MODELING AND ANALYSIS OF QUALITY OF SERVICE (QOS) IN HETEROGENEOUS WIRELESS NETWORK

BY

MOSHARROF HUSSAIN MASUD

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering

Kulliyyah of Engineering
International Islamic University Malaysia

SEPTEMBER 2022

ABSTRACT

Heterogeneous Wireless Network (HWN) is the next-generation wireless communication system platform where Internet services will be offered and delivered through multiple technologies like WiFi, WiMAX, and GSM. Many Internet applications require high bandwidth and therefore, bandwidth aggregation has been considered as one of the effective solutions for high bandwidth required applications in HWN. There are few issues have been raised for bandwidth allocation in HWN including the selection of Radio Access Technology (RAT), bandwidth allocation among these RATs, and packet reordering occurrence leading to quality degradation in HWN. This research aims to model and analyze the RAT section methods, resource allocation policy, and packet reordering pattern. Three models have been followed with the numerical and simulated results to achieve better performances of the proposed models. A multi-criteria selection-based method, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) has been applied to select the most suitable RAT in HWN. The TOPSIS method has been selected due to its sensitivity to the application requirements. The method has been coded in Matlab and numerical models have been analyzed. The TOPSIS method achieved to select the most appropriate RATs based on the types of services like voice calls, file downloading and video streaming according to their priority settings. Resource allocation has been modeled based on Shapley Value, a game-theoretic approach. The amount of bandwidth has been calculated to transmit 600Kbps data over the three networks where 225Kbps, 141Kbps, and 233.33Kbps have been transmitted through, WiFi, Cellular, and WiMAX networks respectively. Packet reordering is a common phenomenon in HWN that has been investigated briefly to analyze its metrics and pattern. An algorithm has been proposed to measure the associated delay and reordering entropy caused due to packet reordering in HWN. It has been compared to the Earlies Delivery Path First (EDPF) method both for CBR and VBR applications on the NS3 simulator. A video clip for 1800 seconds has been transmitted from sender to receiver to analyze the performance in HWN. Based on the simulation results, the proposed method shows around 40% improvement over the EDPF method both for CBR and VBR applications in terms of packet reordering delay. Moreover, the proposed method has shown a significant achievement for the reordering entropy over the EDPF method for both applications.

الملخص

هي منصة الجيل القادم من أنظمة الاتصالات اللاسلكية حيث سيتم (HWN) الشبكة اللاسلكية غير المتجانسة هناك العديد من .GSM و WiMAX و WiFi تقديم خدمات الإنترنت وتقديمها من خلال تقنيات متعددة مثل تطبيقات الإنترنت التي تتطلب عرض نطاق ترددي كبير ، وبالتالي ، فقد تم اعتبار تجميع النطاق الترددي كأحد ومع ذلك ، هناك عدد قليل من .HWN الحلول الفعالة للتطبيقات ذات النطاق الترددي العالي المطلوبة في بما في ذلك اختيار تكنولوجيا الوصول HWN القضايا التي أثيرت لتخصيص عرض النطاق الترددي في ، وتخصيص عرض النطاق الترددي بين هذه الفئران وإعادة ترتيب الرزمة يؤدي إلى تدهور (RAT) الراديوي ، وسياسة تخصيص RAT في هذا الصدد ، يهدف هذا البحث إلى نموذج وتحليل طرق قسم .HWN الجودة في الموارد ونمط إعادة ترتيب الحزمة. تم تطبيق أسلوب اختيار معايير متعددة ، تقنية لتفضيل النظام عن طريق بسبب TOPSIS تم اختيار طريقة .HWN في RAT لاختيار أنسب (TOPSIS) التشابه إلى الحل المثالي وقد تم تحليل النماذج العددية. حققت طريقة Matlab حساسيتها لمتطلبات التطبيق. تم ترميز هذه الطريقة في استنادًا إلى أنواع الخدمات مثل المكالمات الصوتية وتنزيل الملفات وتدفق RATs اختيار أنسب TOPSIS الفيديو وفقًا لإعداداتها ذات الأولوية. وقد تم تصميم تخصيص الموارد على أساس منهجية اللعبة النظرية ، وهي: عبر الشبكات الثلاث حيث تم نقل 225 Kbpsتم حساب كمية النطاق الترددي لنقل بيانات 600 .Shapley قيمة و Cellular و WiFi كيلو بايت في الثانية و 141 كيلوبت في الثانية و 233.33 كيلوبت في الثانية عبر شبكات تم بحثها باختصار من أجل تحليل HWN على التوالي. إعادة ترتيب الحزمة هي ظاهرة شائعة في WiMAX مقاييسها ونمطها. تم اقتراح خوارزمية لقياس التأخير المرتبط وإعادة ترتيب الإنتروبيا الناجم عن إعادة ترتيب و CBR لكل من تطبيقات (EDPF) وتمت مقارنته مع طريقة مسار توصيل الإرث الأول HWN الرزم في تم نقل مقطع فيديو لمدة 1800 ثانية من المرسل إلى جهاز الاستقبال لتحليل الأداء في .NS3 على محاكي VBR لكل من EDPF بناءً على نتائج المحاكاة ، تُظهر الطريقة المقترحة تحسنًا بنسبة 40٪ عن طريقة .HWN من حيث تأخير إعادة ترتيب الحزمة. علاوة على ذلك ، فقد أظهرت الطريقة المقترحة VBR و CBR تطبيقات لكل من التطبيقات EDPF إنجازًا كبيرًا لإعادة ترتيب الإنتروبيا على طريقة.

