OPTIMIZATION OF CELLULAR NETWORK TECHNOLOGY USING SOFTWARE DEFINED NETWORKING

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Master's Thesis

Department of Electrical and Electronics Engineering

Programme in Telecommunication

Supervisor: Assoc. Prof. Dr. Nuray AT

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Anadolu University

Institute of Graduate Programs

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ABSTRACT

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Recently, 5G and the Internet of Things (IoT) has attracted a plethora of attention due to its promises of higher data rates, and interconnecting our surrounding devices efficiently, inexpensive, and more reliable with their operators. The proliferation demand for data traffic will reach 77.49 exabytes per month in 2022, ushering in a new era of communication including 5G and the IoT. In IoT architecture determining the optimal paths for transmitting data in terms of increasing network data traffic while maintaining energy consumption is a major challenge. Because of the hardware and communication constraints of the objects, the network must be able to perform route discovery operations within a reasonable time frame and avoid imposing computational and traffic burdens on specific resources. In this thesis, a new model to reduce energy consumption in IoT using a combination of game theory and Software-defined networking (SDN) is presented. In this architecture, all IoT objects are connected to an SDN controller, and the management of communication between these objects is performed through the SDN controller node. Once the SDN-based topology is formed, the optimal path between each pair of objects will be discovered and selected by a game theory-based model. This algorithm performs the path selection procedure by considering both energy and delay criteria simultaneously. Evaluating the performance of the proposed method in the simulated environment and comparing its performance with previous research show that the proposed method will reduce the energy consumption and end-to-end delay in the network.

Keywords: Software-Defined Networks, Energy Optimization, IoT, Game Theory.

ÖZET

HÜCRESEL AĞ TEKNOLOJİSİNİN YAZILIM TANIMLI AĞLARLA OPTİMİZASYONU

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Son zamanlarda 5G ve nesnelerin interneti (IoT) teknolojileri, vadettikleri yüksek veri hızları ve etraftaki cihazları operatörleriyle etkin, ucuz ve daha güvenli bir şekilde bağlantı kurmalarını sağlamaları sebebiyle oldukça fazla ilgi çekmektedir. 2022 yılında veri trafiği talebinin ayda 77,49 eksabayt seviyesine ulaşmasıyla, 5G ve IoT'yi içeren yeni bir iletişim dönemi başlayacaktır. IoT mimarisinde enerji tüketimi korunurken artan ağ veri trafiğini iletmek için optimal yolların (rotanın) belirlenmesi oldukça zor bir iştir. Benzer şekilde nesnelerin donanım ve haberleşme sınırlılıklarından dolayı; ağ, rota belirleme işlemini makul bir zaman dilimi içinde gerçekleştirmeli ve belirli kaynaklara hesaplama ve trafik yükü oluşturmaktan kaçınmalıdır. Bu tezde, IoT'de enerji tüketimini azaltmak için oyun teorisi ve yazılım tanımlı ağ kombinasyonunu kullanan yeni bir model sunulmuştur. Bu mimaride, tüm IoT nesneleri bir SDN denetleyicisine bağlıdır ve bu nesneler arasındaki iletişim yönetimi bu SDN denetleyicisi tarafından gerçekleştirilmektedir. Bir kez SDN-tabanlı ağ topolojisi oluşturulduktan sonra, her çift nesne arasındaki optimal yol, oyun teorisi-tabanlı model tarafından bulunmakta ve seçilmektedir. Algoritma, enerji ve gecikme kriterlerini eşzamanlı dikkate alarak yol seçim prosedürünü gerçekleştirmektedir. Önerilen yöntem benzetim ortamında gerçeklenip performansı daha önce yapılan çalışmalarla karşılaştırıldığında, önerilen yöntemin enerji tüketimi ve ağdaki uçtan uca gecikmeyi azalttığı gösterilmiştir.

Anahtar Sözcükler: Yazılım Tanımlı Ağlar, Enerji Optimizasyonu, IoT, Oyun Teorisi.

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First and foremost, I thank Allah (SWT) for being so merciful and letting me live to see this moment.

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I fondly dedicate this thesis to my partner, my muse, and my voice of reason Lida Afsari. Without her, nothing would have been possible, and with her support, there have been no limits. I love you all beyond the words.

I dedicate my dissertation work to my family, a special feeling of gratitude to my loving parents, Dr. Sayed Khalil Shah Kazemi, and Mina Kazemi whose words of encouragement and push for tenacity ring in my ears and have never left my side.

Finally, I would like to thank Dr. Ferdi Bozkurt for all your timely supports and the Turkish Scholarship (YTB) committee for providing the scholarship that allowed me to undertake this degree.

Sayed Mansoor KAZEMI

06/08/2020

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with “scientific plagiarism detection program” used by Anadolu University, and that “it does not have any plagiarism” whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

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GLOSSARY OF SYMBOLS AND ABBREVIATIONS

μ_j	:	Game Strategy
3GPP	:	3rd General Partnership Protocol
A	:	Set of Players' choices
API	:	Application Programming Interface
AS	:	Automated Systems
B_i	:	Benefit of the node
BS	:	Base Station
CAPEX	:	Capital Expenditures
CBR	:	Continuous bitrate
CDS	:	Connected Dominating Set
C_{ij}	:	Weight of the link between nodes i and j
CPE	:	Customer Premises Equipment
D2D	:	Device to Device
DCN	:	Data Center Network
DS	:	Dominating Set
DVFS	:	Dynamic Voltage Frequency Scaling
E	:	Set of Edges
EAR	:	Energy-aware Routing
Ej	:	Current energy level of node j
Emax	:	Initial energy of the node
eNB	:	Evolved Node B
EPC	:	Evolved Packet Core
E-UTRA	:	Evolved Universal Terrestrial Radio Access
GHz	:	Giga Herts
HD	:	High Definition
HQ	:	High Quality
HSS	:	Home Subscriber Server
I	:	Set of Players
IoT	:	Internet of Things

IP	:	Internet Protocol
IS-IS	:	Intermediate System to Intermediate System
K_i	:	Constant of Influence
LSA	:	Link Statement Advertisement
LTE-A	:	Long Term Evolution – Advanced
M2M	:	Machine-to-Machine
MME	:	Mobility Management Entity
MTC	:	Machine Type Communication
NFV	:	Network Function Virtualization
OPEX	:	Operating Expenses
OR-BFT	:	Opportunistic Routing – Best-fit Traversing
OSPF	:	Open Shortest Path First
OVS	:	Open Virtual Switches
PCRF	:	Policy and Charging Rules Functions
PDR	:	Packet Delivery Ratio
P-GW	:	Packet Gateway
P_i	:	Probability of forwarding data
QoE	:	Quality of Experience
QoS	:	Quality of Service
RIP	:	Routing Information Protocol
RS	:	Relay station
RSSI	:	Received Signal Strength Indication
RWP	:	Random Waypoint
SCC	:	Square Clustering Coefficient
SDN	:	Software-defined Networking
S-GW	:	Soft Gateway
SID	:	Segment Identifier
SR	:	Segment Routing
TCP	:	Transfer Control Protocol
TE	:	Traffic Engineering
U	:	Utility Function
UE	:	User Equipment
UHD	:	Ultra-High Definition

V	:	Set of vertices
VLAN	:	Virtual Local Area Network
VM	:	Virtual Machine
Γ	:	Neighboring set
φ	:	Delay Constant
ω	:	Delay ratio

1. INTRODUCTION

Recently, 5G and the Internet of Things (IoT) has attracted a plethora of attention due to its promises of higher data rates, and interconnecting our surrounding devices efficiently, inexpensive, and more reliable with their operators. It is being expected that the proliferation demand for data traffic will reach 77.49 exabytes per month in 2022 (Cisco, 2019), ushering in a new era of communication including 5G and the IoT. The current cellular networks have many challenges such as energy efficiency, delay, bandwidth utilization, Quality of Service (QoS), Quality of Experience (QoE), etc. So the next generation network needs to fill the gap. A combination of technologies like Software Defined Networking (SDN), Machine-to-Machine (M2M) communications, relay devices, and small cells can lead to approaches for overcoming the existing challenges of next-generation networks (Chen & Zhao, 2014). Generally, 5G networks are composed of a collection of network functions concentrated in the Evolved Packet Core (EPC) and Evolved Universal Terrestrial Access Network E-UTRAN. Relay nodes can be used as relay stations (RS) to assist the user equipment (UE) in connecting the network infrastructure through a Base Station (BS) also called as evolved NodeB (eNB). BSs or eNBs may be provided to one or more relays (3GPP.TS.36.216, 2011). Therefore, new resource management initiatives are critical to achieving QoS. The resources of interest include power, buffer size, bandwidth, etc.

Many studies (Le & Hossain, 2007; Saleh et al., 2010; R. Schoenen, Halfmann, R., & Walke, B. H. , 2008; R. Schoenen, Zirwas, & & Walke, 2008; So, 2005) have shown that with support for multi-relay architecture, better performance can be achieved from the aspects of network coverage and its capacity.

One of the nowadays hot research topics is the IoT and 5G-enabled IoT. Internet of Things can be defined as the network of smart devices (computing devices) and sensors with the capability to transmit and exchange data over the internet in order to develop a smart environment. The aforementioned objects and devices connect to a network using different technologies such as radio frequency identification RFID tags, sensors, and actuators.

Although 3G and 4G are used in IoT applications but are not completely optimized for the internet of things' applications. The 5G wireless network can expand the coverage of IoT by providing the fastest communication and capacity. IoT can be used in different fields such as personal, utilities, healthcare, industries, smart cities, etc., which requires a network with massive connectivity capability. According to (Statista, 2016) the total installed base of IoT connected devices is projected to amount to 75.44 billion worldwide by 2025.

In this thesis we propose a model to increase energy-efficiency of IoT architecture. Using a combination of SDN-based architecture, game theory, and connected dominating set CDS can be considered as one of the innovative aspects of the proposed approach which has not been addressed in previous studies.

Research Hypothesis

We introduce an SDN-based architecture for the network in this thesis. In this architecture, the computational unit in the objects will be out of reach of the decision algorithm and all decisions will be made by the controller to select the routing paths. This allows all the processing power of the network resources to be allocated to the data processing algorithms, thereby increasing the processing power of the objects.

The main works studied in this thesis are below:

a. Introducing an SDN-based topology for the network
b. Using a hierarchical communication architecture for IoT nodes as Connected Dominating Sets (CDS)
c. Using a centralized control logic for improving energy efficiency in the network.
d. Introducing an optimal path selection strategy in the controller node by game theory.

Thesis organization

The structure of the thesis is as follow:

In chapter 2 background information about the SDN is presented. Furthermore, different energy-efficient techniques such as Green SDN and Green routing are discussed.

Chapter 3 first defines the scenario and introduce the definition and assumptions used in this research. After that, we dig into the detailed structure of the proposed method, how is the topology constructed using CDS is explained. Then the route discovery mechanism between the active nodes, and the controller using game theory and the Dijkstra algorithm is presented.

In chapter 4, the design and implementation of our method are discussed. First, an introduction to the simulation environment and the procedure taken are discussed. Then an insight on the difference between the proposed method and the study which is used for comparison is given. Then the obtained results are presented in detail.

In the final chapter of this study a sum up of our proposed method along with future work recommendations are presented.

