OPTIMIZING VERTICAL HANDOVER DECISION MAKING IN HETEROGENEOUS WIRELESS NETWORKS

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

BEERAPPA RAMA CHANDAVARKAR

DEPARTMENT OF INFORMATION TECHNOLOGY

NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,

SURATHKAL, MANGALORE - 575025

AUGUST, 2016

DECLARATION

by the Ph.D. Research Scholar

I hereby declare that the Research Thesis entitled **OPTIMIZING VERTICAL HANDOVER DECISION MAKING IN HETEROGENEOUS WIRELESS NETWORKS** which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in **Information Technology** is a *bonafide report of the research work carried out by me.* The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

(IT09P02, Beerappa Rama Chandavarkar)
Department of Information Technology

Place: NITK-Surathkal
Date: August 27, 2016

CERTIFICATE

This is to *certify* that the Research Thesis entitled **OPTIMIZING VERTICAL HANDOVER DECISION MAKING IN HETEROGENEOUS WIRELESS NETWORKS** submitted by **BEERAPPA RAMA CHANDAVARKAR** (Register Number: **IT09P02**) as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of **Doctor of Philosophy**.

Prof. G. Ram Mohana Reddy
Research Guide

Prof. G. Ram Mohana Reddy
Chairman - DRPC

Acknowledgments

I would like to express my sincere gratitude to my research guide Prof. G. Ram Mohana Reddy, Head, Department of Information Technology, NITK, Surathkal, for his guidance, support and encouragement throughout my research work.

I express heartfelt thanks to my Research Progress Assessment Committee (RPAC) members Prof. Murulidhar N. N. and Prof. Muralidhar Kulkarni, for their valuable suggestions and constant encouragement to improve my research work.

I sincerely thank all teaching, technical and administrative staff of the Computer Science and Engineering, and Information Technology Department for their help during my research work.

I would like to thank my parents for their exhaustive support and encouragement and I owe this work to my wife Tulasi, sons Master Srajan and Master Sankalp. Without them, surely, this research work would not have been possible.

Finally, I would like to express my gratitude to my students for proof reading the papers submitted to conferences, journals and also the thesis.

Place: NITK-Surathkal B. R. Chandavarkar

Date: August 27, 2016

Abstract

Ever-increasing demands of users and the development of modern communication technologies have led to the evolution of 4^{th} Generation (4G) heterogeneous wireless networks. The integration of wireless networks of different characteristics and the demands of: user, mobile device, applications and service providers result in issues such as seamless mobility management, security, administration, billing, etc. The key issue among these challenges is the handover process of mobility management for seamless communication of mobile devices in heterogeneous wireless networks with maximized users' satisfaction. Always Best Connected (ABC) services anywhere at anytime is one of the key objectives of 4G in integrating IEEE and cellular technologies.

This thesis mainly addresses the Vertical Handover Decision (VHD) making in heterogeneous wireless networks for seamless communication of mobile devices. The dependency of VHD on multiple attributes in heterogeneous wireless networks demands an optimized handover process in terms of minimized complexity with improved reliability and flexibility. Several existing methods like fuzzy logic, neural networks, game theory and Multiple Attribute Decision Making (MADM) have been used for VHD. However there are still open issues such as, complexity, reliability and flexibility in these methods. MADM is one such method which supports multiple attributes based decision with minimum complexity for multiple criteria dependent VHD in heterogeneous wireless networks. The main problem with the MADM method is unreliable network selection and the rank reversal problem due to its dependency on attributes normalization and weight calculation methods. Hence, this thesis presents an optimized MADM method referred to as Simplified and Improved Multiple Attributes Alternate Ranking (SI-MAAR) for overcoming the limitations of classical MADM methods. Thus, SI-MAAR method is optimized in terms of minimized computational complexity and improved network selection reliability with the elimination of rank reversal problem. With MATLAB simulations, the analytical model of SI-MAAR method is demonstrated for 100% reliable VHD with the 0% rank reversal problem in heterogeneous wireless networks.

Further, many of the classical MADM methods used in VHD in heterogeneous wireless networks depend on attributes weight computation techniques such as, Entropy, Variance, Analytical Hierarchy Process (AHP) etc. Expectations of users and applications during VHD in heterogeneous wireless networks is subjective in nature. AHP is one such popular method which supports computation of subjective attributes weight. The main problem with AHP is computation of reciprocal matrix through the involvement of the decision maker which will result in unreliable attributes weight and further to unreliable network selection in VHD. Hence, this thesis also presents an optimized AHP method referred to as Simplified and Improved Analytical Hierarchy Process (SI-AHP) to overcome unreliability in attributes weight computation. Thus, SI-AHP method is optimized in terms of minimum involvement of the decision maker resulting in reduced attributes weight computational complexity with the improved reliability. With MATLAB simulations, SI-AHP method is demonstrated for 100% reliable attributes weight computation used for VHD in heterogeneous wireless networks.

In this thesis, SI-MAAR and SI-AHP methods are numerically analysed using MATLAB simulations and results demonstrate that SI-MAAR and SI-AHP methods are outperforming classical MADM and AHP methods respectively. Similarly, simulations using network simulators and further validation by testbed-based approaches are also required for justifying the proposed analytical solutions. Among the available open source network simulators such as NS2, NS3, OMNET++ and J-Sim, simulation of heterogeneous wireless networks is supported only in NS2's distribution provided by National Institute of Science and Technology (NIST). The major problems with the NIST's NS2 distribution are: (i) support for only one mobile node simulations (ii) minimal support for VHD and (iii) non-availability of configuration and result analysis tools such as TCP Performance Evaluation suite for simulations of heterogeneous wireless networks. Hence, this thesis also presents NS2 based Evaluation Suite for User Datagram Protocol applications referred to as "ES-UDP" for configuration, simulations and results analysis of multiple mobile nodes in heterogeneous wireless networks. Thus, ES-UDP tool provides both text and graphical results of handover, packets sent and received, throughput, packet delay and jitter of heterogeneous wireless networks simulations.

