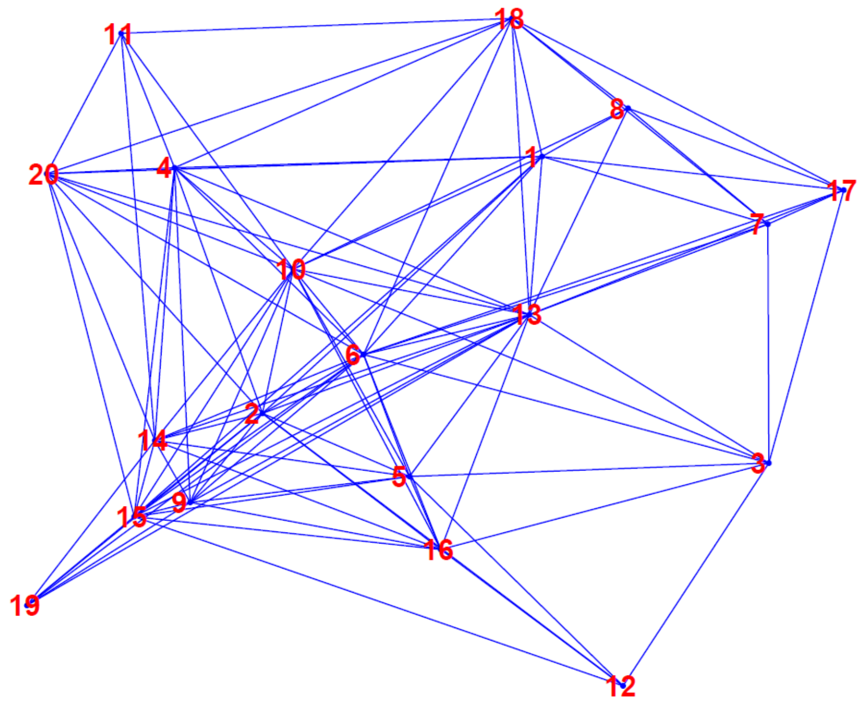

Figure 3.19. First Waxman topology

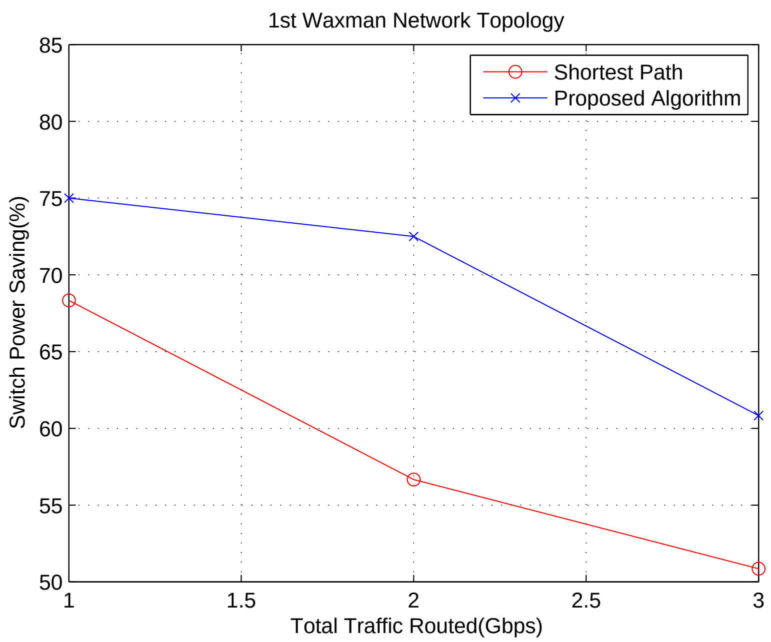

Figure 3.20. Performance results of the proposed algorithm for the first Waxman topology

In the second Waxman topology shown in the Figure 3.21, node 15 and node 36 are chosen as the possible sources and node 6, node 17 and node 22 are selected as the possible destinations. The requirements of flows have generated as uniformly distributed demands by 100 Mbps, 300 Mbps and 500 Mbps.