2. LITERATURE REVIEW

Advances in the smartphone industry, graphics (HQ, HD, UHD, 4k videos), Telehealth, automation, etc., have increased the demand for faster data access and faster internet, resulting in the evolution of wireless technology generations from 1G, 2G, 3G to LTE and 4G which also referred as LTE advanced. The evolution in the mentioned technologies is shown below in figure (2.1). Major challenges in the mobile networks including QoE, higher data rate, lower delay, etc. still have not efficiently been resolved in the LTE, hence an evolution toward 5G is required based on current drifts. (Gupta & Jha, 2015)

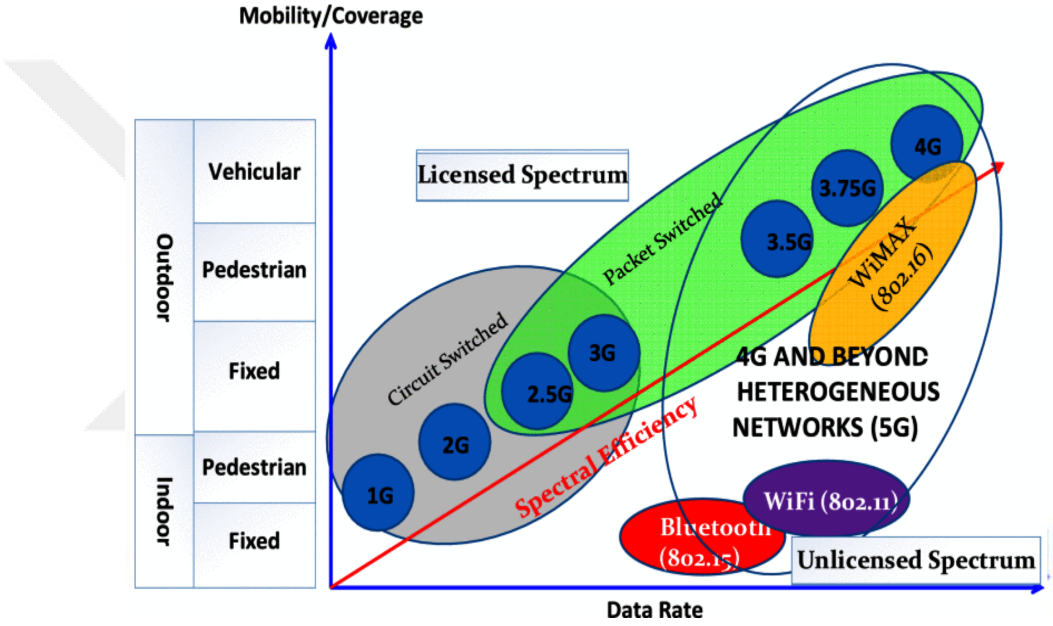

Figure 2.1. *Evaluation of networks (Gupta & Jha, 2015)*

5G network is capable of supporting and operating on different frequency bands, ranging from the current cellular bands to up to 60 GHz (millimetric waves) and beyond (Li et al., 2014).

Software Defined Networking (SDN) and Network Functions Virtualization (NFV) are key techniques to achieve network slicing based 5G networks. The figure (2.2) illustrates the LTE architecture with and without NFV. The user equipment UE is connected to the Evolved Packet Core (EPC) which is LTE core network. EnodeB refers to upgraded base station (BS) and E-UTRAN is the evolved radio access network (RAN) in LTE networks. The UE is connected to the EPC via EnodeB and E-UTRAN, respectively. The main components of LTE core are as follow:

a. Mobility Management Entity (MME)

b. Home Subscriber Server (HSS)

c. Serving Gateway (S-GW)

d. Packet Gateway (P-GW)

e. Policy and Charging Rules Functions (PCRF)

NFV replaces the abovementioned elements with Virtual Machines VMs which are responsible for implementation of the virtualized network functions and will be placed in the edge/core cloud in figure (2.2). (Mijumbi et al., 2016; Yazıcı, Kozat, & Sunay, 2014; Zhang et al., 2017).

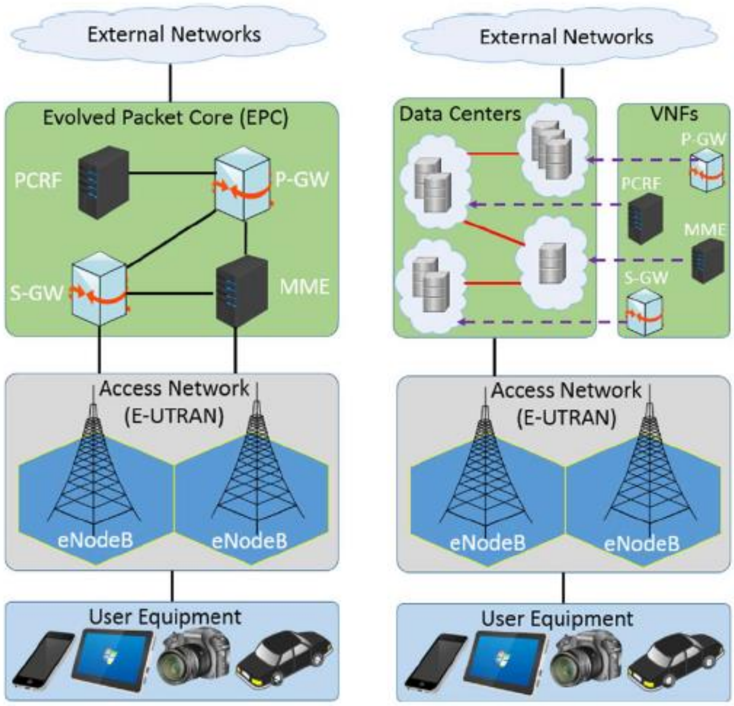

Figure 2.2. *Virtualization of the EPC (Mijumbi et al., 2016)*

Different technologies like Device to Device (D2D) communication, massive MIMO, small cells, Internet of Things IoT, and links between them and a general 5G architecture are shown in figure (2.3). Some of the aforementioned technologies are describe as follow:

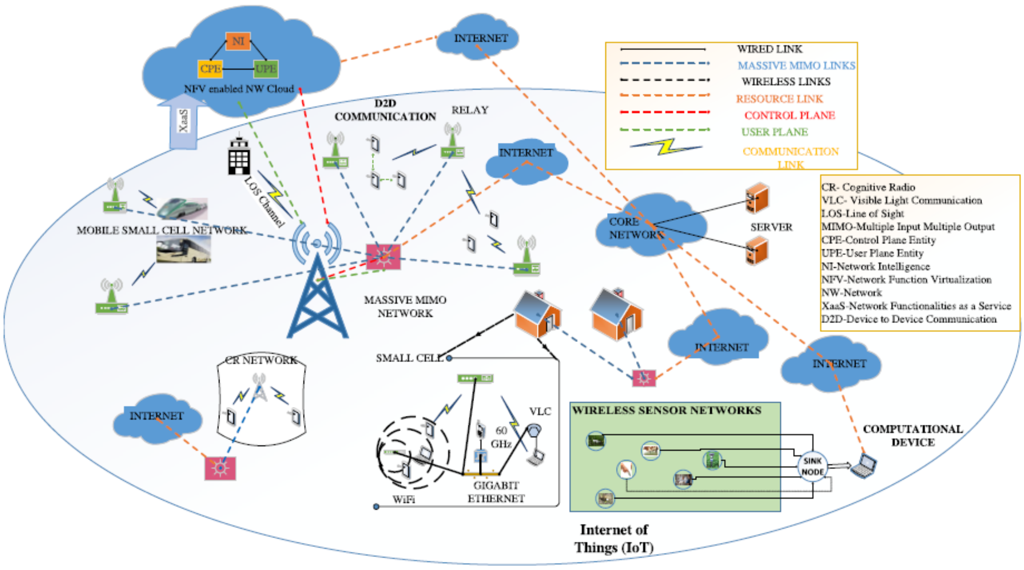

Figure 2.3. *A general 5G network architecture (Gupta & Jha, 2015)*

- Device to Device (D2D) communication

Refers to a dedicated connection between UEs, without entering the EPC. This communication may include the EnodeB. D2D communication improves the energy efficiency and delay of the network.

- Massive MIMO

This technology is the extended version of multiple-input multiple-output (MIMO) and is used to enhance the network coverage. Massive MIMO increases the capacity and spectrum.

- Small Cells

Small cells are deployed to increase the frequency reuse cover small geographical area, hence lower energy for transmission would be required.

- Internet of Things (IoT)

Internet of Things is a network in which mostly all devices (home appliances, smart devices, smart cars, drones, etc.) having the ability to access the network are interconnected (Agyapong et al., 2014). It has been expected that interconnected devices will reach the number 24 billion device by 2020, which makes about $ 1.3 trillion revenue for the service providers and network operators.

As per (Blial, Ben Mamoun, & Redouane, 2016; Gubbi et al., 2013) the IoT applications are shown in figure (2.4) and can fall into the following subcategories.

- Home/Personal
- Enterprise
- Utilities
- Mobile

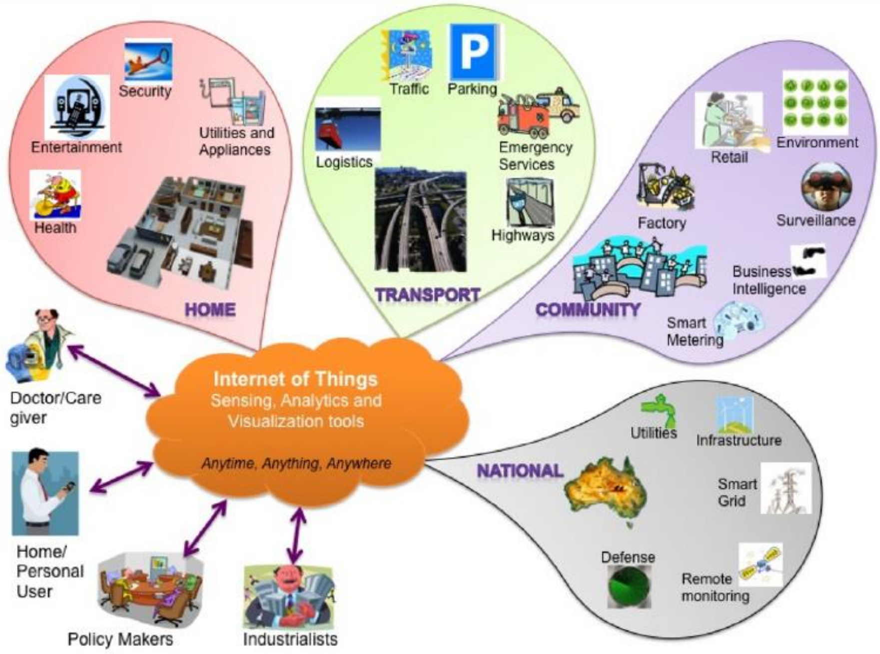

Figure 2.4. *End users and application areas of IoT (Gubbi et al., 2013)*

2.1. Software Defined Networking (SDN)

Software Defined Network (SDN) (Nunes et al., 2014) is a unique technology that will play an important role in 5G technology rollout because of its promising network management attributes. SDN enables control plane programming and abstracts the underlying network infrastructure for applications and network services, for example, through OpenFlow protocol. Conventional networks have many disadvantages. These challenges are given below:

- Network hardware are built with management and control planes attached therefore the networks are not flexible. This will deprive the network world of growth and innovation.
- The complexity of conventional networks is high because because there are many different protocols used to deal with various network issues such as security, quality of service, etc.

To solve the mentioned problems, separation of the control layer from the data layer has been proposed. This idea is shown in figure (2.5).

The protocols and algorithms for controlling network behavior and managing them are in the control layer, and the hardware and software for conducting packets are in the data layer. In the current networks, the router makes decisions and executes them well, but if these two layers can be separated, it can be allowed to make those decisions in the control layer (Blial et al., 2016).

This has led to the creation of software-defined networks. In this type of network, there is a single layer of management where all control functions of a network can be defined via network applications, unlike traditional networks where simple command-line commands and services are used. Using northbound APIs, it communicates with the control layer. The second layer is known as the control layer which includes various controllers, which is more intelligent and the most important among the different layers of the network. This layer uses the southbound interface for sending commands to the infrastructure layer.

The third layer, also known as the infrastructure layer, is called the data layer. This layer includes hardware devices such as routers and switches. This layer communicates with the control plane via southbound APIs, works by first receiving commands from the control layer and notifying them to the relevant hardware devices.

The northbound interface is the interface between the control and management layer. In this layer, all kinds of open source APIs can be used. Constructing an interconnection between different controllers can be done through Eastern and Western interfaces but no specific standard has yet been designed for this (Kreutz et al., 2015).