On the other hand, real time experimentation is subject to testbed's deployment complexity, cost and time. The other major challenge of testbed experimentations is Linux kernel support for heterogeneous wireless networks. Although for handover execution, network layer protocol-Mobile IPv6 is supported by Linux kernel, the major issues are lack of testbed deployment informations, high cost, and nonavailability of testing checkpoints and debugging procedures. Thus, this thesis also presents a cost-effective testbed of Mobile IPv6 for handover execution in homogeneous and heterogeneous wireless networks. Further, this testbed can be used for VHD by deploying proposed solutions: SI-MAAR and SI-AHP in the Linux kernel.

To summarize, the main contributions of the thesis are, improving the network selection reliability and the elimination of rank reversal problem of classical MADM methods used in VHD of heterogeneous wireless networks with "SI-MAAR". Simplifying the attributes weight computation and improving the attributes weight reliability of AHP with "SI-AHP". Ease of NS2's configuration, simulation and results analysis of multiple mobile nodes experimentations in heterogeneous wireless networks with "ES-UDP" tool. Finally, simple and cost-effective Mobile IPv6 testbed for handover execution and further to handover decision in heterogeneous wireless networks.

Keywords: Vertical Handover Decision, Multiple Attribute Decision Making, Analytical Hierarchy Process, Mobile IPv6, Sigmoidal utility function.

Contents

List of Figures

List of Tables

Abbreviations and Nomenclature

Abbreviations

4G	4^{th} Generation
ABC	Always Best Connected
AHP	Analytical Hierarchy Process
BA	Binding Acknowledgement
BU	Binding Update
CI	Consistency Index
CN	Correspondent Node
CoA	Care of Address
ED	Euclidean Distance
ES-UDP	Evaluation Suite for User Datagram Protocol
FN	Foreign Network
GRA	Grey Relational Analysis
HA	Home Agent
HN	Home Network
HoA	Home Address
HWNs	Heterogeneous Wireless Networks
IETF	Internet Engineering Task Force

MADM	Multiple Attribute Decision Making
MATLAB	MAtrix LABoratory
MEW	Multiplicative Exponent Weighting
MIH	Media Independent Handover
MIHF	Media Independent Handover Function
mip6d	MIPv6 daemon
MIPv6	Mobile Internet Protocol version 6
MN	Mobile Node
ND	Neighbor Discovery
NIST	National Institute of Science and Technology
radvd	Router Advertisement Daemon
RI	Random Consistency Index
SAW	Simple Additive Weight
SI-AHP	Simplified and Improved Analytical Hierarchical Process
SI-MAAR	Simplified and Improved Multiple Attributes Alternate Ranking
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UDP	User Datagram Protocol
UMIP	Usagi Patched Mobile IPv6
VHD	Vertical Handover Decision
VHE	Vertical Handover Execution
WiFi-AP	WiFi-Access Point
WiMAX-BS	WiMAX-Base Station

Nomenclature

λ_{max}	Largest eigenvalue
ζ	Zeta constant
a_j	Network's attribute j
a_{ij}	Network i versus attribute j
E_j	Entropy of attribute j
i	Network i
j	Attribute j
l_j	Linguistic value of attribute j
m	Total number of attributes
n	Total number of networks
N_1, N_2, N_3, N_4, N_5	Networks
r_{kj}	Pair-wise comparison of attribute k and attribute j
s	Total number of applications
$Score_i$	Score of the network i
U_{ij}	Utility of network i for attribute j
w_j	Weight of attribute j
wc_{ij}	Weight cost matrix of network i attribute j
x_α	Lower limit of a_j
x_β	Upper limit of a_j
x_{ij}	Normalized a_{ij}
${A_j}^+$	Positive ideal solution
${A_j}^-$	Negative ideal solution

Chapter 1

Introduction

Users' interests and demands for better service and simplicity is the driving force behind the evolution of new technologies and thereby enhancing the existing technologies. Ever-increasing demands of users, resulted in the evolution of communication technology from 1^{st} Generation (1G) to 3^{rd} Generation (3G). Moreover, seamless communication of mobile devices from anywhere at anytime resulted in a next-generation communication technology referred to as Beyond 3G (B3G) or 4^{th} Generation (4G) that includes LTE (Long-Term Evolution) with the following key features (Aretz et al. 2001; Hui and Yeung 2003; Siddiqui and Zeadally 2006).

- High usability: anytime, anywhere, and with any technology
- Support for multimedia services at low transmission cost
- Personalization
- Integrated services

4G is the integration of different existing communication technologies such as Wireless Local Area Networks (e.g., IEEE 802.11a/b/g and HiperLAN/2), cellular networks, Wireless Metropolitan Area Networks (e.g., IEEE 802.16) and LTE (Stevens-Navarro et al. 2008; Chen et al. 2014). These are administrated by different service providers to provide Mobile Node (MN) 'Always Best Connected (ABC)' services anywhere at anytime. Integration of these heterogeneous communication technologies, referred to as Heterogeneous Wireless Networks (HWNs), is one of the ways of achieving seamless communication between MNs. In 4G networks, users are provided with the requested services using any of the available networks supported by the users' MNs. The minimum expected data rate supported in 4G is 100 Mbps, so 4G networks provide not only telecommunication services, but also data and multimedia services with low per-bit transmission cost. 4G networks, along with supporting network-controlled selection of available networks, also support MN-controlled network selection using the preference of the users and MNs. Accordingly, in 4G networks, single interface MNs are evolved as multiple heterogeneous interface MNs allowing the users to access multiple services simultaneously.

Table 1.1: Areas of applications of 4G

Sl. No.	**Area**	**Feature**	**Application**
1	Public Safety	Availability, Security, Responsiveness, Reliability and Robustness	Database checks, verification of biometric data, wireless video surveillance, automatic number plate recognition, tracking and monitoring public safety officers which are particularly important for firefighters and officers involved in search and rescue operations.
2	Commercial and Military		To collect, analyse, store and distribute information from/to different entities and for various contexts.
3	Healthcare		Real-time waveform delivery, alarm notification, asset tracking or e-prescription and remote patient monitoring service.
4	Smart farming and environmental monitoring		Remote monitoring and controlling of agricultural farms.
5	Vehicular Networks		Navigation safety applications (crash prevention, road problem warnings, etc.), entertainment: download multimedia, multi-user games, vehicle monitoring, social networking and emergencies.