APPROVAL PAGE

The thesis of Mosharrof Hussain Masud has been approved by the following:

Prof. Dr. Farhat Anwar
Supervisor

Asst. Prof. Dr. Suhaimi Abd Latif
Co-supervisor

Prof. Dr. Shihab A. Hameed
Internal Examiner

Prof. Dr. Kamaruzzaman Seman
Internal Examiner

Prof. Dr. Nor Kamariah Nordin
External Examiner

Assoc. Prof. Dr. Saim Kayadibi
Chairman

DECLARATION

I hereby declare that this thesis is the result of my own investigations, except otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Mosharrof Hussain Masud

Signature …………………………………… Date ……………………..

INTERNATIONAL ISLAMIC UNIVERSITY MALAYSIA

DECLARATION OF COPYRIGHT AND AFFIRMATION OF FAIR USE OF UNPUBLISHED RESEARCH

MODELING AND ANALYSIS OF QUALITY OF SERVICE (QOS) IN HETEROGENEOUS WIRELESS NETWORK

I declare that the copyright holder of this thesis are jointly owned by Mosharrof Hussain Masud and IIUM.

Affirmed by Mosharrof Hussain Masud

…………………………	……………………
Signature	Date

"To my beloved parents, my siblings and my family members for their inspiration, encouragement, guidance and facilitating for me to be where I am today"

This thesis is especially dedicated to all of you.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to Allah (swt.) for enabling me to accomplish writing this thesis successfully.

I wish to express deep appreciation, gratitude, and respect to my supervisor Professor Dr. Farhat Anwar for his continuous support, guidance, and valuable advice that encouraged in enriching my knowledge with new ideas. Special thanks to my co-supervisor Dr. Suhaimi Abd Latif for his intensive support. This thesis would not have been the same if it had not been guided and maintained by my supervisors. I also pay my thanks to the Department of Electrical and Computer Engineering, International Islamic University for various financial support.

I also thank my friend brother Sadakatul Bari for his guidelines, intimate friend Abul Kalam Azad, Br. Akhtaruzzaman, and other colleagues. My special thanks go to my beloved wife Farzana Sharmin for her continuous support and inspiration to complete this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

$\overline{m^{t}{}_{j,u}}$	Normalized vector of decision matrix $\overline{D^t}$
S_i	ALBAM listed possible path of i
L_i	Arrival time of packet *i*
B_i^{av}	The available bandwidth for network i
TI_i	Average interval time
B_l	The bandwidth of path l
R_l	A data rate of the wireless interface *l*
d_p^m	Delay for the m packet over path p
$\Delta_{i,j}^{(m)}$	Delay of multiple paths i,j for packet m
$d_i^{(m-1)}$	Delay of path i for packet m-1
$d_j^{(m}$	Delay of path j for packet m
D^t	Decision matrix
a_i	Estimated delivery time of packet *i*
$B_m^{\max}$	The maximum bandwidth for the MD m
$B^{k,\max}$	Maximum bandwidth requirements
$B^{k,\min}$	Minimum bandwidth requirements
M^t	Multimode terminal in HWN
S_{i-1}^{*}	Nash equilibrium strategies of all players other than player i
S_i^{*}	Nash Equilibrium strategy of player i
r_{ij}	Normalized performance rating of parameter *j* on network *i*
N_{fast}	Number of fast link packets
D_l	One way wire line delay on path *l*
d_l	One way wireless delay on path *l*
α_l	Packet loss rate on path *l*
S_i^p	Pareto optimal strategy
$m_{j,u}$	Performance rating of RAT
P^t	Priority of each call in S^t
π_r	Probability of overall splitting of packets
$\phi_{i,j}^{(m)}$	Probability of path switching from path i to path j
D_p^m	Propagation delay
Q_p^m	Queuing delay
Q_i	Queuing delay experienced by a packet on path i
B_i^k	The required bandwidth for network i
S^t	Set of services supported in HWN
$W^{t,i}$	Set of the user-specified weighting vector