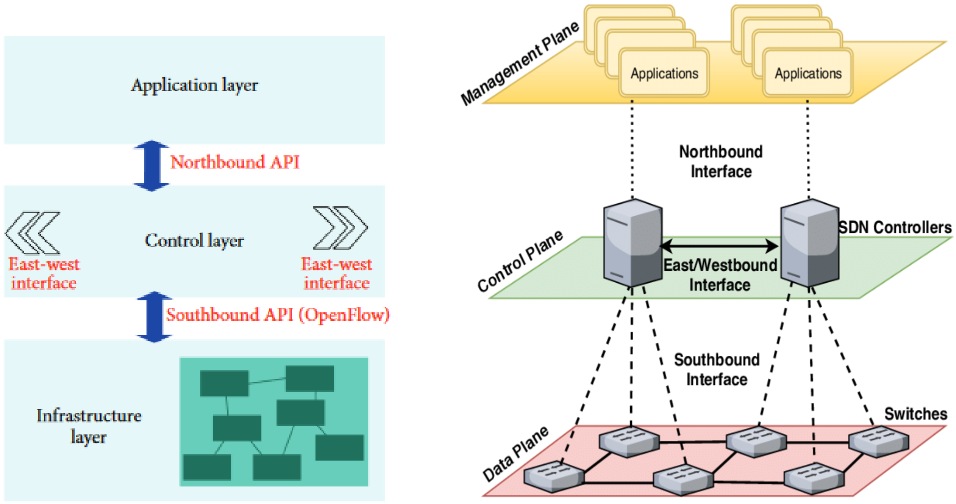

Figure 2.5. *Software-defined networking architecture (Blial et al., 2016)*

The most used and accepted southbound API of SDN-enabled networks is the open-source protocol OpenFlow which is used to interconnect the data plane with the control plane. It is supported by major companies such as Facebook, Cisco, and Google. All traditional network management tasks can be done in a specific and advanced way in this protocol. OpenFlow architecture is shown in figure (2.6).

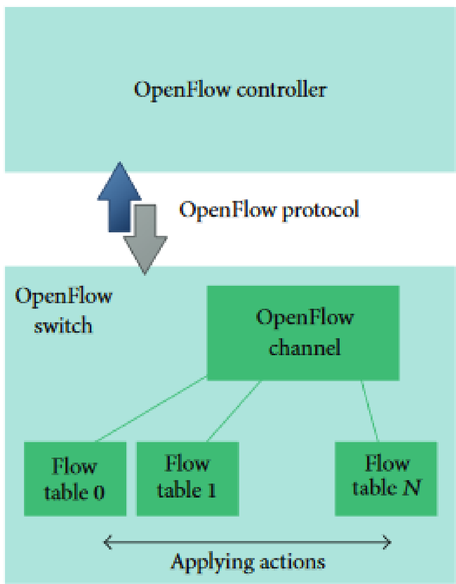

Figure 2.6. *Open-flow architecture (Blial et al., 2016)*

OpenFlow is located on top of the Transfer Layer or TCP. A set of flow inputs is used to match and control the processed packets in the flow table. Message transmission between an OpenFlow switch and OpenFlow controller takes place using the OpenFlow channel. This channel is secured, and all the messages in this channel are encrypted. Three types of messages are used in the OpenFlow switch protocols. Each of them has many sub-types (Anders Nygren et al., 2015).

a. Controller to switch: Used to manage/inspect the state of the switch. Initiated by the controller and may not require an answer from the switch
b. Asynchronous messages: Notifies the OpenFlow controller regarding any change in the state of the switch. These messages are initiated by the switch.
c. Symmetric messages: They are bidirectional messages such as hello or echo messages and can be initiated by either of the switch or the controller.

2.2. SDN and NFV

Network function virtualization (NFV) launched in late 2012. More than twenty big companies in the field of group telecommunications designed NFV, but as time goes by the importance of NFV is realized, more than 150 companies around the world are already using this technology. Most devices in today's telecommunications networks use cloud and virtualization. One of the important reasons for using this technology is to reduce the cost and time to access the desired service and increase the scalability of the network. The similarity between NFV and SDN is that they both take advantage of the cloud environment and also eliminate the space between hardware and software and use a variety of innovations using the control layer (Allan et al., 2014).

To use NFV, one needs to connect endpoints to the performance of the virtual network through large-scale physical and virtual layers. In Figure (2.8) NFV with a variety of applications can be seen.

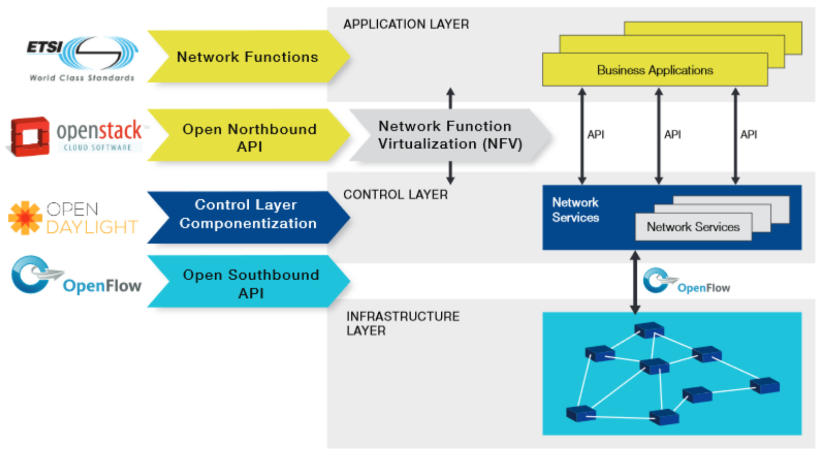

Figure 2.7. *Network function virtualization NFV (Allan et al., 2014)*

Despite the many benefits of using NFV, it has the following challenges

a. Fixed settings

Most of today's hardware has a fixed IP and is located in a fixed physical location. With NFV we need to deliver and configure these hardware automatically without using the traditional manual method

b. The rapid growth of IP endpoints is the result of virtualizing equipment in the network

The number of end-devices in the NFV-based environment is growing much faster than conventional networks, which leads to millions of end-devices for various applications. This increases the stress on specific network mechanisms, like Layer 2 VLANs, or can lead to an increment in required complexity for dual bandwidth scalabilities such as Transparent Interconnection of Lots of Links (TRILL) and Shortest Path Bridging (SPB).

c. Network mobility

Physical equipment is usually provided once in the network lifetime and stays in that location of the network. Physical devices and servers can be separated using NFVs. These devices can appear under various networks or locations, use various addresses. These devices can even have various protocols to access. NFV removes the conventional interconnection between the identity of devices and their IP location.

d. Elasticity

In the virtualization of network functions, virtualized network functions are created in real-time, and deployed on demand. Networks should be able to be configured quickly to achieve the flexibility needed to optimize available resources in an NFV environment.

e. Multiple rentals:

Most NFV use-cases are designed on the basis of cloud offerings. These use cases are applicable for cases like cloud service whose availability depends on several efficient rentals.

2.3. Green SDN

The most significant difference is the fact that physical servers located in data centers are interconnected with each other by high-speed networks. In contrast, in NFV enabled networks out of the data centers restrictions such as delay, and bandwidth are considered crucial. On the basis of this, it is needed to consider various aspects of resource allocation and optimization of the position of VNFs. As a matter of fact, it is better to be decided considering the increase in load on the host node, the increase in traffic on a part of the neighboring node pairs in the network, and the delay which is the result of flows having to cross the node managing the VNF needed; at the same time.

For these reasons, the most important and least studied problems are managing network node, NFV deployment, and orchestration. In fact, as noted in (Faraci & Schembra, 2015; Manzalini et al., 2013; Manzalini & Saracco, 2013; Moens & Turck, 2014). Telecommunication providers prefer to implement network function virtualization by deploying network functions at the edge which is closest to end-users, instead of deploying them in (potentially) expensive multi-purpose data centers; because using cloud data centers for this aim will cause an increment in the traffic load. The result of this situation will be very long routes with high latency and expense. Other reasons that make the provider of Telecommunication services prefer NFV deployment at the edge due to investment smoothing and resulting in immediate revenue, and the fact that common software instabilities and failures exist in the first period of use. It is easier to control and manage applied to edge nodes. Some works have focused on the problem of deploying virtual network function on mobile networks and have provided various deployment solutions for core network gateways, while others have dealt with the deployment problem in scenarios. Various suggests specific optimization algorithms (Faraci & Schembra, 2015; Manzalini et al., 2013; Moens & Turck, 2014).

Considering the fast growth of activities in the cyber environment and growth of environmental concerns, several efforts have been done in recent years to achieve improvement in energy-efficient communications in the networks. “Green” topology is one of the various options which uses SDN based centralized network topology. In this model, an SDN controller is used to control and monitor the centralized network. Centralized topology means that the SDN controller negotiates with network routers for obtaining traffic statistics on specific users, which leads to an improvement in the efficiency of network traffic flows management. Conceptually focused network implementation involves specific technologies, for example, software-defined network (SDN)

In software-defined networks (ONF, 2012), a protocol called OpenFlow, is implemented for exchanging control messages between the SDN controller and each router in the architecture. In SDN, the OpenFlow protocol combines with Traffic Engineering (TE) which makes the OpenFlow protocol essential for complex processing, by which each router between the source and the destination needs to communicate with the main controller for each traffic flow. Concerning the messages overhead, one can adopt Segment Routing (SR) in a traffic engineering-implemented network method. In this case, the SR controller inputs the router (source) with respect to the traffic from source to destination using segment identifiers (SID) (Thaenchaikun et al., 2016).

It is worthy to note that, the SR technology can be used efficiently in the green traffic engineering routing system in order to reduce the consumption of energy in the network. In this paper, consideration is given to Ethernet links, which are predominantly technology-based, with low-power off-mode standardized by IEEE 802.3az. When unused links on the SR TE-routing network are disabled (i.e. off), the controller commands a given root to turn off specific links to save energy. However, this technique involves a complex mechanism in which the controller is required to include individual link commands to enter the OFF state as well as enable ON those links if traffic congestion occurs. Therefore, this current research focuses on the use of IEEE802.3az for sleep and wakeup, whereby the energy efficiency between Ethernet links is achieved through low working mode (i.e. sleep mode). In other words, in the absence of traffic, the device enters a confined state, with limited interruptions to transmit new data. When the transfer is needed, this link is activated in the awake mode.

In the past few years, SDN and NFV have been introduced with the potential to change the scattered Internet paradigm with the ultimate goal of creating a more agile and flexible network while reducing both the cost of OPEX and CAPEX. Hence, several studies have been done to inherit the data center management experience as well as optimizing the implementation of these technologies. However, the orchestration and management of SDN / NFV nodes presents new challenges for data center management mainly because of the telecommunications context in which NFV lives. Therefore, the purpose of the study in (Faraci & Schembra, 2015) is to define a management model for NFV customers and service providers a green customer nodes (CPE) policy, and an analytical model to support their design. This model is then followed by a case study to show how it can be used to optimize system performance and to select the most important parameter for the design of the CPE node.

In the paper (Kondepu et al., 2015), the architecture and implementation of the SDN node controller are proposed for efficient control of heterogeneous technologies present in a single node. The proposed solution relies on a lightweight network controller latency is guaranteed by the reconfiguration of the intra-node traffic scheduling controlled by a lightweight implementation of an SDN controller scaled to work as an intra-node controller. The proposed solution is illustrated in a subway access aggregation node. Sleep mode is activated in the PON segment in combination with the proper scheduling priority applied to the subway, thus successfully maintaining the overall level of service even with additional sleep delay.

In (Thaenchaikun et al., 2016) the research of IEEE802.3az green algorithmic schemes embedded in software-defined workflow routing (SD-based SR) focused work is presented. SDN-based green network proposals (without Extremely AuGmented Energy efficient etheRnet (EAGER) and Congestion aware Augmented eneRgy efficient Ethernet (CARE) criteria) are based on SDN with Traffic Engineering (TE) tunneling. Green metrics save the energy consumption of the IEEE 802.3az to the entire network while tunneling avoids the burden-sharing mechanism in routing this segment that is not suitable for energy conservation. Conventional metrics with TE tunneling, and savings in the CARE tunneling program are twice as high as with the LEGACY tunneling strategy. Meanwhile, the energy-saving performance with all the three mentioned measurements below TE non-tunneling was lower than those with tunneling. However, low end-to-end delay and maximum utilization of low link (MLU) were achieved with a non-tunneling strategy.