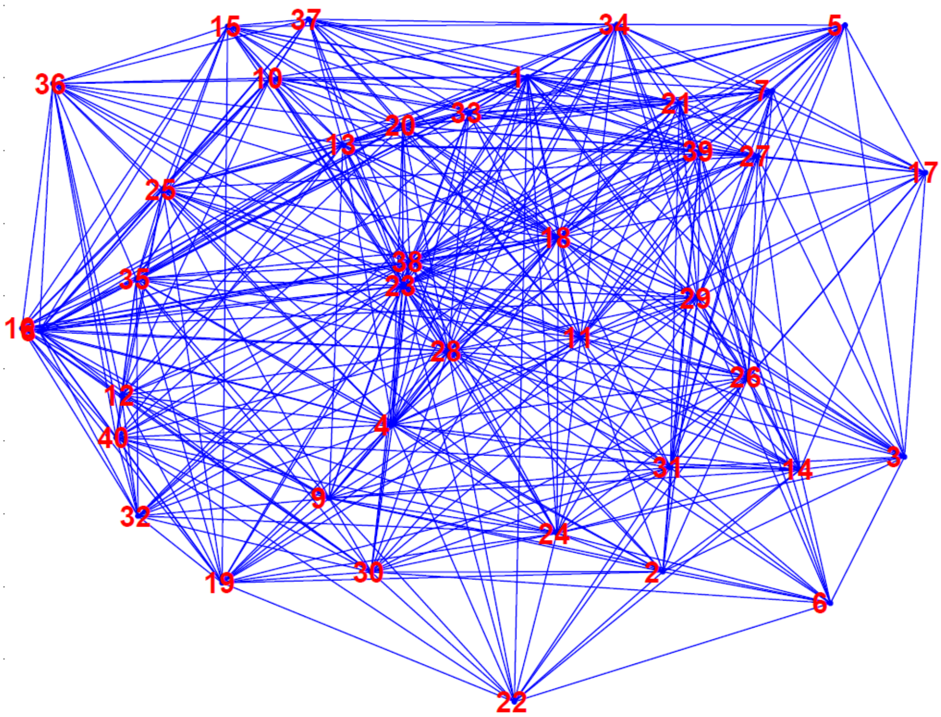

Figure 3.21. Second Waxman topology

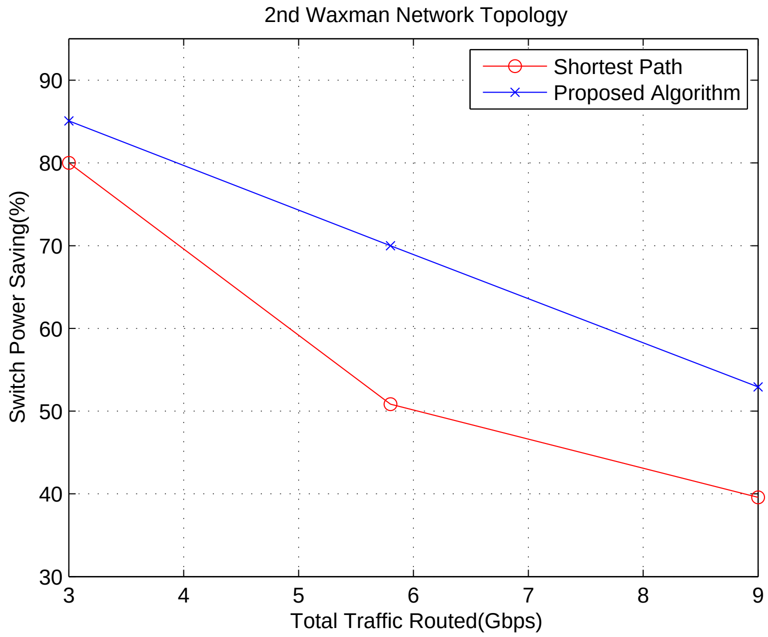

Figure 3.22. Performance results of the proposed algorithm for the Second Waxman Topology

According to the performance results given in Figures 3.20 and 3.22, the proposed algorithm gives better performance up to $\%20$ than the shortest path algorithm.

3.5. Summary

We have proposed an architecture including routing algorithm to design energy efficient software defined networks. For the case when the traffic load in the network is low, we have formulated the optimization problem to enable to shut down switches in the network. We have proposed an efficient low complexity approach which routes the flows sequentially while having almost the same complexity as the shortest path algorithm. We have provided the power consumption performances based on the number of active OpenFlow switches for different throughput constraints for considering various network topologies and scenarios.

CHAPTER 4

ENERGY AWARE ROUTING FOR SOFTWARE DEFINED MOBILE NETWORKS

In this system, our purpose is to minimize the power consumption in mobile networks. In SDN part, the unused switches and ports put sleep mode. In C-RAN part, using the information of user's demands and locations, the flow sizes determined. The total data demand information is sent to SDN controller. SDN controller routes the flows to the corresponding base stations. Exchancing information between SDN and C-RAN allows to reduce power consumption. The proposed model is shown in Figure 4.1.