Because of the above mentioned features of 4G wireless networks, its area of application is not only limited to multimedia services, but also extends to several other application areas of day-to-day activities such as, public safety, commercial and military, healthcare, smart farming and environmental monitoring, and vehicular networks (see Table 1.1) (Zekri et al. 2012).

Also, the features and applications of heterogeneous wireless networks as shown in Table 1.1 will provide many challenging research issues, such as multi-interface MNs, transmission power and co-channel interference, topology and routing, mobility and handover, load balancing, interoperability, security, billing, and Quality of Service (QoS) provisioning (Hui and Yeung 2003). Many of the challenging issues of heterogeneous wireless networks are policy-dependent among service providers, whereas, mobility management of heterogeneous wireless networks is one such issue to be addressed by the MNs or network-controlled devices involved in the communication of ABC anywhere at anytime. The seamless communication of MNs cannot be successfully achieved, unless mobility management in heterogeneous wireless networks is properly taken care of by the MN or by network-controlled devices.

1.1 Mobility Management

In 4G heterogeneous wireless networks, mobility management is the key issue to support roaming of mobile nodes from one network to another of different technologies. Additionally, mobility management in heterogeneous wireless networks can be centralised, decentralised or hybrid (Piamrat et al. 2011). In the centralised mobility management, a central node situated at the core network is responsible for the control of MNs roaming. The major problem with the centralised approach is, the waste of bandwidth, congestions in the network and one point of failure. Further, in the decentralised mobility management, MNs roaming control can be with access routers, wired-cum-wireless entities such as access point or base stations, or MN itself (Nguyen-Vuong et al. 2007). In the case of MN controlled mobility management, the major issues are load balancing and maximized call drops. Whereas, in mobility management without the MNs involvement, achieving the personalization feature of 4G becomes difficult. In such a scenario, hybrid mobility management, which combines both centralised and decentralised approaches is one of the best options for achieving objectives of 4G. With the hybrid option, the MN after collecting the handover related information from other entities of network will control the roaming to address load balancing and call drop.

1.2 Handover Process

Handover process or handover management is one of the prominent steps of mobility management in heterogeneous wireless networks, which controls the switching of nomadic MNs point of attachment during active communications. Proper management of handover in heterogeneous wireless networks is essential for seamless communication of nomadic MNs. Seamless communication in heterogeneous wireless networks is characterized by minimum: packet loss of an active session, handover delay, signalling traffic overhead and handover failure, resulting in an uninterrupted service (Makaya and Pierre 2008). In heterogeneous wireless communication systems, handover process of mobility management is defined as the process of information gathering about accessible networks, handover decision making, and handover execution to transfer the active session through new selected network (Márquez-Barja et al. 2011; Ahmed et al. 2014). Handover delay (latency) of handover process is the difference between the time of handover process initiation and completion. Signalling traffic overhead of handover process is one of the factors of handover delay. Handover failure during the handover process may result due to unavailability of resources at the network entities, time of handover initiation and the decision of handover execution. A handover process in heterogeneous wireless networks also includes mobility scenarios such as centralised, decentralised or hybrid.

With the coexistence of different communication technologies, handover in heterogeneous wireless networks can be horizontal handover or vertical handover. Handover of nomadic MNs between the similar wireless access technology (homogeneous wireless networks) is called as horizontal handover (Antonopoulos et al. 2013). A handover process in homogeneous wireless networks depends on the received signal strength of accessible networks. An accessible network with the acceptable received signal strength is the network through which an MN continues the active communication in homogeneous wireless networks. In homogeneous wireless networks, handover decision making is the MN-executed process of selecting the best accessible network by comparing the received signal strengths of all available networks in the vicinity of the MN. Whereas, handover of nomadic MNs between different access technologies, referred to as heterogeneous wireless networks, is called vertical handover.

Table 1.2: Network selection parameters of handover process in heterogeneous wireless networks

Sl. No.	Category	Parameter	Effect
1	Network-related (refers to, network conditions and system performance)	Network Coverage	How far an MN can use the services provided by a network.
2		Received Signal Strength	How far an MN can get uninterrupted services from a network.
3		Bandwidth	One of the network resources available to MNs.
4		Load	How quickly a network responds to MNs.
5		Link Quality	Services supported by networks.
6		Security	Confidentiality or integrity provided by the networks to MNs data.
7		Power consumption	Lifetime of MNs.
8	Device-related (refers to terminal capabilities and mobility patterns)	Velocity	Speed at which an MN is moving.
9		Battery power	Remaining lifetime of an MN.
10		Supported radio access technology	Capability of an MN to access a network.
11		Network connection time	How long an MN has been connected to the network.
12	Application-related (refers to a different class of service constraints)	Latency, reliability and data transfer rates	Constraints of MNs applications.
13	User-related (refers to user preferences)	QoS	Constraints of MNs applications.
14		Monetary cost	Charge to be paid by an MN for the utilized services provided by a network.

In heterogeneous wireless networks, the handover may not always be due to weak received signal strength (Antonopoulos et al. 2013), but could also be due to an improvement or degradation in QoS attributes of networks (networks' coverage, received signal strength, bandwidth, load, link quality, security, power consumption, etc.), variations in expectations of user (mobile device application, monetary cost, etc.), mobile device capabilities (velocity, battery power, supported radio access technology, network connection time, etc.) and expectations of application (latency, reliability, data transfer rate, etc.)(Márquez-Barja et al. 2011; Zekri et al. 2012). Table 1.2 list the parameters (or attributes) used in network selection (ranking) during the handover process in heterogeneous wireless networks. Hence, a handover decision making of the handover process in heterogeneous wireless networks is also referred to as Vertical Handover Decision (VHD). Similarly, the handover execution to switch the MN's active communication to a new selected network of heterogeneous wireless networks is referred to as Vertical Handover Execution (VHE).