Software-Defined Networking (SDN) attracts dozens of research and industrial areas due to its features such as programmability, controllability, and flexibility. However, the problem of energy loss still exists in both SDN and traditional networks. Fortunately, because of centralized control, energy-saving strategies can be deployed in

SDN. In order to improve energy efficiency of the SDN a green scheme called GreSDN is designed in (Ying et al., 2016), and shown in figure (2.8).

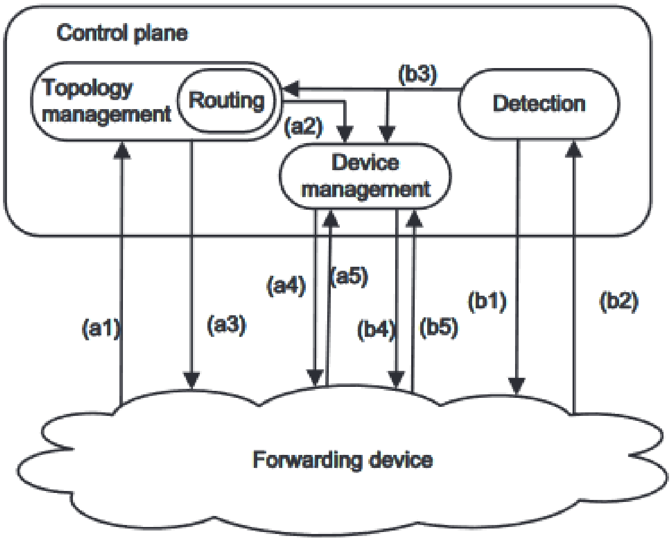

Figure 2.8. *GreSDN (Ying et al., 2016)*

Unlike previous work, GreSDN advocates to minimize network power consumption without altering traffic flow paths until they are finalized. Thereby two heuristic routing algorithms that can be deployed in GreSDN. Simulation results show that algorithms can greatly improve network energy efficiency and have little effect on network performance.

2.4. Green Routing

To guarantee the quality of service (QoS) networks are always planned according to the peak load periods. But during the operation time of the networks, the traffic differs all the time. Mostly network load is less than the peak time and even less than the capacity of the network during the busy time. However, due to the limitations of current hardware technology, the power consumption of network devices is independent of their load. During idle periods, devices are still operating at full speed as working hours. It wastes a lot of energy and reduces energy efficiency. Considering the economic cost and environmental protection reasons, improving energy efficiency is crucial (Ying et al., 2016).

Consequently, putting a higher number of network elements such as switches on idle or low power mode while providing the demanded traffic in the network is achievable. To schedule the required network flow in SDN switches multiple linear programming methods have been proposed by (Moghaddam & Grosso, 2016). A couple of the proposed algorithms achieve approximately 45% energy saving. Also, in (Wang, Wang, Zheng, Yao, & Cao, 2016) research on combining the data flow onto a small number of network elements in a Data Center Networks (DCNs) has been done. They proposed a correlation-aware power optimization (CAPRO) algorithm for energy optimization, a correlation-aware algorithm which turns off the unused network units. Resulting in up to 50% save of energy throughout the experiment, a slight delay was observed.

Reliability is a major setback in the always-on networks. Hence executing the SDN would be auspicious in the always-on networks. Since the SDN is utilized by the telecom companies the reliability remains a setback. Research like (Moghaddam & Grosso, 2016; Wang et al., 2016) mostly addresses the energy aspect of the SDNs regardless of the reliability. So as per the growing demand for the SDN, it is critical to consider reliability in the software-defined networks. Defining the SDN network as a complex system allows us to describe the reliability of complex networks. The concept of reliability has been explored in a graph on a complex network context. The network resiliency and so the reliability will be affected by the network topology regarding delay and packet loss.

In SDN it is necessary that the energy-efficient algorithms must operate continuously in accordance with the defined SDN specifications (Norouzi, Majidi, & Movaghar, 2018).

Routing is the process of finding a path between source and destination node for a packet (traffic) to be sent. Routing can be done within/between or across many networks. The quality of service (QoS) is an important requirement for a wide range of communication network settings and applications. Several QoS based routing algorithms have been evaluated in (Guck et al., 2018).

Automated Systems (AS) are being used to manage the internet network due to its considerable growth. Each AS uses different routing protocols. How the routing information is interchanged between routers is specified by the routing protocols which enables them to discover routes connecting two nodes within a network. Open Shortest Path First (OSPF), Routing Information Protocol (RIP), and Intermediate System to

Intermediate System (IS-IS) discussed in (Dabaghi, Movahedi, & Langar, 2017; Usman et al., 2019) are few examples of the routing protocols. Every router updates its routing table then designates an appropriate immediate hop for each destination node once it received the routing packet.

Furthermore, OSPF as the most typical interior routing gateway protocol broadcasts Link State Advertisements (LSA) messages through the network which contains information about QoS, link utilization, bandwidth, etc. Furthermore, using received LSAs routers construct the network topology in the form of a weighted diagram (Dabaghi et al., 2017; Usman et al., 2019).

Green routing protocols can be achieved by sleep-scheduling. Researchers identified and classified some of the relevant properties of the green routing protocols in (Bilal et al., 2013; Dabaghi-Zarandi & Movahedi, 2018; Dabaghi et al., 2017; Usman et al., 2019). The aforementioned green properties' importance has been abstracted in the Table (2.1).

Table 2.1. *Classification of green properties*

	Category	**Description**	**Possible Values**
a	Type of sleep-scheduled component	Type of components selected for sleep-scheduling	Nodes, links, or both
b	Decision structure	Whether the sleep-scheduling decisions are carried out by distributed or centralized controllers	Centralized or distributed
c	Network traffic awareness	The availability and type of network traffic knowledge for sleep-scheduling decisions	Traffic-unaware, off-line traffic-aware, on-line traffic-aware
d	QoS awareness	The QoS parameters considered by sleep-scheduling decisions	QoS-unaware, QoS-aware using MLU, paths length, delay, or a combination of these parameters

Energy optimization in first-class carrier networks raises concerns in the network. Studies have shown that the energy consumed by carrier-grade networks may reach 50% by 2020 of the entire network (R. Maaloul et al., 2018). Therefore, optimizing the consumed energy in carrier networks gained importance. The amount of energy used in a network is directly proportional to the technology and elements employed in the network.

These elements are able to be turned on using an ON-OFF power profile presented by Carrier Ethernet elements.

Despite the traffic load, each network device consumes energy when it is on. In the case of an ON-OFF power profile, it saves more energy if the traffic is aggregate on a small set of devices. consequently, to minimize the energy consumption Energy-Aware Routing (EAR) techniques are good solutions (R. Maaloul et al., 2018).

In packet-switched networks, a ternary content addressable memory TCAM-based flow table is a greedy hardware that is used in some very fast searching operations. In (Huang et al., 2016) a Green Datapath for TCAM-Based SDN is proposed. In this proposal, they introduce a Dynamic Voltage and Frequency Scaling (DVFS) energy management method. As a result, under the Green Datapath architecture power consumption remained constant even during maximum tunable operating frequency.

Researchers in (Dutra, Bagaa, Taleb, & Samdanis, 2017) propose a solution based on multi-path routing that enables queue-based QoS in OpenFlow and allows an SDN-equipped network operator to effectively allot network resources according to the clients' demands. It allows users to allocate, reduce, or even remove the need for over-provisioning. The proposed technique guarantees the quality of service for each traffic flow while effectively controlling the use of Open Virtual Switches (OVS), hence the lower the number of the OVSs activated in different data centers, the lower the cost. The achieved results show this method is cost and delay efficient.

While designing/planning an SDN topology, scheduling and routing should be considered according to the network topology to achieve a better network efficiency. Creating the SDN graph is a key factor in designing an energy-efficient software-defined network because the network topology in SDN changes rapidly once the virtual devices are off or on by the controller. Hence in energy-efficient networks selecting a reliable path is of importance. To this end, (Norouzi et al., 2018) proposed a routing method to choose the most reliable route among the shortest paths connecting a source to its destination. The obtained results of the experiment state that their method optimizes energy by 73% while ensuring network reliability.

3. PROPOSED METHOD

In this chapter first an introduction about the method is given. The definitions and assumptions used in design of this study is discussed. In the rest of this chapter the structure of our method (SDN-based topology construction, optimal path selection using game theory) is explained in detail respectively.

3.1. Introduction

In IoT architecture, the paths of data transmission must be determined based on the processing abilities of the objects, the data type, and the location of source and destination. Determining the optimal paths for transmitting data in terms of increasing network data traffic is a major challenge. Because of the hardware and communication constraints of the objects, the network must be able to perform route discovery operations within a reasonable time period and avoid imposing computational and traffic burdens on specific resources. Under these circumstances, the optimal state for the IoT will depend on the strategies chosen by users and network resources. This makes it possible to determine the optimal strategy for data transmission using game theory. In this study, a combination of Software Defined Networking (SDN) and game theory approaches were used to solve this problem. In our proposed model, SDN-based architecture will be used to control the communication between IoT objects. The optimal path selection problem was also defined as a game model. In this way, "energy consumption" and "delay" will be considered as the criteria for optimal path selection in game theory.

3.2. Definitions and Assumptions

Before describing the details of the proposed algorithm, we will make some assumptions about the model used in the design of the proposed algorithm. These assumptions are:

- The initial location of IoT objects is random with uniform distribution, and a fraction of things (e.g. mobile phones, vehicles …) have the ability to move in the environment. Also, the density of network nodes in different areas of the environment is almost uniform.
- The distance between nodes can be estimated by the Received Signal Strength Indication (RSSI). It is therefore assumed that the nodes of the network are aware of their position based on their signal strength relative to their neighbors.

- In the proposed method, each object identifies its neighbors through broadcasting Hello packets. This packet also contains node information (including id, residual energy, and node estimated position).
- The amount of initial energy and the maximum transmission power (communication range) of the nodes in the network will be different and therefore the assumed IoT network is heterogeneous.

3.3. Proposed Method

The proposed model to reduce energy consumption in the Internet of Things network consists of two main components. These components are:

1. SDN-based topology construction
2. Optimal path selection using game theory

In the following we will describe these two components in the proposed method.

3.3.1. SDN-based topology construction

The proposed method uses SDN architecture to define the IoT network topology. A simple definition of SDN is as follows: A new generation of networks using virtual layers, virtual switches, central controllers, communication standards and high-level APIs which are trying to manage some parts of switches and routers' controlling and managing network tasks, through software in the upper layers of the network. In other words, SDN reduces hardware dependency and enhances software capabilities and network intelligence. In this way, organizations and large companies can plan and develop their own network and create custom capabilities that result in new customer services.