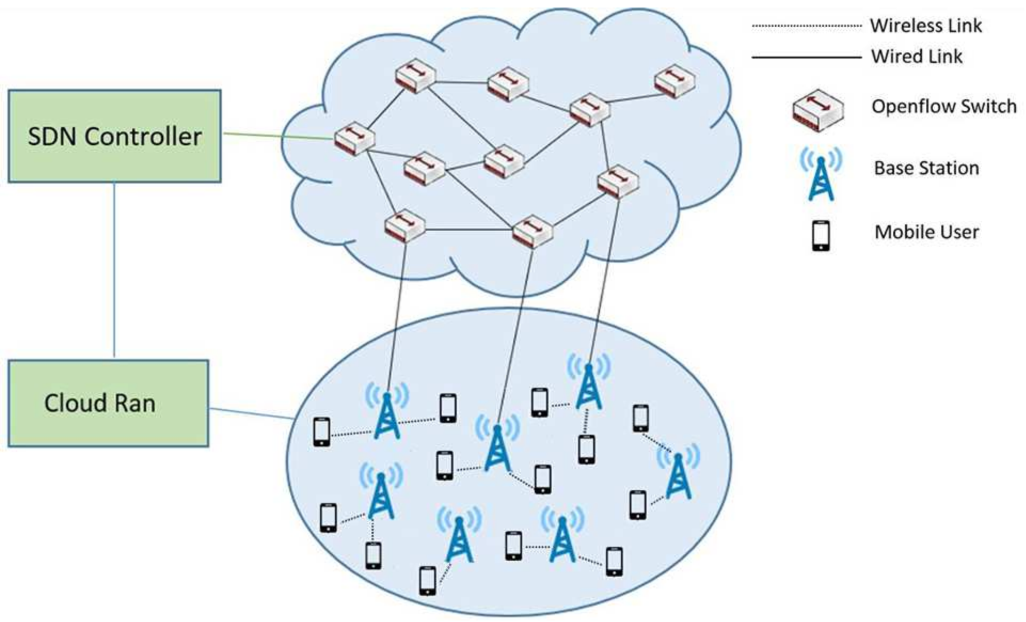

Figure 4.1. The proposed SDMN model

4.1. Network Model

The SDN can be modeled as a graph $G < \mathbb{V}, \mathbb{Z} >$ where $\mathbb{V}$ is the set of switches and $\mathbb{Z}$ is the set of possible links between the switches through available ports. $N_{u,t}$ links can be established between node u and node t proportional to the number of ports in the nodes. Each link $(u_y, t_y) \in \mathbb{Z}$ has a capacity $C_{(u_y,t_y)}$ where $y = 1, \ldots, N_{u,t}$. The capacity of each link is determined as fixed and it is adjusted according to the number of available ports in the switches and the maximum available capacity, $C_{(u,t)}$. $\mathbb{F}$ is the set of K flows and each flow $f_k \in \mathbb{F}$ has several parameters, source, s_{f_k}, destination, d_{f_k}, throughput requirement, R_{f_k} and delay requirement $d^g_{f_k}$.

The aim of our solution is to find the set of routes $\mathbf{p} = \{\mathrm{p}_{f_1}, \mathrm{p}_{f_2}, ..., \mathrm{p}_{f_K}\}$ where p_{f_k} is the set of routes composed of the active links through source to destination belonging to the flow f_k. While finding the routes $\mathbf{p}$ that satisfies throughput requirements of all flows which are determined based on availability of wireless links and demands of the users, we reduce the power consumption based on the number of active switches and the number of active links in the network. Let $x_v \in \{0, 1\}$ indicate whether the switch v is active or not. If the switch v is used through the links selected for the route $\mathbf{p}$, then its indicator, x_v, becomes 1. Let $x_z \in \{0, 1\}$ indicate whether the link z is active or not. If the link z is used for the route $\mathbf{p}$, then its indicator, x_z, becomes 1.

The total power consumption in the network is determined by

$$P(\mathbf{p}) = \sum_{v \in \mathbb{V}} x_v(\mathbf{p}) P_{switch} + \sum_{z \in \mathbb{Z}} x_z(\mathbf{p}) P_{port} \tag{4.1}$$

In order to achieve power awareness in the network, the optimization problem is defined as,

$$\min \quad P(\mathbf{p}) \tag{4.2}$$

subject to

$$R_{f_k} \leq C^w_{f_k} \quad \forall f_k \tag{4.3}$$

$$\sum_{y=1}^{N_{u,t}} C_{(u_y,t_y)} \leq C_{(u,t)} \quad \forall u, t \tag{4.4}$$

$$\mathrm{d}^g_{f_k} \leq D^{max} \quad \forall f_k \tag{4.5}$$

where $d^g_{f_k}$ is the total number of hops in the route and D^{max} is the maximum acceptable hops for the flow f_k. The first constraint states that the link capacity must be equal to or lower than throughput requirement of each assigned flow which is determined according to wireless links and users' demand. The second constraint denotes that the total link capacity, $C_{(u,t)}$ between switch u and t must be equal to or higher than demanding rate of total established $N_{u,t}$ links. The third constraint satisfies the delay requirements for each flow.

4.2. Proposed Algorithm

In the proposed algortihm, the $C^w_{f_k}$ is calculated by performing resource allocation at the C-RAN, which will be explained.

We consider a cellular system based on an orthogonal frequency-division multiple access (OFDMA) system where BS is located in the center of the cell. Let $\mathbb{D}$ be the set of base stations and $\mathbb{E}$ be the set of users. The users are selected from the set of $\mathbb{E}$=$\{1, 2, .., E\}$.

In OFDMA system, the total available bandwidth, B_w, is divided into Q clusters and each cluster consists of a set of adjacent OFDM subcarriers to further reduce feedback load. $H_{d,e,q}$ is the channel coefficient between the base station d and the user e that includes pathloss, shadowing and multipath for the cluster q. The channel coefficient of a cluster is determined by $H_{d,e,q} = \bar{H}_{d,e,m}$ where $\bar{H}_{d,e,m}$ is channel coefficient of mth subcarrier. The value of m is determined by $m = (q-1)N_Q + \arg\min_{1\leq i\leq N_Q}\{|\bar{H}_{d,e,(q-1)N_q+i}|^2\}$ for each cluster where $N_Q = M/Q$ is the number of subcarriers in one cluster and M is the number of subcarriers.