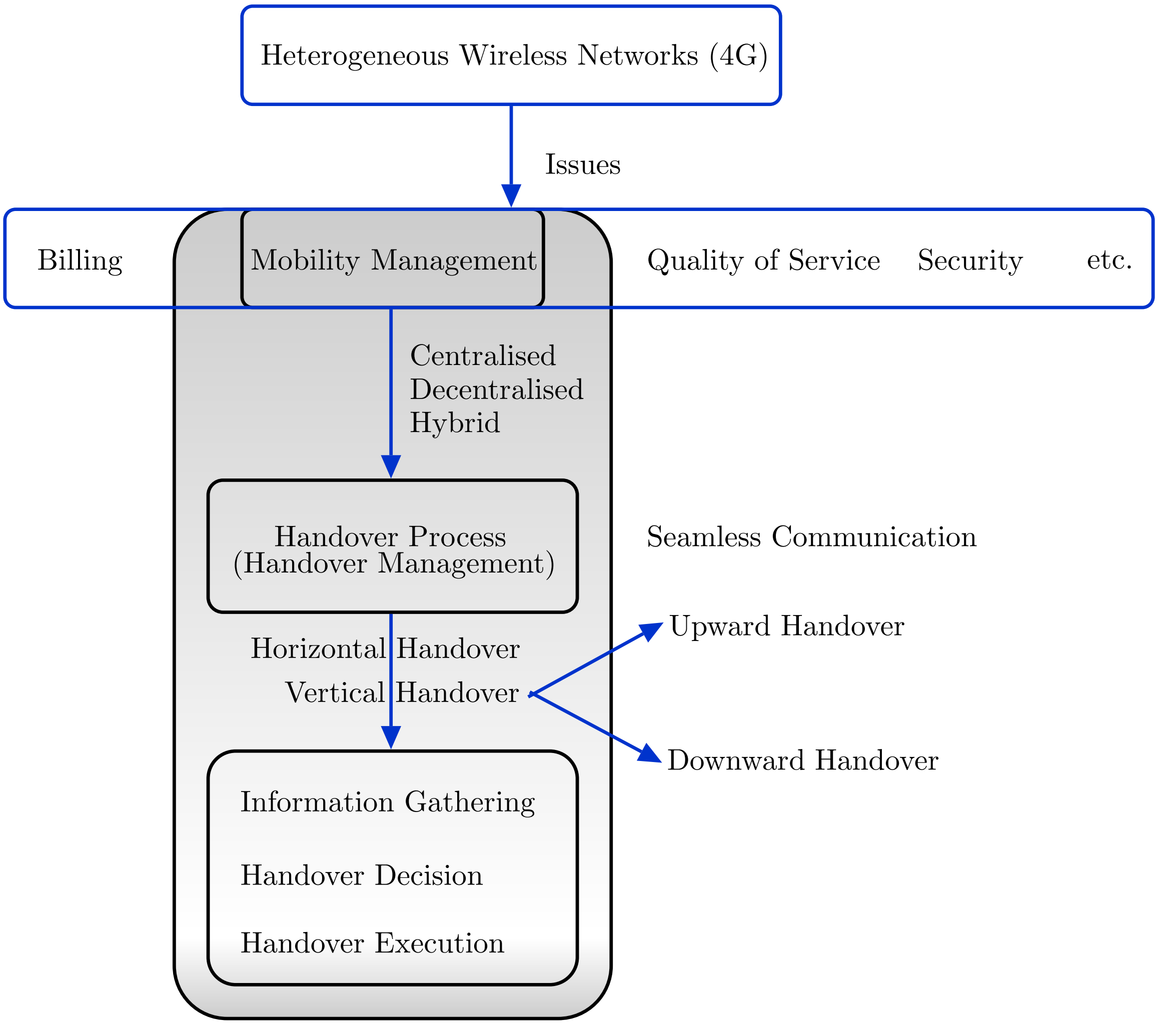


Figure 1.1: Summary of mobility management in heterogeneous wireless networks

Vertical handover in heterogeneous wireless networks can be upward or downward vertical handover (Siddiqui and Zeadally 2006). This depends on switching of MNs active communication from smaller coverage area network like WiFi to larger coverage area network like WiMAX referred to as upward vertical handover or vice-versa referred to as downward vertical handover. Designing an optimized VHD, with heterogeneous information of accessible networks for VHE in heterogeneous wireless networks mobility management, is the main concern of industry and researchers in the successful implementation of 4G for ABC services anywhere at anytime. Figure 1.1 summarizes the issues and concept related to mobility management of heterogeneous wireless networks discussed in previous Sections 1.1 and 1.2.

Recent developments in heterogeneous wireless networks in terms of IEEE 802.21 - Media Independent Handover (MIH), which is used in the handover processes' for information gathering of accessible networks (De La Oliva et al. 2008). Mobile IPv6 (MIPv6) [1] developed by Internet Engineering Task Force (IETF) has handover execution for packet-switched devices in homogeneous and heterogeneous wireless networks (C. Perkins and Arkko 2011).

1.3 Vertical Handover Decision Making

VHD-making is one of the prominent steps of the handover process of mobility management in heterogeneous wireless networks, for selecting a suitable network for the seamless handover of an MN between n accessible heterogeneous wireless networks (McNair and Zhu 2004). Many VHD strategies (Kassar et al. 2008; Yan et al. 2010; Piamrat et al. 2011; Zekri et al. 2012) have been proposed in the literature, such as Function-based, User-Centric, Markov (Stevens-Navarro et al. 2008), Fuzzy Logic (Chamodrakas and Martakos 2012), Multiple Attribute Decision Making (MADM) (Ning and Zhang 2012) and Game Theory (Trestian et al. 2012) with differences in complexity, flexibility and reliability.

However, multiple interface MNs have limited resources, in terms of battery lifetime (Song et al. 2014), computational capabilities and memory. Hence, it is essential to have an optimized and simple multiple attributes VHD-making method for seamless migration of MN in heterogeneous wireless networks. Among the existing VHD schemes, MADM is one of the few strategies that considers multiple attributes with medium complexity (Charilas and Panagopoulous 2010; Zekri et al. 2012). On the other hand, the complexity of other VHD strategies increases with an increase in the number of handover decision attributes.