In the proposed model, an SDN-based architecture is used to replace the conventional communication scheme between IoT objects. In the conventional communication model of objects in the IoT, each node will have to transmit broadcast messages periodically, in order to find out the status of adjacent nodes and synchronize processes. This operation in wireless communications will dramatically increase the time of transmission and energy consumption. As a result, in addition to increasing the energy consumption of objects, end-to-end delay and transmission overhead will also be increased. These conditions are illustrated in Figure (3.1)

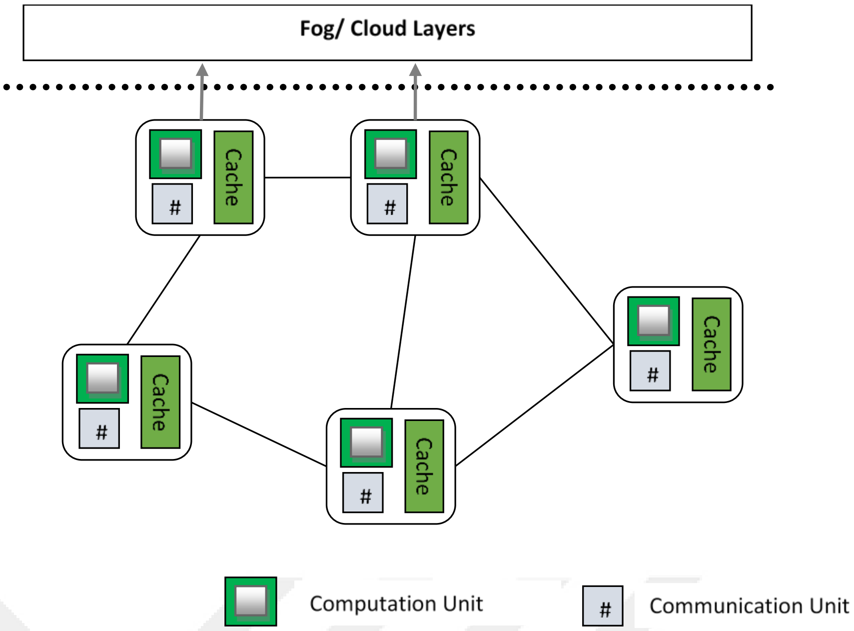

Figure 3.1. *The traditional architecture of communication in IoT*

According to Figure (3.1), in the conventional communication scheme of IoT, the wireless nodes receive data from other objects and can transmit it to the Fog/cloud layers for further processing. Given that each object has the ability to route and process certain types of network data; each object can process the received data and then send it to higher layers to send data to the Fog/cloud servers, or can only forward data without processing it. One of the key issues in this architecture is choosing the optimal path for sending data over the network. Packet routing across large networks must be based on general knowledge of network status, and a node cannot decide about data transmission individually. In order to obtain network status information, each node in the network must know the status of adjacent nodes. This is done through the exchange of control packets. As shown in Figure (3.1), in the conventional architecture of wireless communications, all control packets are routed directly between the network resources. This will increase the sending time, increase the latency, and also increase the energy consumption of the network. As a result, network throughput will decrease.

The use of SDN-based architecture will eliminate these operations and thereby reduce the latency and energy consumption in IoT. The proposed SDN-based network architecture is illustrated in Figure (2.3). In this architecture, all IoT objects are connected to the SDN controller, and the management of network nodes and route selection is performed through this controller. This will increase the flexibility of the entire network.

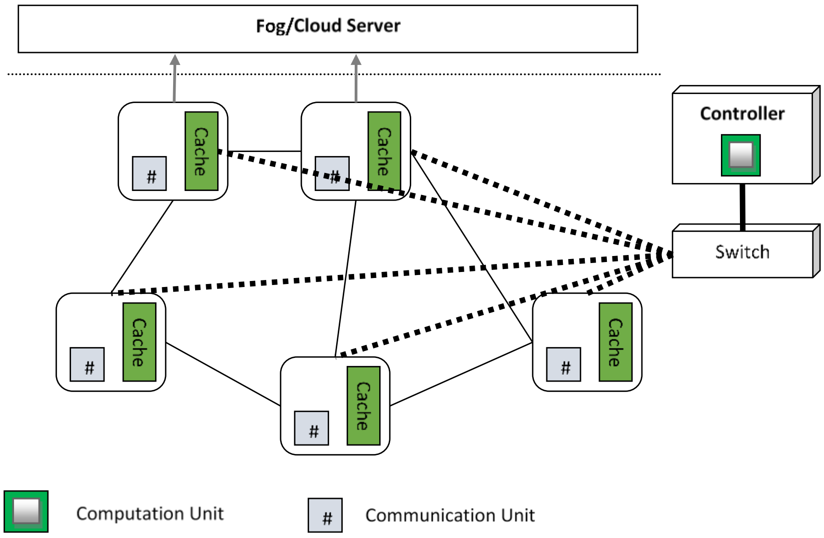

Figure 3.2. *Proposed SDN-based architecture*

In SDN-based architecture in the proposed method, the computational unit in the objects will be out of reach of the decision algorithm and all decisions will be made by the controller (assuming it has sufficient power and processing power) to select the routing paths. This allows all the processing power of the network resources to be allocated to the data processing algorithms (e.g. content analyzers, compressors …), thereby increasing the processing power of the objects. After the controller selects the route, this decision is sent to the nodes via the switch unit. Therefore, each node in this network will contain a communication unit and a temporary memory to communicate with the switch. This architecture eliminates the need for all broadcast operations at the beginning of the data transmission and route selection processes, thereby reducing total transmission time and power consumption on the network.

In order to construct an efficient network topology, SDN controller needs to identify reliable communication links between IoT objects and use these links for path discovery and selection. In the proposed method, SDN controller constructs network topology as a Connected Dominating Set (CDS) structure. Let's consider all communication links between objects in the network as a graph like G (V,E), which V refers to set of active IoT objects and E refers to set of communication links between each object pair. Then we can define Dominant Set (DS) and CDS structures as follows:

Definition 1: For a graph like G = (V, E), where V is the set of vertices and E is the set of edges, a DS is a subset of the vertices in the graph S∈V, which each vertex of the graph G, is either a member of or connected to S.

Definition 2: A CDS is a specific type of DS, which all of its vertices are connected.

Two examples of CDS and DS for a graph, are illustrated in Figure (3.3).

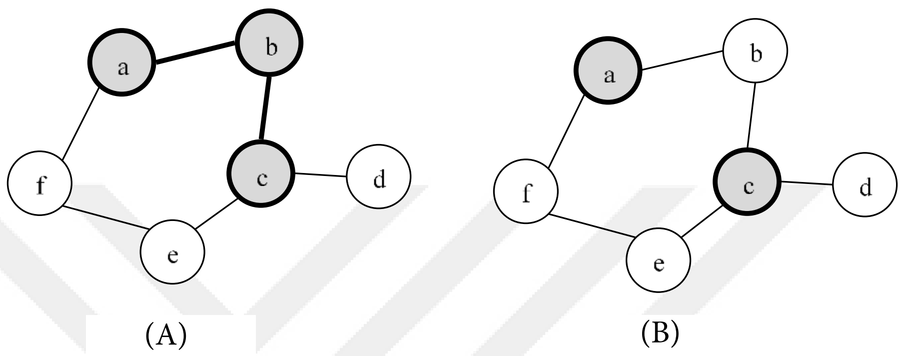

Figure 3.3. *(A) An example of CDS graph (B) DS graph*

As mentioned earlier, SDN controller stores all communication links between IoT objects as a form of graph. Given this graph, the SDN controller will create the CDS topology structure through the following steps:

1. Mark all active nodes in the network as 0.
2. For each active node, if it has at least two non-connected neighbors, then mark it as 1.
3. If the neighborhood set of a node v_i, it is a subset of the neighborhood set of another node such as v_j $\left(\Gamma(v_i) \subseteq \Gamma(v_j)\right)$; and both nodes are marked as 1.
4. If the neighborhood set of node v_i, is a subset of the union of neighborhood sets of two other nodes such as v_j and v_k $\left(\Gamma(v_i) \subseteq \{\Gamma(v_j) \cup \Gamma(v_k)\}\right)$ and these nodes are marked as 1. Then mark v_i as 0.
5. The topology structure will be equal to the set of nodes marked with a value of 1. Since the members of this set are interconnected and all the nodes in the network are associated with this set, so the topology formed will be a CDS.

After the topology is constructed, the optimal routing paths between each node pair will be selected by the SDN controller in the proposed algorithm. This algorithm performs the selection of optimal paths for data transmission by considering both energy and delay criteria in the game theory model. In the following we will discuss the details of this component in the proposed method.

3.3.2. Optimal path selection using game theory

As mentioned earlier, the SDN controller uses game theory to select optimal paths for data transmission. In this way, the game theory model is implemented at the controller node and the optimal paths between each node pair in the network will be identified. In the remainder of this chapter, we will discuss how to do this using game theory.

3.3.2.1. The game model

Game theory tries to mathematically estimate the optimal behavior in strategic situations or in a game in which one's success in choosing depends on the choice of others. A game model consists of a set of players, a set of strategies, and a specific outcome for each combination of strategies. Winning every game is not only about luck, but it also has its own rules, and each player tries to bring himself closer to the goal by applying appropriate principles.

Since the communication topology of the network in the proposed method is based on SDN architecture, the communication structure between IoT objects is stored as a graph in the SDN controller. The SDN controller describes the network structure as a supply and demand model. In this model, the network nodes are divided into three groups from the routing point of view:

- Source node
- Intermediate nodes
- Destination node

The destination node will pay M if it receives the data P successfully. The source node will also pay Qi to any intermediate node such as vi involved in the routing process. In order to simplify the computation, it is assumed that the value of Qi for all intermediate nodes is equal to Q. Therefore, each object can play a role in the game strategy and be present in the routing path, if it evaluates a positive benefit in participating. This means that the amount of benefit a node receives from sending data is greater than the cost it pays after transmitting it.

We show the game model used in the proposed method as $F = < I, A, U >$. In this model, I represents the set of players. The set $A = \{a_i \mid i \in I\}$ represents players' choices in game strategy, and $U = \{u_i \mid i \in I\}$ represents a utility function.

In a network consisting of n nodes (including source and destination), the game strategy for each node (with the exception of the node whose strategy is ignored in the game model) is described as follows:

$$A_i = \left(a_{i1}, a_{i2}, \dots, a_{(ii-1)}, a_{(ii+1)}, \dots, a_{in}\right) \tag{3.1}$$

In the above relation, $a_{ij} \in \{0,1\}$, and if the node v_j is the next hop in the current path, then $a_{ij} = 1$, otherwise its value will be zero. Since each path has no branch and each intermediate hop has exactly one previous hop and one next hop, so in each A_i vector, only one vector element is equal to one and the other elements are zero. Also, if the strategy of node like i is a completely zero vector, then node i will not play a role in the current path. In the proposed game model, the utility function for node i is described as follows:

$$u_i = K_i\left(B_i - C_{ij}\right) \tag{3.2}$$

In this equation, K_i is defined as a constant of influence. If node i is participating in the current path, then K_i is set to one, otherwise zero. In the above equation, B_i represents the benefit of node i on the path, and C_{ij} indicates the weight of the link (edge) between nodes i and j. In the above equation, the benefit of node i on the path is calculated as follows:

$$B_i = b_i \prod_{v_i}^{v_k} p_i \tag{3.3}$$

In this respect, p_i represents the probability of forwarding the data received by node i. This criterion is calculated by computing the ratio of the number of packets previously sent by node i divided by the number of packets received by it. Also, the coefficient b_i is calculated as follows:

$$b_i = \begin{cases} M - h.Q & \text{if } i \text{ is source} \\ Q & \text{otherwise} \end{cases} \tag{3.4}$$

Where, h referes to the number of intermediate nodes in the path. Energy and delay criteria will be used to calculate the weight of each intermediate hop (C_{ij}) in equation (3.2). Therefore, the cost function C_{ij} consists of two separate and independent parts and each part of this function depends on one of the energy and delay criteria. Below, we will explain how to calculate the cost function C_{ij}.

A) Energy: In the path selection process, the higher energy levels of the nodes located in the path will be desired, because this will reduce the probability of sudden outage of node energy and disruption of the routing process. In this case, the energy-dependent part of the cost function in the proposed method will be calculated as follows:

$$C_{E_{ij}} = \frac{E_j \mu_j}{E_{max}} \tag{3.5}$$

In the above equation, E_j is the current energy level of node j and E_{max} is the initial energy of this node. Also, if node j has the minimum required energy for activation ($E_j > E_{min}$), then node j will be able to participate in the game strategy and $\mu_j = 1$, otherwise μ_j will be equal to zero.

B) End-to-End Delay: The second criterion for evaluating the cost of communication with a node is delay. The delay of node i, is defined as the time interval between the point of data transmission to node i and the point of successful delivery confirmation from it. For forwarding data of node i through node j, the delay-dependent part of the cost function in the proposed method will be calculated as follows:

$$C_{D_{ij}} = \left\lceil \frac{D_{i,j}}{\omega} \times \varphi \right\rceil \tag{3.6}$$

In this respect, $D_{i,j}$ is the Euclidean distance between two nodes, and ω, φ parameters are delay ratio and delay constant, respectively. As mentioned in the previous section, the distance between two nodes can be estimated by measuring RSSI of the nodes.