Our aim is to satisfy data rate requirements of the users during a whole transmission frame while maximizing the total system capacity as:

$$\max \sum_{e=1}^{E} R_e \tag{4.6}$$

subject to

$$R_e \geqslant R_e^{th}; \quad \forall e \tag{4.7}$$

where R_e is eth user' data rate and R_e^{th} is the eth user' threshold data rate that must be satisfied at the end of the whole transmission frame.

In order to achieve Eq.(4.6) with the constraint Eq.(4.7) for OFDMA system, we perform resource allocation for each cluster. The achievable data rate between base station and the user is calculated for each cluster by,

$$R_{d,e,q} = \frac{B_w}{Q}\log_2\left(1 + \frac{P_d|H_{d,e,q}|^2}{N_0 B_w}\right) \tag{4.8}$$

where P_d is transmitted power of dth base station, N_0 is the noise power density and B_w is the transmission bandwidth.

Initialization: Let $\mathbb{Q} = \{1, 2, ..., Q\}$ be the set of clusters. $\mathbb{U}$ and $\mathbb{S}$ are the unsatisfied and satisfied users set, respectively. $\mathbb{U} = \{1, 2, ..., E\}$, $\mathbb{S} = \{\emptyset\}$, $R_{d,e} = 0$, $\forall e \in \mathbb{E}$, $\forall d \in \mathbb{D}$.

Step 1*: The resource allocation is performed for $\forall q \in Q$ at each base station d:*

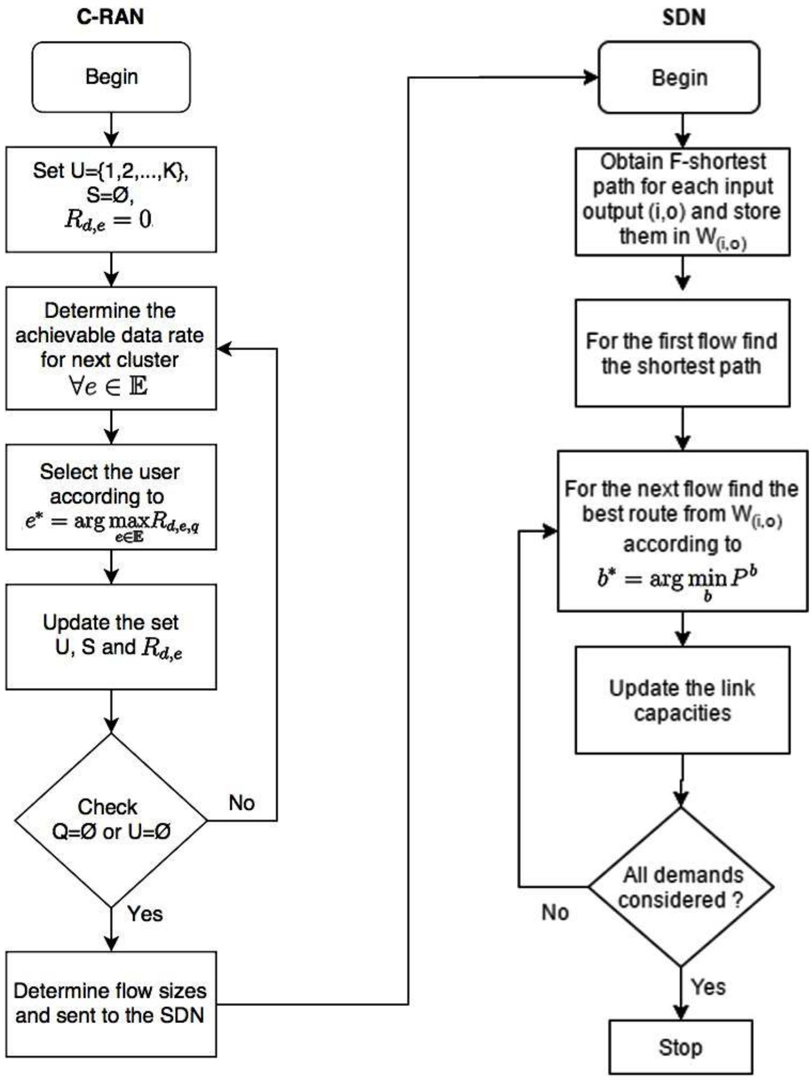

Figure 4.2. SDN and C-RAN resource management flowchart

- Determine the achievable data rate $R_{d,e,q}; \forall e \in \mathbb{E}$.
- Select the user that provides the highest rate as $e^* = \arg\max_{e\in\mathbb{E}} R_{d,e,q}$.
- Update the data rate as $R_{d,e^*} = R_{d,e^*} + R_{d,e^*,q}$.
- If $R_{d,e^*} \geq R^{th}_{d,e^*}$, e^* is satisfied then $\mathbb{U} \leftarrow \mathbb{U} \setminus \{e^*\}$, $\mathbb{S} \leftarrow \mathbb{S} \cup \{e^*\}$.