d_i^l Shortest delivery time for packet *i* via path *l*

SAW_i Simple Additive Weighting on network *i*

t_d Total end-to-end delay

w_j Weight of parameter *j*

V_i^* Weight parameter $\Delta_{i,j}^{(m)}$ of path i

B_{mns} Bandwidth allocated to Mobile Device (MD) m from network n through BS/APs

$\Omega(\Delta_{i,j}^{(m)})$ The conditional probability of packet reordering when the path switches from i to j with the function $\Delta_{i,j}^{(m)}$

G_n The geographical coverage area of network n

$B_m^{\min}$ Minimum bandwidth for the MD m

MEW_i Multiplicative Exponential Weighted on network *i*

$\pi_i()$ Payoff function of player i

S_n Set of base stations or access points for networks n

A_l A time when path l is available

$TOPSIS_i$ TOPSIS method for i network

C_n Transmission capacity of network n

$idealsolution_i$ Ideal solution for network i

$worstsolution_i$ Worst solution for network i

LIST OF ABBREVIATIONS

2G	Second Generation
3G	Third Generation
4G	Fourth Generation
AHP	Analytic Hierarchy Process
ALBAM	Adaptive Load Balancing Algorithm
ASM	Adaptive Self-clocked Multi-server
BAR	Bandwidth Aggregation Router
BER	Bit Error Rate
CBR	Constant Bit Rate
CDMA	Code Division Multiple Access
CEA	Constrained Equal Award
CMTS	Concurrent Multipath Transmission Scheme
DBA	Dynamic Bandwidth Aggregation
E-DCLD	Effective Delay Controlled Load Distribution
EDGE	Enhanced Data Rates for GSM Evolution
EDPF	Earliest Delivery Path First
ELECTRE	Elimination and Choice Expressing Reality
FIFO	First In First Out
GPRS	General Packet Radio Service
GRA	Grey Relational Analysis
GSM	Global System for Mobile
HWN	Heterogeneous Wireless Network
IP	Internet Protocol
ISP	Internet Service Provider
ITU	International Telecommunication Union
JRRM	Joint Radio Resource Management
LAN	Local Area Network
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
MADM	Multi Attribute Decision Making
MCDM	Multiple Criteria Decision Making
MCGDM	Multi Criteria Group Decision Making
MD	Multimode Device
MEW	Multiplicative Exponential Weight
MIMO	Multiple Input and Multiple Output
MMD	Multimode Mobile Device
MTCS	Multipath Transmission Control Scheme
NS2	Network Simulator 2
NS3	Network Simulator 3
OMNeT++	Objective Modular Network Testbed in C++
OPNET	Optimized network Engineering Tools
OSI	Open System Interconnection
OTcl	Object-Oriented extension of Tcl
QoS	Quality of Service
RA	Random Arrival
RAT	Radio Access Technology

RBD	Reorder Buffer-occupancy Density
RD	Reorder Density
RR	Round Robin
RRM	Radio Resource Management
SAW	Simple Additive Weight
SCTP	Stream Control Transport Protocol
SIG-ACK	Signaling Acknowledgement
SRR	Surplus Round Robin
SS	Simple Summation
TCP	Transport Control Protocol
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TS-EDPF	Time Slot based Earliest Delivery Path First
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunication System
VBR	Variable Bit Rate
VoIP	Voice over Internet Protocol
WiFi	Wireless Fidelity
WiMAX	World Interoperability for Microwave
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WRR	Weighted Round Robin

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

The next generation of wireless technology systems is being devised with the vision of heterogeneity where a Multimode Device (MD) would be connected to multiple wireless networks like Global System for Mobile (GSM) communication, Wireless Fidelity (WiFi), and World Interoperability for Microwave Access (WiMAX). Quality of Service (QoS) for real-time applications has been given the highest priority (Falk et al., 2022). Bandwidth is one of the main resources of these technologies; though operated independently it needs to be aggregated among these technologies in a Heterogeneous Wireless Network (HWN). To address these issues, this chapter aims to present the research motivation, the problem statement, the research objectives, the research methodology, the research scope, and finally, the thesis organization.