In the proposed method, after calculating two independent cost segments, the cost function is calculated as follows:

$$C_{ij} = \frac{1}{C_{E_{ij}} . C_{D_{ij}}} \tag{3.7}$$

In the next step of the proposed method, the SDN controller will use the game model presented in this section to select the optimal path between each pair of objects. In the following section we will describe the process of route selection based on the proposed game model.

3.3.2.2. Optimal path selection

In the proposed approach, the SDN controller uses utility function equation (3.2) to select optimal multi-hop path between each pair of objects. It should be noted that the utility function for all intermediate nodes on the selected path must be positive. Therefore, the purpose of the proposed SDN controller node is to select paths with the following two properties:

- The utility function for all the intermediate nodes on the selected path must be positive.
- The selected route must have the lowest cost function equation (3.7).

In order to achieve these goals, we use Dijkstra algorithm (J.-C. Chen, 2003) in the SDN controller. For this purpose, in each iteration of the Dijkstra algorithm, if the value of the utility function is negative for a hop, then that link (edge) will be eliminated. The steps of proposed algorithm for selecting the best path by SDN controller, are shown in the following pseudo code. Due to the use of the Dijkstra algorithm, the time complexity of this algorithm is $O\ (n^2)$.

```
Input: G(V,E), source vs , destination vq
Output: optimal path between source and destination
```

```
begin
  // Initializing
  W= Null; // W is set of labeled nodes
  L(vq) = 0;
  M(vq) = 1;
  - for all vi in {V-vq}
    L(vi)= Infinity;
    Previous(vi) = Undefined;
    M(vi) = 1;
  - end for;

  // Main Loop
  - while( (vs is not in W) & (Neighbor(W) is not Null) )
    Select vj is in V , such that ∀vk ∈ {V − vj}, L(vj) ≤ L(vk);
     remove vj from V ;
    add vj to W;
     - for all vi in V such that (vi,vj) ∈ E
      x = L(vj) + C+ij;
      - if (L(vi) > x)
        L(vi) = x; // label of vi node
        M(vi) = pi .M(v) ;
   - if ( (M(vi) - Cij ) < 0)
   delete edge (vi,vj) from E
        - else
          Previous( vi) = vj ;
   - end if;
   - end if;
    - end for;
  - end while;
end.
```

4. EVALUATION AND RESULTS

This chapter introduces the simulation aspects following by discussing the difference between the proposed method and the comparison method. Then we will discuss the description of the simulation environment, after that we will evaluate the results and experiments for the three different scenarios (changing the number of IoT nodes, changing the velocity of the nodes, and changing the communication range) respectively.

4.1. Introduction

MATLAB software was used to evaluate the performance of the proposed method. In order to achieve comprehensive and valid results, the performance of the proposed method has been investigated in various scenarios in this chapter. Therefore, in this chapter, we will evaluate the proposed method with respect to energy consumption and end-to-end delay criteria and compare the results of the proposed method with previous methods in the literature. In order to evaluate the improvement of network performance in the literature, we compare the simulation results with the Opportunistic Routing - Best-fit Traversing (OR-BFT) algorithm in (AlZubi, Al-Maitah, & Alarifi, 2019). This opportunistic routing (OR) is based on best-fit traversing (BFT) algorithm to improve the accessibility of the device in a precise manner. The best-fit algorithm in OR-BFT discovers flawless neighbors for resuming interrupted communications in a prolonged manner. The opportunistic local information based searching process avoids frequent disconnection and redundancy that is common in a single device multi-application scenario. On the other hand, the proposed method can achieve the same goal (improving the accessibility of the device) by using SDN architecture, with less cost and more efficiency. The OR-BFT algorithm uses a combination of Opportunistic Routing and Best-fit traversing. Our method also uses a game model to construct paths that outperform best-fit algorithm. In the following, we will present the results after describing the details of the simulation environment and the parameters used. Simulation Environment

The simulation is performed in MATLAB software. In the simulation environment, we have considered some mobile nodes with variable speed which move freely within the network area. Random Waypoint (RWP) movement model was used to simulate the mobility of nodes. RWP is a basic model for the description of movement patterns in mobile nodes. In this model, a mobile node moves along a zigzag line and its movement direction changes periodically.

The simulation parameters are presented in Table 4.1. These parameters are considered constant during tests and are used as a criterion for comparison with similar methods.

Table 4.1. *Simulation parameters*

Parameter	Value
Area Dimension	200 * 200 m
Number of Nodes	75 to 175 mobile nodes
Mobility of Nodes	0.5 to 2.5 m/s
Transmission Range	30 to 50 m
Packet Size	1 KB
Buffer Capacity	10 KB
Simulation time	Transmitting 100K packets

4.2. Simulation Results

The following experiments were performed to evaluate the efficiency of the proposed method:

1. **Changing the number of IoT nodes:** In this experiment, the number of IoT nodes in the network is changed from 75 to 175 nodes and end-to-end delay, total energy consumption and Packet Delivery Ratio (PDR) are calculated for these changes.
2. **Changing the velocity of IoT nodes**: In this experiment, the velocity of the IoT nodes is changed from 0.5 to 2.5 m/s. Then end-to-end delay, total energy consumption and PDR are calculated for each velocity value.
3. **Changing the communication range of IoT nodes:** In this experiment, the effect of changing communication range of IoT nodes on the performance of the proposed method will be calculated.

In all of these experiments, the obtained results are compared with OR-BFT algorithm presented in (AlZubi et al., 2019). In the following, we will describe the results.

4.2.1. Changing the number of IoT nodes

The purpose of this experiment is to investigate the effect of changing network density on end-to-end delay and total energy consumption criteria in the proposed method. To this aim, in this experiment, the number of IoT nodes was changed from 75 to 175 nodes. The speed of each IoT node has been set as a random value between 0.5 and 2.5 m/s. Other simulation parameters have been set according to Table 4.1. It should be noted that the results shown in this section are the average results of 10 repeated tests. Figure (4.1) illustrates the effect of the number of IoT nodes on the end-to-end delay.

As the number of nodes in the network increases, the traffic load of the network will increase as well as the number of requesting nodes. The increment of traffic load will result in an increment of latency in routing. Thus, the average end-to-end delay will increase as the number of nodes in the network increases. These results show that the proposed method can work well against this increase. According to figure (4.1), the proposed method can reduce the average end-to-end delay by 8.76 % compared to OR-BFT. This improvement can be a result of using SDN-based topology in the proposed method.

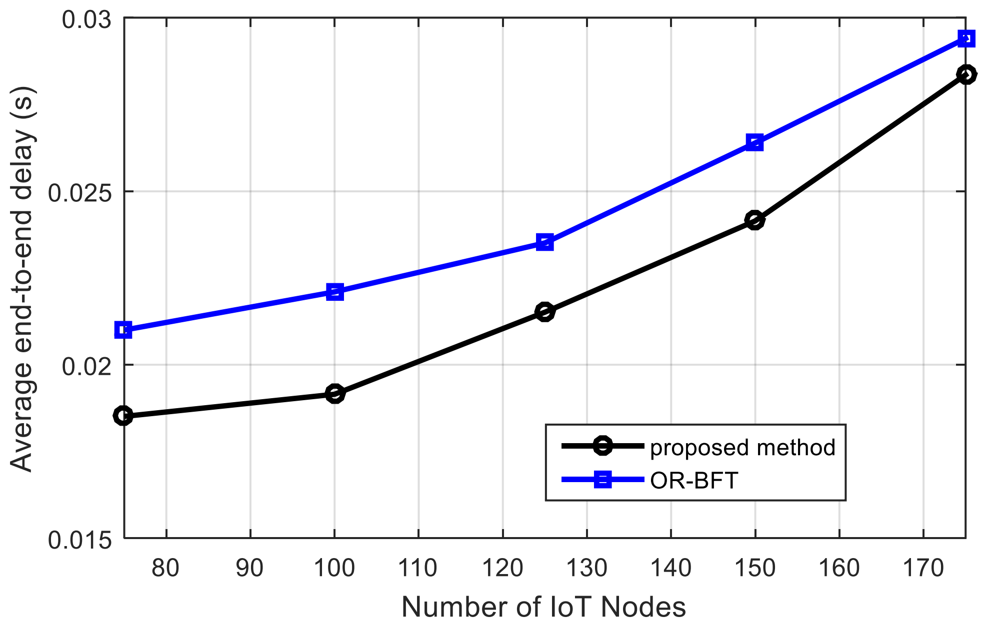

Figure 4.1. *End-to-End delay versus number of IoT nodes*

Also, Figures (4.2) and (4.3), illustrate the effect of number of IoT nodes on total energy consumption and packet delivery ratio respectively.

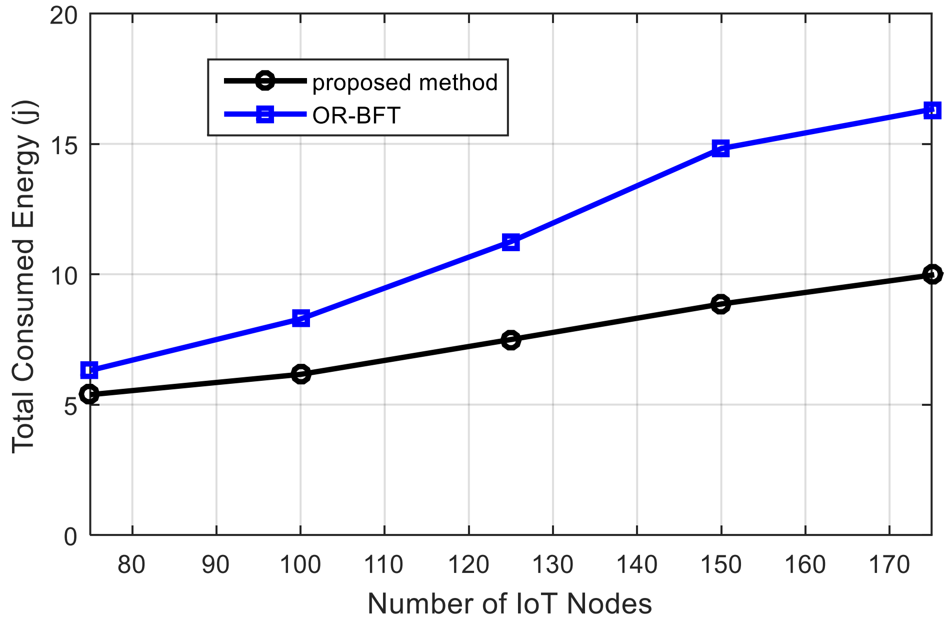

Figure 4.2. *Total energy consumption versus number of IoT nodes*

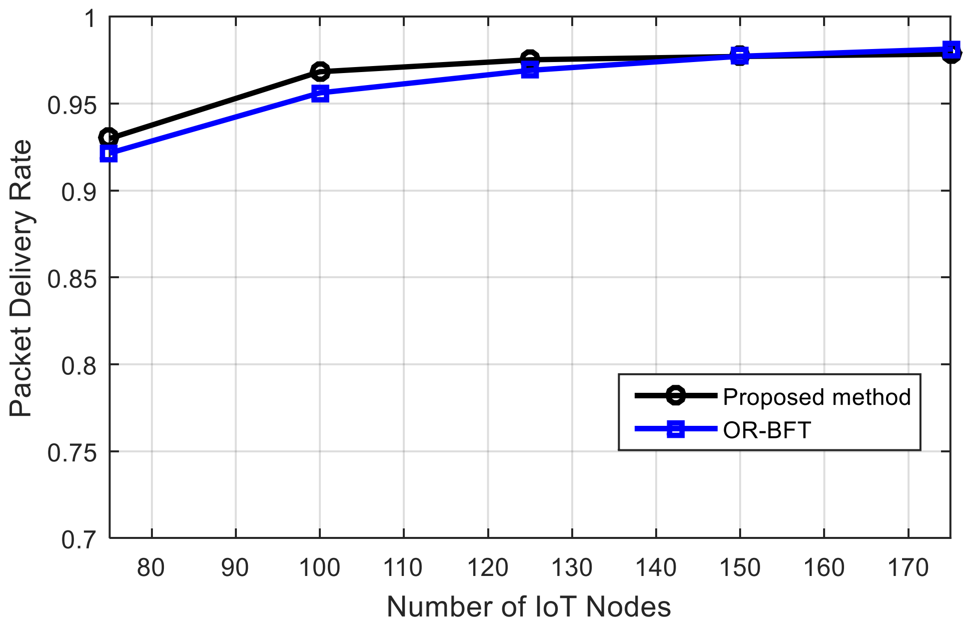

Figure 4.3. *Packet delivery ratio versus number of IoT nodes*

Increasing the number of IoT nodes actually means increasing the amount of energy consumed. Because each node is constantly consuming some energy based on its topological location and operating conditions. As a result, as shown in Figure (4.2), the total energy consumption increases as the number of nodes increases. The proposed method can more effectively resist this increase because using SDN-based topology in the proposed method will eliminate the need for all broadcast operations at the beginning of the data transmission and route selection processes. This causes energy consumption to grow less. Obtained results show that the proposed method can reduce energy consumption by 33.55% compared to OR-BFT.