Then, we sum up all required capacity whose source and destination are the same which corresponds to link requirements of each flow:

$$C^w_{f_k} = \sum_{g\in\mathbb{G}} \sum_{e=1}^{E} R_{g,e} \tag{4.9}$$

where $\mathbb{G}$ consists of base stations which are connected to the same OpenFlow switch and has the same source.

At the SDN, we perform routing according to proposed low complexity algorithm:

- *Initialization*: The sets of input OpenFlow switches, $\mathbb{I}$, which are connected to SDN controller and the output OpenFlow switches, $\mathbb{O}$, which are connected to such as base stations for the wireless networks are determined in a given network topology. Then, F-shortest paths [Yen1971] for each input and output pair (i, o) are computed and stored in the set $W_{(i,o)}$ for $\forall i \in \mathbb{I}$ and $\forall o \in \mathbb{O}$.

- *For the first flow*, f_1:

  - For the flow f_1 with source s_{f_1} and destination d_{f_1}, choose the shortest path p_{f_1} which satisfies requirements from the set $W_{(\mathrm{s}_{f_1},\mathrm{d}_{f_1})}$ since it is the first flow to be routed in the network.
  - Update the available link capacities in the network by using the equation $C_{(u,t)} = C_{(u,t)\in \mathrm{p}_{f_1}} - R_{f_1}$.

- For $k = 2, \cdots, K$

  - For flow f_k, find the $B \leq F$ routes having shortest paths as $\mathrm{W}^b_{(\mathrm{s}_{f_k},\mathrm{d}_{f_k})}; b = 1, \ldots, B$ while satisfying the given constraints.
  - Select the best route for flow f_k in terms of minimum power consumption:

  $$b^* = \arg\min_b P^b \tag{4.10}$$

  where $P^b = \sum_{v\in\mathbb{V}} x_v(\mathrm{p}^{b^*}_{f_k}) P_{switch} + \sum_{z\in\mathbb{Z}} x_z(\mathrm{p}^{b^*}_{f_k}) P_{port}$
  - Update the available link capacities in the network by using the equation $C_{(u,t)} = C_{(u,t)\in \mathrm{p}_{f_k}} - R_{f_k}$.

- End.

4.3. Performance Evaluations

We consider the second network topology in Figure 3.11 which is given in Chapter 3. There are 20 OpenFlow switches with given total link capacities by varying between 0.01 Gbps, 0.02 Gbps, 0.05 Gbps and 0.1 Gbps. Then, the number of total ports per switch is determined for each OpenFlow switch depending on the capacity per port which is defined as 10 Mbps.

At each BS, the number of connected users are generated according to Poisson distributions. The users' demand are generated uniformly distributed among $168kb/s$, $336kb/s$ and, $672kb/s$.

The consumed power of switches and ports are given in the Table 4.1.

Table 4.1. The power used by network elements

Power Consumption per Switch	Power Consumption per Port
80W	4W

The power saving performances of the proposed low complexity approach for the second network topology are illustrated in Figure 4.3 according to the users' arrival rate. As a result of proposed routing algorithm, the achievable percentage of power saving that can reach up to $\%10$ depending on the traffic load compared to the shortest path algorithm and using C-RAN can increase power saving up to $\%4$ compared to the traditional mobile network.

By excluding the users which cannot receive their demanded traffic due to their low SNR, the total traffic is reduced compared to only SDMN case. This leads to conservation of power.

The power consumption performance of the proposed algorithm is given in Figure 4.4. Power consumption is calculated by taking into account total switch and port usage. The results shows by using C-RAN, it is possible to save power up to $100W$ compared to traditional mobile network for the second network topology.

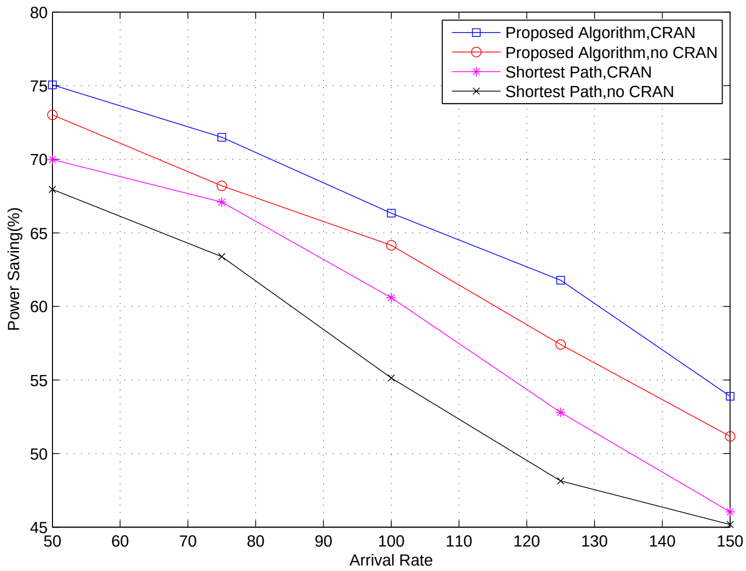

Figure 4.3. Performance results of the proposed algorithm for the second network topology.