[1] RFC 6275-Mobility Support in IPv6. Available: `http://www.ietf.org/rfc/rfc6275.txt`

1.4 Mutiple Attribute Decision Making

MADM is one of the methods used in operations research for decision making in the case of multiple attributes or criteria. The background of the MADM approach is, multiple alternatives and each alternative with multiple attributes (criteria). MADM rank the alternatives based on the score computed using the respective alternate's attributes value. The alternate with the maximum score is selected for further processing in operations research. In the scenarios such as heterogeneous wireless networks, network represents an alternative, each with multiple attributes (see Table 1.2) referred to as network versus attribute (a_{ij}).

Many classical MADM methods (Piamrat et al. 2011; Tzeng and Huang 2011) such as Simple Additive Weight (SAW), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)(Behzadian et al. 2012; Yang and Tseng 2013), Multiplicative Exponent Weighting (MEW)(Tzeng and Huang 2011), ELimination Et Choice Translating REality (ELECTRE)(Tzeng and Huang 2011), Grey Relational Analysis (GRA) (Kuo et al. 2008; Tzeng and Huang 2011) and Preference Ranking Organization METHods for Enrichment Evaluations (PROMETHEE)(Yan et al. 2010) are available in operations research. These classical MADM methods rank the alternative (network) based on the computed score. The calculated score of a network using any of the classical MADM methods depends on individual network versus attribute value.

Table 1.2 list the attributes used by the classical MADM methods during VHD in heterogeneous wireless networks. The attributes and their weight used in selecting the candidate network for handover in heterogeneous wireless networks can be grouped as a benefit (higher the value of the network, the better that network) or cost (lower the value of the network, the better that network) attributes. As shown in Table 1.2 attributes of Sl. Nos. 2, 3, 5, 6, 12 and 13 are the benefit attributes and Sl. Nos. 4, 7 and 14 can be grouped as cost attributes. Whereas, attributes of Sl. Nos. 1, 8, 9, 10 and 11 are not a part of benefit or cost attributes.

This thesis mainly focuses on four well known classical MADM methods: TOPSIS, SAW, MEW, and GRA. Table 1.3 summarizes the strengths and weaknesses of TOPSIS, SAW, MEW and GRA.

Table 1.3: Strengths and Weaknesses of TOPSIS, SAW, MEW and GRA

Sl. No.	Method	Advantages	Limitations
1	TOPSIS	Simple, comprehensive, scalable, highly efficient and flexible, and generate accurate results.	Imprecise data cannot be handled, unreliable network ranking and the rank reversal problem.
2	SAW	Easy to understand and implement, and support multiple attributes.	Poor-valued attributes can be outweighed by a very good value of another attribute, unreliable network ranking and the rank reversal problem
3	MEW	Medium implementation complexity and the least sensitive method.	Heavily penalizes alternatives with poor-valued attributes, unreliable network ranking and the rank reversal problem.
4	GRA	Integrates subjective appraisals with numerical statistics and supports multiple attributes with precise solutions.	Complicated, unreliable network ranking and the rank reversal problem.

The major drawbacks with classical MADM methods are:

- Dependency of classical MADM methods on attributes normalization and weight calculation methods, which substantially influences the ranking (selection) of the networks. Further, this results in an uncertainty in selecting the appropriate attributes normalization and weight calculation methods with respect to a specific classical MADM method.

- The way the attributes are normalized or the weight are calculated, depends on the relation between one network's attribute and those of the others existing in the network selection list. The outcome of this dependency is the rank reversal problem with classical MADM methods (Wang and Luo 2009). The rank reversal problem is the reversal of the relative ranking of the networks during the removal and insertion of network in the network selection list.

1.5 Motivation

Decision making systems for the selection of highly reliable alternative based on multiple attributes or criteria is a concern not only in the field of networking, but also in areas such as Logistics and Supply Chain Management, Design of Engineering and

Manufacturing Systems, Business and Marketing Management, Health, Safety and Environmental Management, Human Resources Management, Energy Management, Chemical Engineering, and Water Resources Management (Tzeng and Huang 2011; Behzadian et al. 2012).

One of the main challenges of the classical MADM methods in an overlay HWNs, is the weight calculation of heterogeneous wireless networks-related, application-related, user-related and device-related attributes shown in Table 1.2. The heterogeneous nature of the attributes increases the computational complexity and time of the attributes' weight calculation, which in turn affects the performance of MADM's VHD approaches. Among the available subjective weight calculation methods, Analytical Hierarchy Process (AHP) computes the attributes weight using the perceived pairwise comparison of the attributes (Saaty 1990; Saaty 2006). The main drawback of AHP is manual computation of the reciprocal matrix with pairwise comparisons of the attributes. This leads to higher computational time for attributes weight calculation and an inconsistency represented by a consistency ratio greater than 0.1. In the manual pairwise comparisons of the attributes, the decision maker should be competent enough to identify the relational differences between the attributes.

The other major problems with classical MADM methods are their dependency on the attributes normalization and weight calculation methods. Hence, these dependencies not only provoke unreliable selection of the network for handover (Charilas and Panagopoulous 2010), but also give rise to a rank reversal (abnormality) problem, in the case of the removal and insertion of the network in the network selection list during network ranking (Wang and Luo 2009). The rank reversal problem with classical MADM methods leads to the reversal of the relative ranking of the networks, if an alternative network is removed from or inserted into the candidate network selection list. For example, consider the ranks of three different networks N_1, N_2 and N_3 as $Rank_{N1} > Rank_{N2} > Rank_{N3}$. The removal of network N_1 should result in the rank of the other two networks becoming $Rank_{N2} > Rank_{N3}$. However, as in classical MADM methods, computation of network rank and score depends on the remaining other networks' attributes value, the removal of network N_1 may result in the rank of the other two networks becoming $Rank_{N3} > Rank_{N2}$, resulting in a rank reversal problem. The same may be observed when a new network is inserted into the network selection list. Moreover, the presence of a rank reversal problem with classical MADM methods raises a reliability issue with respect to the selected network for handover.