1.2 BACKGROUND

Heterogeneous Wireless Network (HWN) is the next generation of wireless communication system platform where Internet services are offered and delivered through multiple technologies like WiFi, WiMAX, Cellular, and Long Term Evolution (LTE). Some Internet applications require high bandwidth, and therefore, bandwidth aggregation has been considered one of the effective solutions for high bandwidth required applications in HWN. A Multimode Device (MD) user can access any of these resources based on his application demand running on his device. The most popular and available wireless technology is cellular followed by WiFi and WiMAX. Therefore, the aggregation of these different bandwidths into an MD can play an important role to enhance the performance of real-time applications. In a heterogeneous wireless network, an MD user can toggle among different Radio Access Technologies (RATs) and select the best suitable RAT for its applications. The general architecture of HWN is depicted in Figure 1.1 for a typical scenario. The Bandwidth Aggregated Router (BAR) at the sender side splits the packets and transmits them through the suitable RATs in the HWN. On the receiver side, the BAR merges the sent packets and the receiver can receive the data. Hence, there are a few issues that have been identified, how the BAR can determine which RAT is the most suitable for the data transmission, how much amount of data can be transmitted, and how to deal with packet reordering issues due to the multiple path transmission. This research aims to investigate these three issues and proposes a comprehensive solution for three segments.

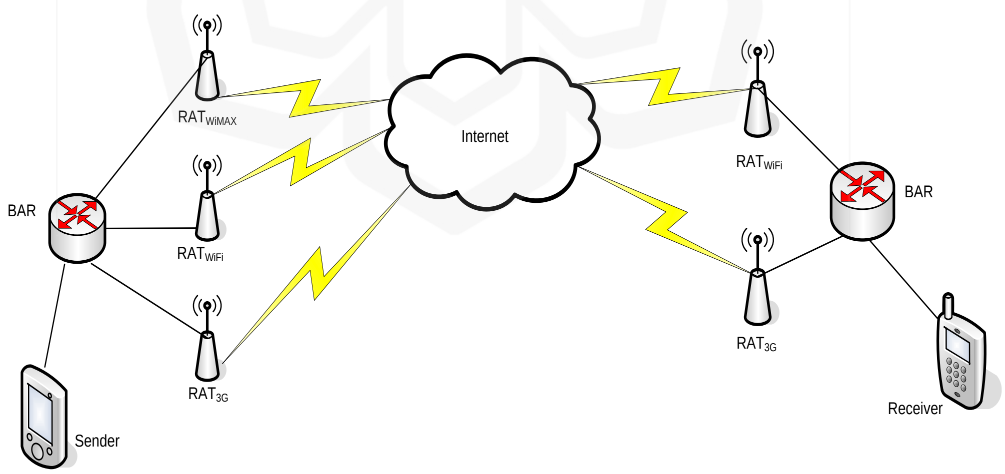

Figure 1. 1: General architecture of HWN

If there is no single RAT that does not have enough bandwidth to meet the desired applications, multiple RATs can be selected and their bandwidth can be aggregated to create a single logical link that has enough bandwidth to serve the application (Ramaboli, Falowo & Chan, 2012; Bosch, De Schepper, Zeljković, Famaey & Latré, 2020). In an HWN environment, a multimode device is connected with one default interface where two other interfaces are also available. If the default interface is unable to transmit the data, the available interfaces could make a logical link to transmit that data. The concept is explained in figure 1.2 whereby the default interface, 3G is not capable of handling this data and, therefore, makes a logical link in cooperation with other interfaces.

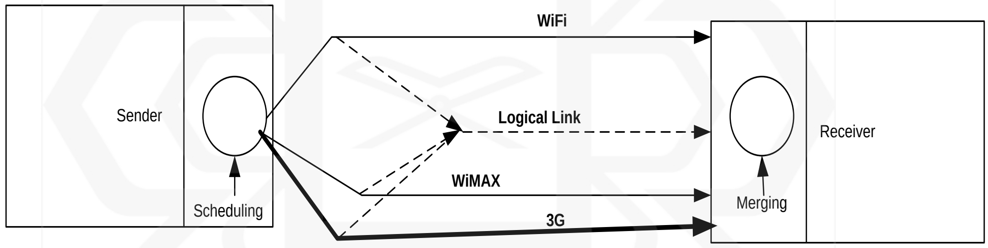

Figure 1. 2: Logical link in HWN

However, sharing available resources does not guarantee effective real-time data transmission. Delay, packet loss, and packet reordering can occur by sharing multiple RATs. Therefore, inconsistencies need to be resolved by designing an appropriate resource-sharing scheme to ensure that data is transmitted sequentially from the same sender and application (Wenxuan et al., 2022).