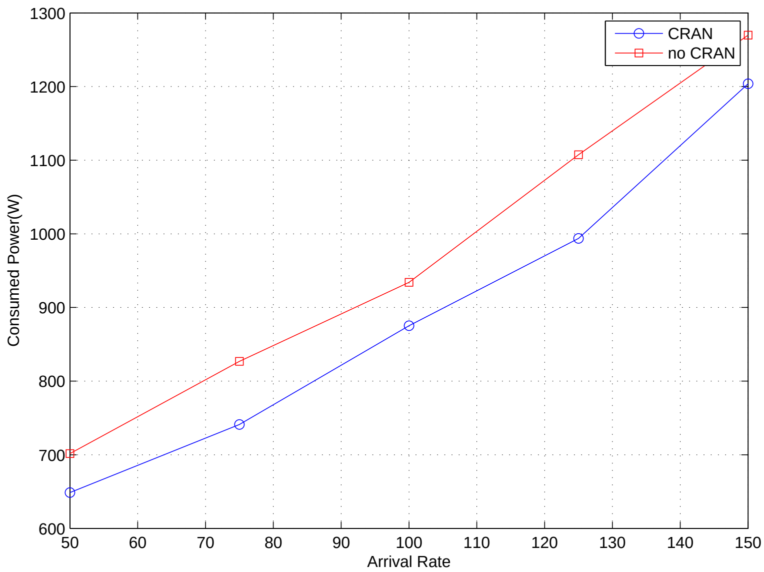

Figure 4.4. Average power consumption for the second network topology.

The previously generated Waxman topologies in Chapter 3 again used to illustrate the performance of the proposed algorithm. In this model, all links between any two nodes have the capacity of 0.05 Gbps.

In the first Waxman topology shown in the Figure 3.19, node 12 and node 19 are chosen as the possible sources and node 11, node 17 and node 18 are selected as the possible destination. The requirements of users have generated as uniformly distributed demands by among $168kb/s$, $336kb/s$ and, $672kb/s$. The power saving results are given in Figure 4.5. For the first Waxman topology, using C-RAN can increase power saving up to $\%3$. The power consumption results are given in Figure 4.6. According to the results, using C-RAN can save the power up to $100W$ compared to the traditional mobile network for the first Waxman topology.