The unreliability in network ranking and the rank reversal problem are the key challenges for the seamless handover of MNs using classical MADM methods in heterogeneous wireless networks. The wrong selection of a network during the VHD in heterogeneous wireless networks results in poor QoS of the applications in terms of maximum: packet delay, packet loss, unnecessary handover (ping-pong effect) and handover failure (rejecting the MN handover request by the selected network due to insufficient resources). This leads to user dissatisfaction and maximum consumption of MN resources such as memory and battery life. Hence, there is a need for improving the reliability of the network selection in classical MADM methods, thereby eliminating dependence on the attributes normalization and weight calculation methods.

Moreover, other challenges of heterogeneous wireless networks are the implementation and verifications of the proposed solutions either with network simulator or testbed approach for realistic results. Even though National Institute of Science and Technology (NIST) [2] provided the network simulator NS2 [3] distribution for simulating heterogeneous wireless networks, researchers need to design their own NS2 results analysis scripts, which is time-consuming and tedious. Further, heterogeneous wireless networks testbed deployment with Mobile IPv6 (MIPv6) for handover execution is another challenging issue for the research community to obtain realistic results because of its deployment complexity, cost and time.

1.6 Issues and Challenges

The main focus of this research involves improving the reliability of attributes weight and ranking of the networks, and eliminating the rank reversal problem of classical MADM methods for VHD in heterogeneous wireless networks. Additionally, ease of configuring, simulating and result analysis of heterogeneous wireless networks in network simulator NS2, and deploying simple and cost-effective MIPv6 testbed for realistic results.

[2] National Institute of Science and Technology (NIST) - Seamless and Secure Mobility. Available: `http://www.nist.gov/ctl/wireless-networks/ssm_seamlessandsecure.cfm`

[3] Network Simulator - NS2. Available: `http://www.isi.edu/nsnam/ns/`

The major challenging issues in proposing the optimized solutions for reliable attributes weight computation, rank reversal and unreliable ranking in classical MADM methods, HWNs simulation, and testbed deployment are as follows:

- *Improving AHP for reliable attributes weight*: Decision makers' involvement and manual process of attributes weight computation in AHP, results in unreliable weight of the attributes. Minimizing the involvement of the decision maker and automatically computing the reciprocal matrix is the main challenge in proposing an improved AHP for reliable attributes weight.

- *Improving ranking reliability and elimination of the rank reversal problem of Classical MADM methods*: Dependency of classical MADM methods on attributes normalization and weight computation methods, results in unreliable selection of network and the rank reversal problem during vertical handover decision in heterogeneous wireless networks. In classical MADM methods, executing attributes normalization and weight computation are the two specific steps involved during ranking of networks. The main challenge in addressing these problems of classical MADM based VHD-making is replacing heterogeneous attributes normalization by its equivalent, as well as eliminating the dependency of heterogeneous attributes weight (importance of attributes) during the computation of networks rank.

- *Ease of simulating heterogeneous wireless networks*: Despite the availability of many distributions to simulate HWNs using NS2 in the research community, researchers need to design their own result analysis scripts. The main challenge in designing result analysis scripts is the presence of mobile nodes with multiple heterogeneous wireless interfaces and change in the hierarchical address of the mobile node's interface during vertical handover in HWNs.

- *MIPv6 Testbed*: The deployment complexity, cost and time are the main issues in deploying testbed for obtaining realistic results. In deploying MIPv6 testbed for homogeneous or heterogeneous wireless networks to study handover process, the challenging issue is the lack of detailed testbed deployment information, testing checkpoints and debugging procedures.

1.7 Problem Statement

The goal of this research work involved, developing an optimized MADM based VHD-making, with minimum complexity and maximum reliability. Accordingly, the research problem is stated as follows:

> "To minimize the complexity of multiple attributes vertical handover decision making in heterogeneous wireless networks by using improved attributes weight computation, and by eliminating the attributes normalization and weight computation method".

1.8 Research Objectives

- To explore classical MADM methods such as TOPSIS, SAW, MEW and GRA thereby addressing their major drawbacks such as networks rank unreliability and network's rank reversal problem during VHD making.

- To design and develop a simple and improved reliable attributes weight computation method referred to as Simplified and Improved Analytical Hierarchy Process (SI-AHP) for reliable selection of network.

- To design and develop state-of-the-art Simplified and Improved Multiple Attributes Alternate Ranking (SI-MAAR) method for eliminating the dependency on attributes normalization and weight computation of the classical MADM methods. Additionally, to improve the network ranking reliability and eliminating the rank reversal problem.

- To explore the simulation of vertical handover decision in heterogeneous wireless networks with NS2's Mobile IPv6 (MIPv6) and Media Independent Handover (MIH) implementation.

- To design and deploy a simple and cost-effective Mobile IPv6 testbed for handover execution in homogeneous and heterogeneous wireless networks.

1.9 Research Contributions

Following are the contributions of this research work and they are available to the research community in the form of journal and conference publications.

- **Sigmoidal function based network selection in heterogeneous wireless networks**

  Sigmoidal function based utility functions is a well-known approach used for network selection during VHD. This contribution of research work presents the comparisons and analysis of sigmoidal utility functions used for network selection in heterogeneous wireless networks. The outcome of the MATLAB simulations demonstrated the influence of attributes weight and sigmoidal utility function constants on network selection.

- **Entropy-based network selection in heterogeneous wireless networks**

  Entropy-based attributes weight computation is one of the well-known methods used in MADM-based VHD-making in heterogeneous wireless networks. In this contribution of research work, six different entropy-based MADM approaches for selecting a best network during handover using MATLAB are developed and their performances is compared. Simulation results demonstrated that separation of attributes as benefit and cost, and ongoing service expectations during VHD selects the network with maximum satisfaction index.

- **Mobile node's speed and battery lifetime dependent handover in heterogeneous wireless networks**

  In the selection of a network during handover execution, speed and battery lifetime of MNs are vital. The execution of VHD during MN with the maximum speed results in ping-pong effect and also, short battery lifetime of a MN results in a discontinuity of services. In this contribution, MN's speed and battery lifetime dependent VHD in heterogeneous wireless networks using network simulator NS2 is developed.