On the other hand, increasing the number of IoT nodes will results in improving PDR; because, increment of nodes in a fixed area will increase network density. Thus, average number of neighbors for each IoT node will increase also. This means that the average number of paths between each pair of nodes will increase. As a result, the probability of constructing more efficient routes will increase. As shown in Figure (4.3), using the game model, the proposed method can perform 0.9% better than OR-BFT in terms of PDR.

4.2.2. Changing the velocity of IoT nodes

In this experiment, we intend to investigate the effect of node mobility changes on the performance of the proposed method. In this experiment, the number of wireless nodes in the network is set to 100 and the velocity of these nodes varies from 0.5 to 2.5 m/s. For these changes, end-to-end delay and energy consumption criteria have been calculated. Each experiment has been repeated 10 times and average values have been considered as final results. Other simulation parameters are selected according to Table (4.1). In Figure (4.4) the end-to-end delay versus velocity of nodes is presented.

Based on the results shown in Figure (4.4), the proposed method can reduce the routing end-to-end delay. The game model used in the proposed method, uses delay criterion as one of the factors to choose the optimal path between source and destination nodes. This feature has made the path selection strategy of the proposed algorithm to select routes with less end-to-end delay. Also, the SDN-based topology structure used in the proposed method can control IoT communications and this model significantly prevents the exchange of control packets with the neighbor nodes. These reasons have made the proposed method to perform 12.22 % better than the compared method in terms of end-to-end delay.

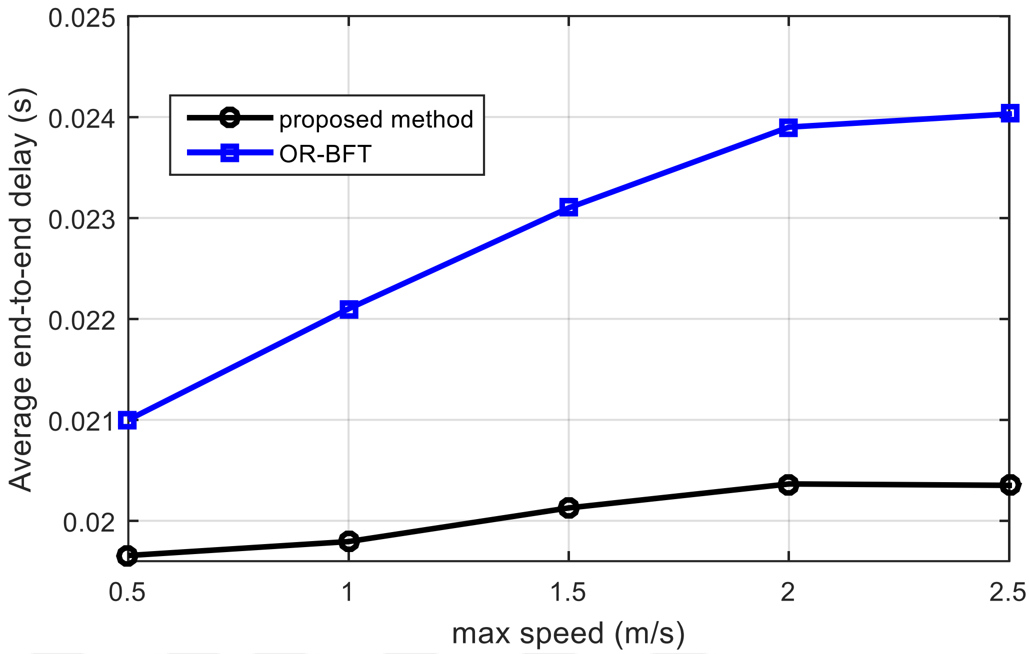

Figure 4.4. *End-to-End delay versus velocity of the nodes*

In Figures (4.5) and (4.6), the total energy consumption of the entire network and packet delivery ratio for different velocities of nodes are shown, respectively.

Increasing the speed of nodes increases the total energy consumed in the network because increasing the speed of a node, reduces the durability of links between neighbor objects, and thus increases the probability of disconnection in the intermediate hops of a path which results in losing packets and reducing PDR. This feature also increases the total energy consumption. Considering the energy consumption criterion as one of the factors for choosing the right strategy of the game model in the proposed method leads to data transmission through routes that reduce the network energy consumption as much as possible. On the other hand, as suggested, the proposed approach uses SDN-based architecture to reduce communication overhead, which in turn reduces energy consumption in the network. As shown in Figure (4.5), the proposed method in most cases reduces energy consumption, compared to the method. As a result, it can be said that software-defined networking and game theory can improve energy efficiency in the network. According to these results, the proposed method can reduce energy consumption by 6.2% and increase PDR by 6.24%, compared to OR-BFT.

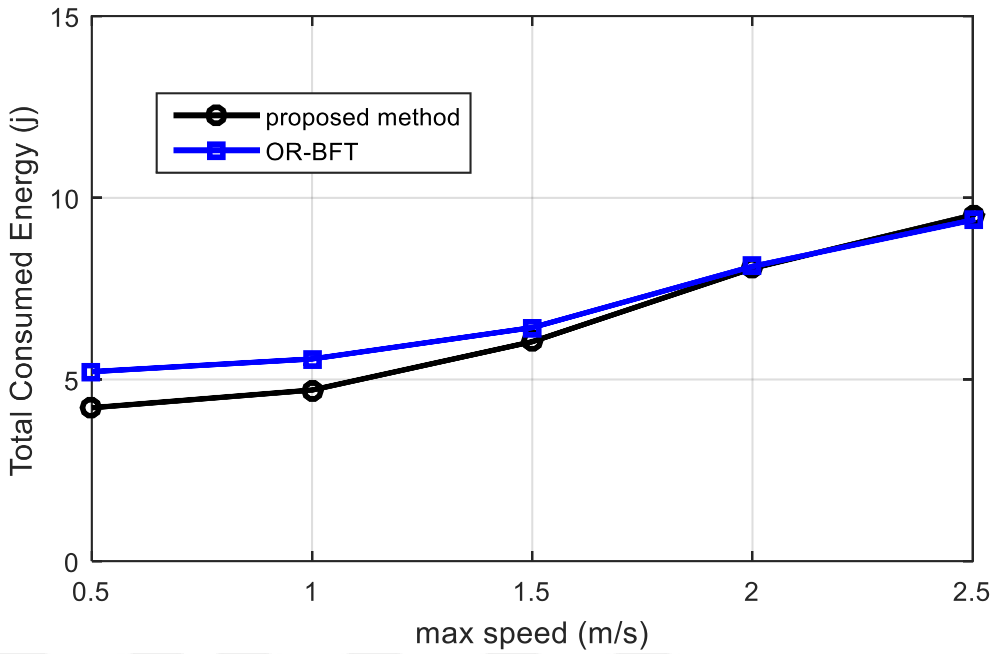

Figure 4.5. *Total energy consumption versus velocity of the nodes*

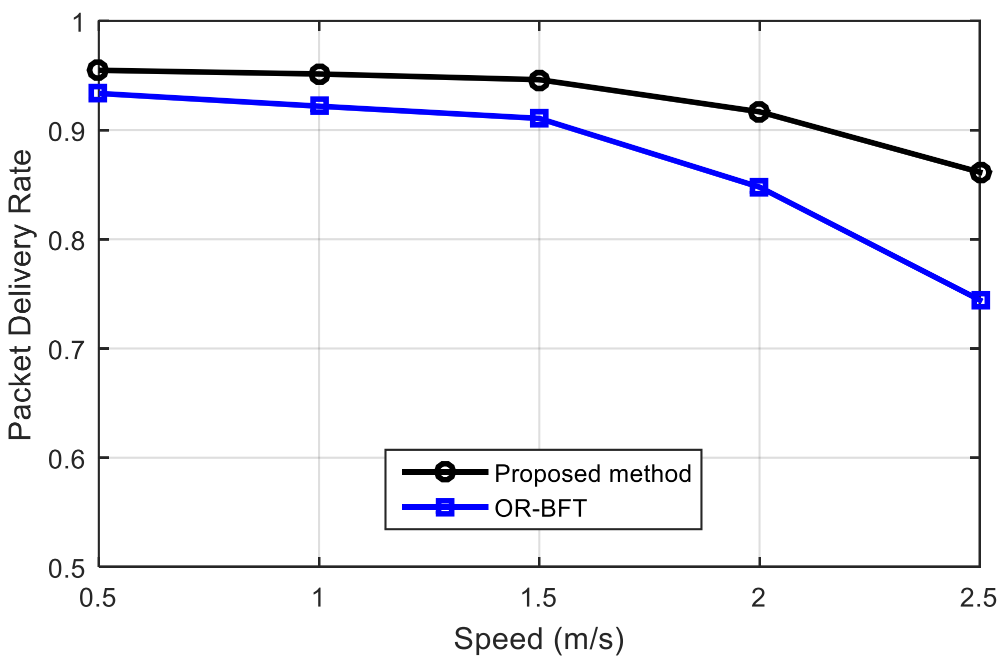

Figure 4.6. *Packet delivery ratio versus velocity of the nodes*

4.2.3. Changing the communication range

In this experiment, we intend to investigate the effect of communication range changes on the performance of the proposed method. In this experiment, the communication range of the nodes in the network was changed from 30 to 50 meters and the evaluation criteria were calculated for these changes. The number of nodes in the network is set to 100 and the velocity of each node is considered as a random number between 0.5 and 2.5 m/s. Other simulation parameters have been set according to Table (4.1).

Figure (4.7), shows the end-to-end delay versus the communication range of the nodes.

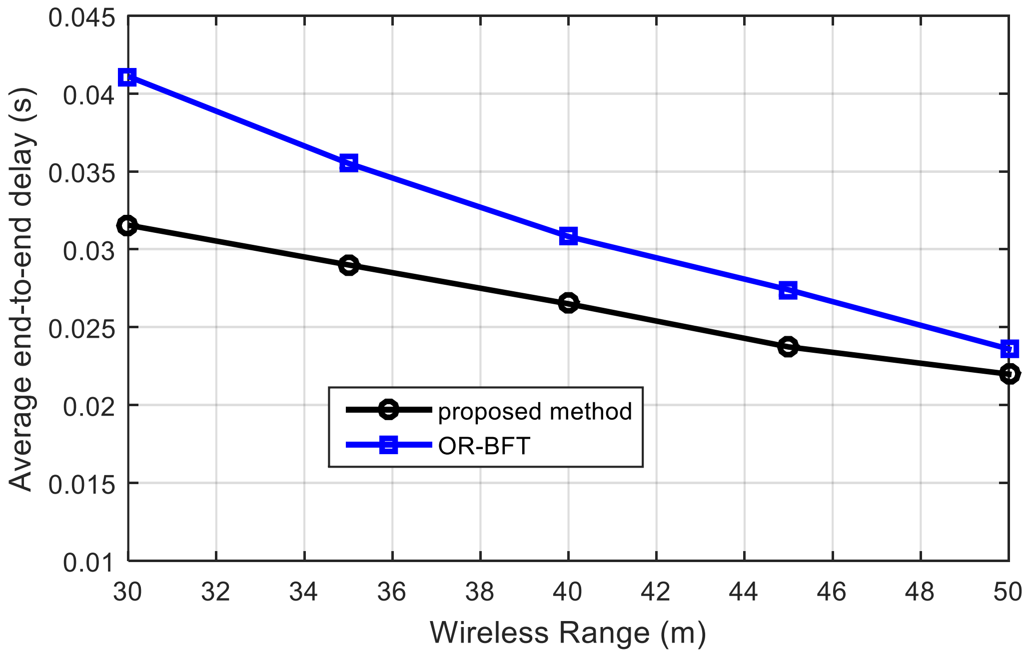

Figure 4.7. *End-to-End delay versus communication range of the nodes*

Increasing the communication range of the IoT nodes will increase the average number of active objects in the vicinity of each mobile node, thereby increasing the number of available intermediate nodes for each transmission path on the network. As a result, the proposed route discovery algorithm can select routes with less end-to-end delay. This feature has reduced the average end-to-end delay by increasing the communication range of the IoT nodes. As the results of this experiment show, using the proposed method, it is possible to decrease the average end-to-end delay in the network by 16.2 % compared to OR-BFT.