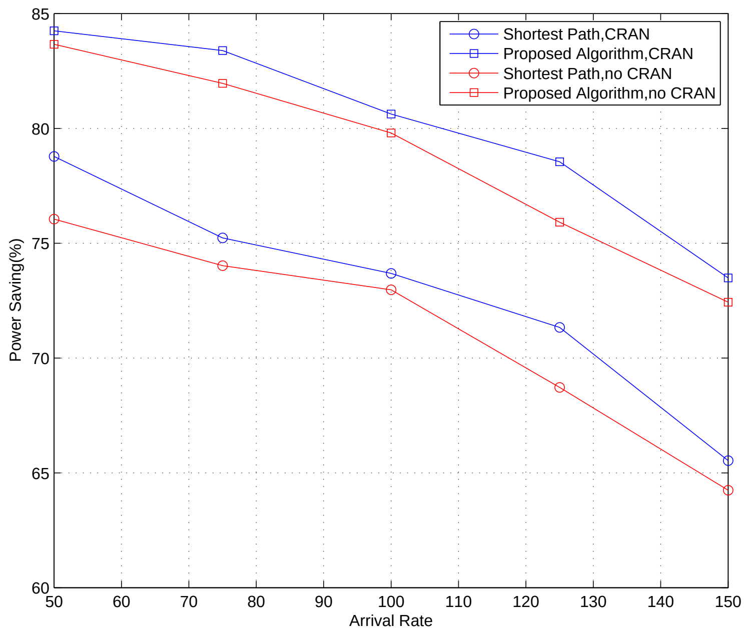

Figure 4.5. Power saving for the first Waxman topology

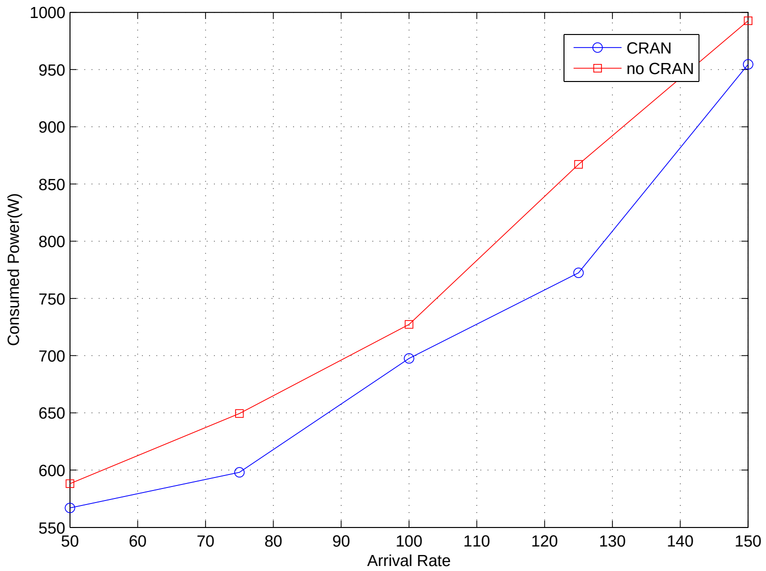

Figure 4.6. Average power consumption for the first Waxman topology

In the second Waxman topology shown in the Figure 3.21, node 15 and node 36 are chosen as the possible sources and node 6, node 17 and node 22 are selected as the possible destinations. The requirements of flows have generated as uniformly distributed demands by among $168kb/s$, $336kb/s$ and, $672kb/s$. The power saving results are given in Figure 4.7. Using C-RAN can increase power saving approximately $\%0.5$ for the second Waxman topology with 3 base stations. The power consumption results are given in Figure 4.8. According to the results, using C-RAN can save the power up to $70W$ compared to the traditional mobile network for the second Waxman topology.

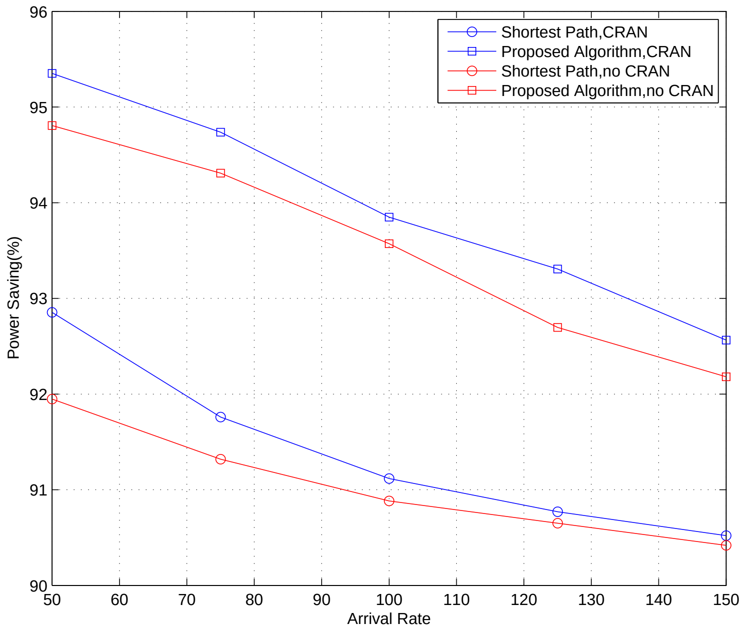

Figure 4.7. Power saving for the second Waxman topology with 3 base stations

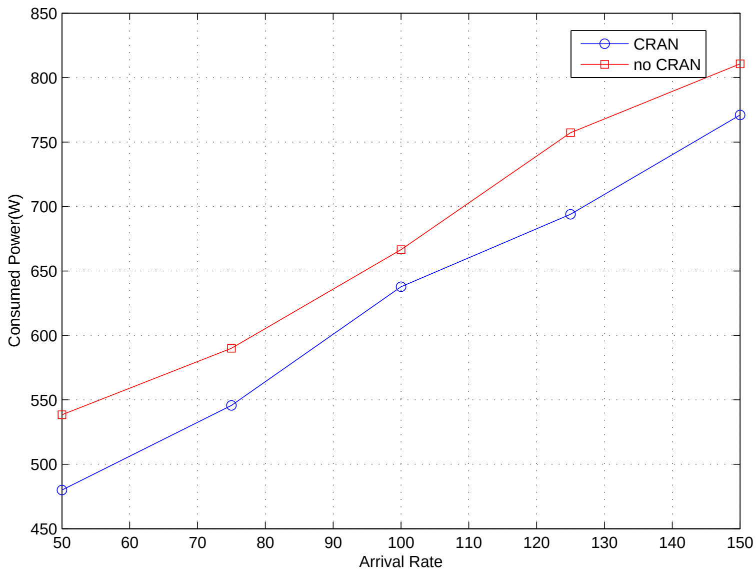

Figure 4.8. Average power consumption for the second Waxman topology with 3 base stations

We also increase the number of base stations for the second Waxman topology. Source nodes again chosen as node 15 and node 36. Destination nodes are chosen as node 6, node 17, node 22, node 27, node 3 and node 5. The requirements of flows have generated as uniformly distributed demands by among $168kb/s$, $336kb/s$ and, $672kb/s$. The power saving results are given in Figure 4.9. C-RAN increased power saving performance up to $\%1.5$ compared to the traditional mobile network for the second Waxman topology with 6 base stations. Also, using C-RAN can save the power up to $100W$ compared to no CRAN case as shown in Figure 4.10. The proposed algorithm provides up to $30W$ more power consumption saving in the second Waxman topology with 6 base stations than the second Waxman topology with 3 base stations.