- **Simplified and Improved Analytical Hierarchy Process aid for selecting candidate network in heterogeneous wireless networks**

  Analytical Hierarchy Process (AHP) is one of the well known methods used for attributes weight computation during VHD in heterogeneous wireless networks. The reliability of attributes weight computed in AHP depends on knowledge of the decision maker about attributes which is utilized during the derivation of the reciprocal matrix (pairwise comparisons of attributes). To address this problem, a Simplified and Improved Analytical Hierarchy Process (SI-AHP) for computing consistent eigenvector or attributes weight using MATLAB is developed. SI-AHP is further used in multiple attributes decision making methods for selecting the candidate network for seamless handover during VHD in HWNs.

- **Simplified and Improved Multiple Attributes Alternate Ranking Method for VHD in heterogeneous wireless networks**
  Dependency of classical MADM (TOPSIS, SAW, MEW and GRA) based VHD on attributes normalization and weight computation methods results in unreliable selection of the network and the rank reversal (abnormality) problem. To address this problem, a Simplified and Improved Multiple Attributes Alternate Ranking (SI-MAAR) method by eliminating the dependency on attributes normalization and weight computation methods is developed. SI-MAAR has been compared with classical MADM methods such as TOPSIS, SAW, MEW and GRA using MATLAB. The results show that SI-MAAR eliminates the unreliable selection of the network and the rank reversal problem.

- **User Datagram Protocol Evaluation Suite for WiFi and WiMAX heterogeneous wireless networks**
  The dependency of researchers on NS2 for implementation and verifications of innovative solutions lead to the tedious and time-consuming task of developing the results analysis scripts using AWK or Perl. NS2's distribution for HWNs simulation developed by NIST provided a tool to the research community to work in mobility management, security and other aspects of HWNs. In this contribution of research work, a Graphical User Interface (GUI) -based heterogeneous wireless networks configuration, simulation and result analysis tool for NS2 is developed. The tool provides the analysis of throughput, number of handover, total packets sent and received, delay and jitter for the User Datagram Protocol (UDP) applications in HWNs.

- **Simple and cost-effective Mobile IPv6 testbed for the study of handover execution in heterogeneous wireless networks**
  Deployment complexity, cost and time of setting up any testbed forces the researchers to opt for either analytical or simulation based approach for implementing and verifying their innovative ideas. This contribution of research work presents the deployment of a simple and cost-effective Linux-based MIPv6 testbed to initiate the implementation of horizontal and vertical handover decision in homogeneous and heterogeneous wireless networks respectively.

1.10 Outline of the Thesis

The rest of the thesis is organized as follows.

Chapter 2 provides an overview of recent work in the areas of heterogeneous wireless networks mobility management, attributes weight computation, VHD-making and support for simulation of heterogeneous wireless networks using the network simulator NS2. This chapter also presents the state-of-the-art classical MADM methods: TOPSIS, SAW, MEW, and GRA addressing their major drawbacks such as network selection unreliability and the rank reversal problem. Further, this chapter presents state-of-the-art AHP method of attributes weight computation with its drawback of unreliable attributes weight.

Chapter 3 presents the analysis of state-of-the-art classical MADM methods: TOPSIS, SAW, MEW, and GRA by numerically demonstrating their major drawbacks such as network selection unreliability and the rank reversal problem. Further, the chapter presents comparisons and analysis of sigmoidal utility functions used in MADM during handover decision in heterogeneous wireless networks. This chapter also discusses the challenges in using NS2 distribution for simulating heterogeneous wireless networks provided by NIST. Moreover, this chapter also presents an NS2 evaluation suite of User Datagram Protocol (UDP) applications called ES-UDP for configuring, simulating and result analysis of heterogeneous wireless networks.

Chapter 4 presents Simplified and Improved Analytical Hierarchy Process (SI-AHP) for computing reliable attributes weight used in VHD in heterogeneous wireless networks.

Chapter 5, in continuation with the drawbacks of classical MADM methods presented in Chapter 2, introduces a state-of-the-art simplified and improved classical MADM referred to as SI-MAAR by eliminating dependency on attributes normalization and weight computation.

Chapter 6 presents a simple and cost-effective Linux-based Mobile IPv6 testbed for the study of handover execution in homogeneous and heterogeneous wireless networks with testing checkpoints and debugging procedures.

Finally, Chapter 7 summarizes the contributions of research work and highlights possible directions for future work.

1.11 Summary

This chapter presented 4^{th} Generation heterogeneous wireless networks with its features, applications and challenges. Moreover, this chapter introduced mobility management, handover process, different approaches of VHD and state-of-the-art classical MADM methods: TOPSIS, SAW, MEW and GRA. Additionally, the core issues of research, such as reliable attributes weight computation, network rank unreliability and the rank reversal problem of classical MADM methods, simulation of heterogeneous wireless networks and testbed for study of handover execution are presented with their issues and challenges. Finally, this chapter concluded with a problem statement, research objectives, summary of the research contributions and an outline of the thesis.

Chapter 2

Literature Survey

This chapter of the thesis presents an overview of related work in the following areas:

- Mobility Management in heterogeneous wireless networks
- Vertical handover decision of mobility Management in heterogeneous wireless networks
- Multiple attribute decision making approach for VHD
- Attributes weight computation method - AHP
- Simulation of heterogeneous wireless networks using NS2
- Deployment of MIPv6 testbed

2.1 Mobility Management in Heterogeneous Wireless Networks

Several research papers on mobility management and vertical handover decision methods are available in the literature, presenting several issues such as key features of heterogeneous wireless networks, future heterogeneous wireless technologies, handover methods in wireless overlay networks, differences between traditional and next generation handover strategies, handover metrics, mobile device requirements for future heterogeneous wireless networks, and research challenges for mobility management in heterogeneous wireless networks (Siddiqui and Zeadally 2006; Nasser et al. 2006).

This section presents related work on mobility management of heterogeneous wireless networks.