In Figures (4.8) and (4.9), the total energy consumption of the entire network and packet delivery ratio for different values of communication ranges have been shown, respectively.

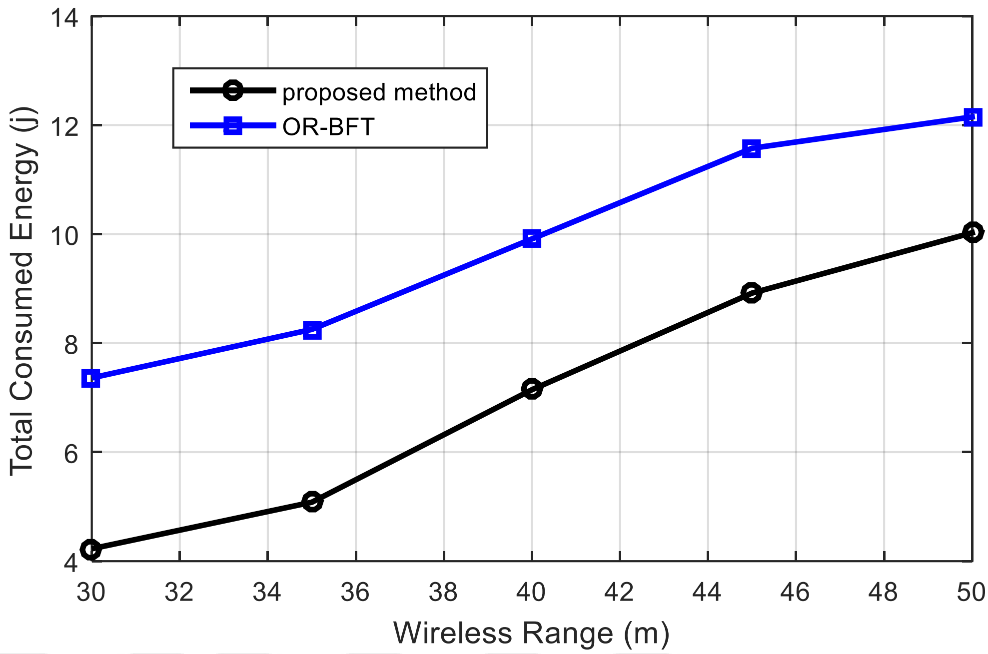

Figure 4.8. *Total energy consumption versus communication range of the nodes*

By increasing the communication range of the nodes, each carrier node can send its packet to intermediate nodes at farther locations. This feature will increase the average length of routing hops, which results in an increase in energy consumption. But as shown in the results of this experiment, the energy consumed in the proposed approach is 28.12% less than the compared one. And this reduction in energy consumption can be attributed to the use of game theory in the proposed method because the proposed method avoids the increase in energy consumption by considering energy as a detrimental criterion in the game strategy.

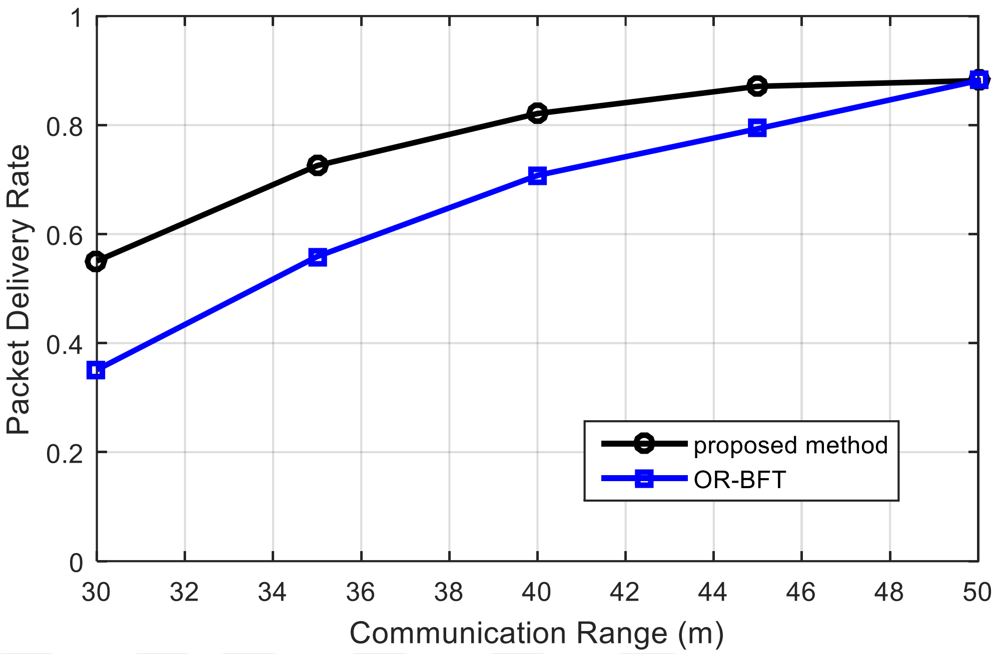

Figure 4.9. *Packet delivery ratio versus communication range of the nodes*

As shown in Figure (4.9), increasing the communication range will result in increasing the PDR, because reaching further nodes will increase the average number of neighbors for each IoT node. This means increasing the overall network density. As mentioned earlier, by the increment of network density, the probability of constructing more efficient routes will increase. This experiment shows that using the game model, the proposed method can perform 16.94% better than OR-BFT in terms of PDR

5. CONCLUSION AND FUTURE WORKS

5.1. Conclusion

In this thesis, a new model to reduce energy consumption and delay in IoT network using a combination of game theory and software-defined networking was presented. The proposed model to reduce energy consumption in IoT architecture consists of two main components. These components are:

- SDN-based topology
- Optimal path selection based on game theory

Using a combination of SDN-based architecture and game theory can be considered as one of the innovative aspects of the proposed approach which has not been addressed in previous studies. In the proposed model, SDN-based architecture is used to improve the conventional communication scheme between IoT objects. In this architecture all IoT objects are connected to an SDN controller and the management of communication between these objects is performed through the SDN controller node. This will increase the flexibility of the entire network. In the proposed SDN-based architecture, the computational unit of the objects will be out of reach of the decision algorithm. All decisions will be made by the controller to select the routing paths, which allows all the processing power of the network resources to be allocated to the data processing algorithms, thereby increasing the processing power of the objects. Once the SDN-based topology is formed, the optimal path between each pair of objects will be discovered and selected by a game theory-based model. This algorithm performs the path selection procedure by considering both energy and delay criteria simultaneously.

The proposed model was simulated in MATLAB environment. Evaluating the performance of the proposed method in the simulated environment and comparing its performance with previous research show that the proposed method will reduce energy consumption and end-to-end delay in the network.

5.2. Future Works

- Replacement of the proposed game model with optimization algorithms such as genetics, ant colony, etc. can be studied in future works.
- Using linear programming to determine the optimal paths between each pair of objects in the SDN controller could be the subject of future research.

- In future works, it is recommended to study the performance of the proposed method in presence of Fog/Edge computing architectures.

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APPENDIX

CURRICULUM VITAE

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EDUCATION

Master of Science, Telecommunication Engineering

Anadolu University, *Eskisehir – Turkey (2017-Current)*

Bachelor of Science, Telecommunication Engineering

Balochistan University of IT, Engineering, Management sciences (BUITEMS), Pakistan (2009-2013)

PROFESSIONAL EXPERIENCE

Network/RF Engineer

Asia Consultancy Group (ACG), Kabul, Afghanistan (Nov 2014 – Aug 2016)

Worked as Network and RF engineer with ACG on multiple telecommunication and broadcasting projects located in Kabul, Parwan, Panjsheer provinces, Afghanistan.

Responsibilities:

- Coordinated with project manager and administer efficient working of two projects in Kabul city and suburbs of Kabul province and prepare all project controls and update as per requirement and document all processes.
- Prepared optimization reports for the GSM sites of the TDF phase-1 project after the drive tests and reported to the NPI manager.
- Technical responsible for Digital Television Broadcasting Terrestrial 2 DVBT2 project of Afghanistan Broadcasting System (ABS)/OQAAB, prepared the weekly reports and submitted to Network Planning and Implementation (NPI) manager.
- Planning and Implementation of Point to Point (P2P), Point to Multipoint (P2MP) radio links between the TV stations, Main Office, and the main transmitter.
- Identified and resolved any technical issues in the DVBT2 project. Prepared/scheduled effective appraisal reports to be submitted to the NPI manager.
- Managed and ensured all materials in compliance with required quality for all projects and prepare reports for all final project turn over and maintain records of all implementation procedures and prepare progress reports for same.

Network Engineer

National Rural Access Program (NRAP), Ministry of Public Works,
Kabul, Afghanistan (May 2014 – Nov 2014)

Worked as Network Engineer with the NRAP project of Ministry of Public works, in Kabul Afghanistan.

Responsibilities:

- Prepared procurement list for IT and Network appliances, submit it to Information Technology manager, and Procurement department.
- Troubleshoot all the hardware and software technical issues in communication between different offices.
- Performs other job-related duties or special projects as assigned.

Engineering Skills

1) **Software:**
   - Microsoft Office
   - MATLAB
   - Map info
   - Google Earth Pro
   - Familiar to almost all UI based built-in software of Routers, Switches, Hubs, Transmitters
2) **Hardware:**
   - Excellent skills of cabling
   - Very good knowledge of working with networking appliances (Routers,Switches, Hubs)
   - Installation of P2P Microwave antennas
   - Installation of P2MP Microwave antennas

Additional Skills:

- Very good Administration and Management skills
- Excellent teamwork ability
- Microsoft Office
- logistics' basics administration
- Leadership and Planning skills
- Excellent communication skills
- Proficient in the preparation and implementation of Telecommunication/Network, developing status reports and project schedule.

Language Skills:

- Persian – Mother tongue
- Pashto -- Excellent
- English – 80 TOEFL-iBT (2015)
- Turkish – C1
- Urdu – Very Good

Grant and Funding:

- B.Sc. final year project's funding by the R&D, Pakistan.

Certifications:

- Certificate of appreciation for outstanding, hard work and support from Asia Consultancy Group ACG. Sep 2016.
- Certificate of appreciation for outstanding work and support from NRAP, Ministry of Public Works. Nov 2014.
- Certificate of membership, Pakistan Engineering Counsel ACT 1976, Mar 2014.
- Certificate of English medium of instruction, Balochistan university of Information Technology, Engineering & Management Sciences BUITEMS, Jan 2014.
- Best volunteer award, BUITEMS Student affairs, Dec 2013.

- Certificate of excellence Poster design competition (1st Place), Balochistan university of Information Technology, Engineering & Management Sciences BUITEMS. April 2013.
- Certificate of excellence Project design competition, Balochistan university of Information Technology, Engineering & Management Sciences BUITEMS. April 2013
- Certificate of Participation, Volunteer in organizing 8th convocation BUITEMS, Dec 2012.

Membership:

- Anadolu University’s International students club, current.
- Anadolu university's European student's forum (Association des Etats Généraux des Etudiants de l'Europe) - AEGEE Eskisehir, current.
- Student Affairs, Balochistan university of Information Technology, Engineering & Management Sciences BUITEMS, 2011-2012.

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AVAILABLE UPON REQUEST