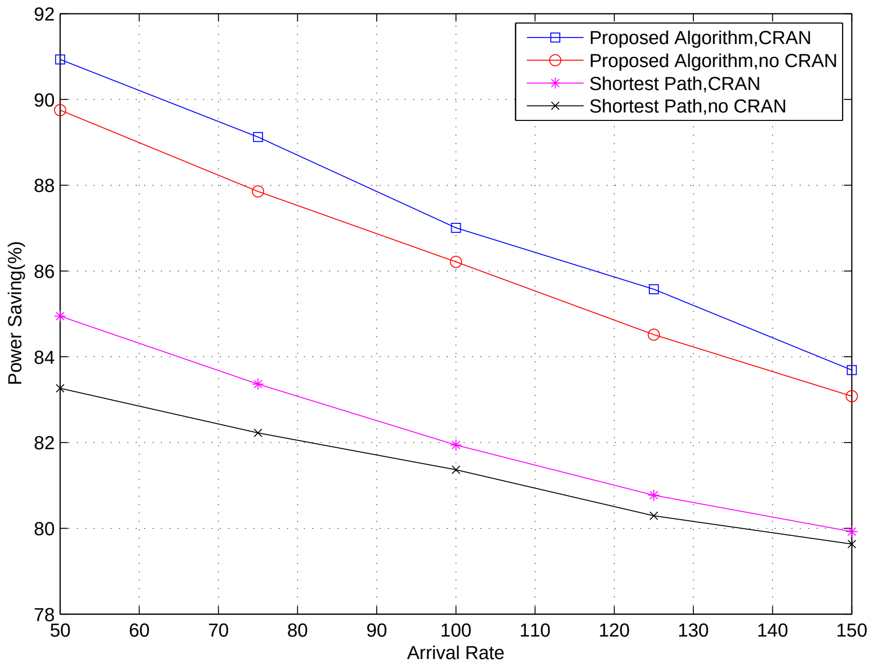

Figure 4.9. Power saving for the second Waxman topology with 6 base stations

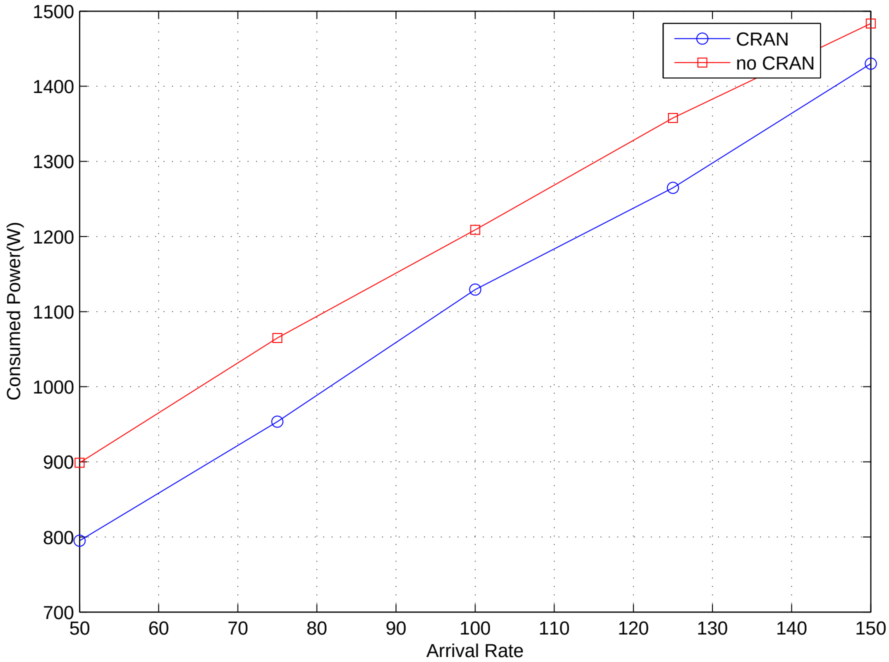

Figure 4.10. Average power consumption for the second Waxman topology with 6 base stations

CHAPTER 5

CONCLUSION

The increasing number of mobil devices such as smartphones, tablets, e-readers etc. and growing popularity of mobile applications created need of huge data traffic. The more number of data demanding devices go up, the more network resources needed. When the number of the network resources increases, the more power is needed. Therefore, energy efficiency has critical importance. The use of SDN and C-RAN shows good promises satisfying the this increasing data demand and allows to manage network resource more efficiently.

One of the advantages of SDN is global network optimization. The proposed algorithm exploiting this feature to route all flows by minimizing the uses of switches while shutting down the unused ones. In this thesis, a low complexity energy efficient routing algorithm which routes the flows sequentially has been proposed. The aim of the algorithm is to minimize the use of network resources while satisfying the data demands of users. The performance of the algorithm is compared with the genetic and the shortest path algorithms in terms of power consumption based on the number of active OpenFlow switches and ports for different network topologies and scenarios. It has significantly less computational complexity compared to the genetic algorithm and gives almost the same performance performance as the genetic algorithm. Morever, the proposed algorithm gives better results compared to the shortest path algorithm.

The proposed algorithm has been extended for SDMN by employing both C-RAN and SDN. Joint routing and resource allocation have been applied in case of coexistance SDN and C-RAN. The total traffic demands of base stations are known due to the presence of C-RAN and the resource allocation is performed accordingly. Thus, users' maximum achievable rates can be determined. Using this information, the total traffic recalculated and flows sizes are rearranged. This information is shared with SDN and the routing is carried in that way. This allows to reduce unnecessary usage of network resources, hence reduce power consumption in proposed method.

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