1.3 RESEARCH MOTIVATION

Bandwidth aggregation or resource sharing has numerous benefits, providing quality data transmission, especially for real-time applications. Network capacity can be scaled up for network operators to fulfill high bandwidth demands that increase throughput and decrease latency (Welzl, Teymoori, Gjessing & Islam, 2020; Glaroudis, Iossifides & Chatzimisios, 2020). Furthermore, resource sharing can increase service reliability, improve fault tolerance by transmitting redundant data over multiple RATs and increase coverage area by combining multiple RATs (Srivastava, Prakash & Tripathi, 2020; Kim, Lee & Chong, 2019; Singh & Rai, 2019). Wireless resources can be shared from multiple RATs to create a high-speed logical link and can be used in a multimode device for high bandwidth-demanding applications. It has been shown in Figure 1.1 that the sender MD is connected to a router where three routes are available, namely WiMAX, WiFi, and 3G but on the other hand, the receiver side has two RATs, namely WiFi and 3G. The sender Bandwidth Aggregation Router (BAR) will split the packets among these three RATs and the receiver BAR will merge the packets and direct them to the receiver. Therefore, there is a high possibility to occur packet reordering on the receiver side. If the desired application needs high bandwidth and cannot be transmitted through only one RAT, for example, 3G then it can be shared with other available RATs' bandwidth like WiMAX and WiFi and make a logical link. In this case, the transmitting packets can be transmitted through different RATs as multiple RATs are shared (Yun et al., 2022). In addition to that, application centric RAT selection also been considered to achieve the required QoS in the HWN (Garg, 2022).

1.4 PROBLEM STATEMENT

Determination of a suitable RAT is one of the most challenging issues in HWN. Bandwidth is the main resource in HWN that has been operated independently in GSM, WiFi, and WiMAX. The aggregation of these bandwidths into an MD is a great challenge. Bandwidth aggregation, bandwidth allocation, Radio Resource Management (RRM), or resource sharing are similar terms and the focus of this research. Packet reordering, packet scheduling, interference-free channel assignment to appropriate RAT, and power consumption are the most important issues in HWN. Packet reordering causes a delay in the real-time transmission that leads to packet loss. Packet scheduling is needed for efficient transmission over the HWN. This research only addresses the details of RAT selection, resource allocation, and packet scheduling including packet reordering while power consumption is not included in the scope of this research. It is expected that bandwidth aggregation will enhance the real-time transmission and increase the efficiency of data transmission.

1.5 RESEARCH PHILOSOPHY

Real-time data transmission including audio and video transmission has been increasing due to the advancement of technology over wireless media. Voice over IP (VoIP) and video streaming applications have been gaining popularity due to their low cost.

However, wireless media suffer due to limited bandwidth resources. Real-time data transmission demands high bandwidth that could not be available from a single RAT in certain places. To transmit high bandwidth-demanding data, bandwidth aggregation in a particular area is needed. It has been observed from the literature that there are still some challenges to aggregating the bandwidth into an MD for real-time data transmission. Selection of RAT, data distribution among RATs, and packet scheduling are the main issues for the RRM system in HWN. It is expected that designing an efficient resource management scheme will enhance the quality of real-time data transmission in HWN.

The proposed scheme will be implemented in the sender router that aggregates the available interfaces and the receiver end router that splits among available interfaces. For example, it can be assumed that the sender side has three interfaces, namely, GSM, WiFi, and WiMAX while the receiver side has two interfaces like GSM and WiFi as depicted in Figure 1.1. It is also assumed that all these interfaces are connected to the Internet with the same delay on all links and the sender sends the UDP-based video stream to the receiver. The aggregation sender router will divide the UDP datagram into three pieces in such a way that 10% datagram will be sent through the GSM interface, 30% will be sent using the WiFi interface and 60% will be sent via the WiMAX link. The receiver router will receive 30% and 70% of these datagrams using GSM and WiFi interfaces, respectively. Hence, it is expected that the proposed bandwidth aggregation scheme can improve the QoS in HWN and enhance real-time application transmission efficiently.

1.6 RESEARCH OBJECTIVES

i. To investigate the findings of HWN and assesses their current limitations for RAT selection, resource allocation, and packet reordering issues.

ii. To develop three models that incorporate RAT selection, resource allocation, and packet reordering.

iii. To validate and benchmark the proposed design through numerical and simulation modeling.