Hui and Yeung (2003), presented research challenges and the solutions with respect to a mobile station, system and service in the migration of 4G heterogeneous wireless networks. The key challenges of a mobile station in 4G wireless networks are, multimode device, wireless system discovery and wireless system selection. Whereas, key challenges with respect to the system in 4G wireless networks are, mobility, QoS, security and fault tolerance. Finally, key challenges of service are, multi-operator and billing system, and personal mobility.

Cavalcanti et al. (2005), presented 4G and the architecture of heterogeneous wireless networks along with the ingredients such as, mobile device, base station and access point, IP network and protocol stack. Additionally, the authors also presented a protocol stack of dual mode MN in heterogeneous wireless networks and the open research issues with respect to each of the layers, namely, routing, scalability, seamlessness, security, billing, etc.

Siddiqui and Zeadally (2006), presented various components of handover management with different handover techniques and their implementation issues and challenges for mobility across heterogeneous wireless access networks. Finally, the authors concluded that current roaming techniques are not well suited to support seamless communication in heterogeneous mobile environments because of multi-modality, handover, QoS, billing and pricing, and security.

Fernandes and Karmouch (2012), presented a comprehensive review of the literature on mobility management architectures with an in-depth analysis of main goals, assumptions, and requirements for seamless handover of mobile users in heterogeneous networks. Additionally, the authors also presented cross-layer, context-aware and interactive Context Aware Mobility Management System referred to as CAMMS.

Zekri et al. (2012), presented a survey and comparative analysis of vertical mobility management over heterogeneous wireless networks. Decisions based on user preferences, available radio resources, application requirements and terminal capabilities introduced computational complexity and signalling overhead. The authors concluded by stating that introducing an uncertainty factor and using inference or reasoning techniques may be useful to make decisions with incomplete knowledge.

Xenakis et al. (2014), presented a survey of mobility management for femtocells in LTE-A with a comparative list of different handover decision algorithms based on different handover decision parameters. Further, the authors also presented a comparison of different handover decision algorithms with respect to handover metrics. The different handover decision algorithms listed by the authors with respect to the LTE-A femtocells are also used in mobility management for heterogeneous wireless networks.

Inference: 4G is the future of communication technology with the additional new features and provides support for new applications. Through the literature survey on mobility management of 4G networks, it can be concluded that additional features and applications bring forth many challenges in the successful deployment of 4G.

2.2 Vertical Handover Decision of Mobility Management in Heterogeneous Wireless Networks

Section 1.3 of Chapter 1 presented, vertical handover decision as one of the prominent step of mobility management responsible for seamless communication of MNs. This section presents the related work on VHD of mobility management in HWNs.

In (Kassar et al. 2008; Charilas and Panagopoulous 2010; Zekri et al. 2012), the authors presented vertical handover process (system discovery, handover decision and handover execution) along with the comparison of different VHD strategies.

Sun et al. (2008), proposed a Constrained Markov Decision Process (CMDP) vertical handoff decision algorithm, based on connection duration, QoS parameters, mobility and location information, network access cost, and the signalling load incurred on the network for 4G wireless networks. The constraint of the problem is on the user's budget for the connection.

Yan et al. (2010), presented the survey of VHD algorithms designed to provide the required QoS to a wide range of applications. The authors also highlighted four different VHD algorithms based on received signal strength, bandwidth, cost, and artificial neural network and fuzzy logic with their comparative features. Finally, the authors concluded that none of these VHD algorithms comprehensively consider various network parameters.

Márquez-Barja et al. (2011), presented the survey of VHD and the steps of heterogeneous information gathering, handover decision and handover execution. The authors classified the most widely used VHD algorithms in different sets of algorithms depending on the information used to make decisions, and the techniques employed. Finally, the authors presented the use of Media Independent Handover (MIH) for system discovery along with additional open research issues such as QoS, Quality of Expectation (QoE), security, and service provider management and evaluation.

He et al. (2011), proposed a VHD method based on the classification of mobile nodes (resource-poor and resource-rich) and dynamic new call blocking probability. The major drawbacks of this method are the classification of mobile nodes and the weighting of decision parameters. The final ranking of the networks depends on the attributes normalization and weight computation methods; hence, their method did not address network rank unreliability and the rank reversal problem.

Ahuja et al. (2014), proposed an algorithm for network selection in heterogeneous wireless networks using received signal strength, distance and outage probability. The proposed algorithm consists of two stages: during the first stage, a distance parameter is used to select the best network for handover, and in the second stage, received signal strength and outage probability are used for the same. The major problem with this algorithm is, its complexity increase with an increase in the number of decision-making parameters and available networks during the handover decision. This leads to unreliable selection of the network.

Wen and Hung (2015), proposed three algorithms for selecting the most energy efficient networks in heterogeneous wireless networks based on application characteristics and transmission loads. However, since the main constraints of mobile devices are memory and computational capabilities apart from energy consumption, these algorithms are too complex for mobile devices.

Khloussy et al. (2015), proposed a Markov Decision Process (MDP)-based distribution of overlay heterogeneous wireless networks among MNs with the objective of maximizing the operators' revenue. This method did not consider the time taken to complete handover decision and handover execution. Further, the authors did not address the computation of the weight associated with a request, to handover to a particular network.

Table 2.1: Comparisons of existing VHD strategies (Kassar et al. 2008; Zekri et al. 2012)

VHD Strategies	**User Consideration**	**Multi-attribute**	**Complexity**	**Flexibility**	**Reliability**	**Multi-Service**
Function-based	Medium	Yes	Low	High	Medium	No
	Merits: Minimum degradation in high load and congestion situations.					
	Demerits: Time-consuming if services and/or available access points increase.					
User-Centric	Strong	Yes	Low	High	Medium	No
	Merits: Maximizes users' utility and has low implementation complexity.					
	Demerits: Non-real-time support, simple rate prediction method and medium precision.					
MADM	Medium	Yes	Medium	High	Medium	No
	Merits: Multiple criteria being considered, easy to implement, scalable and accurate results.					
	Demerits: Medium implementation complexity, selection of suitable method and normalization.					
Markov	Low	Yes	Medium	Medium	High	No
	Merits: Adaptive and applicable to a wide range of conditions.					
	Demerits: Implementation complexity.					
Fuzzy Logic	Medium	Yes	High	Low	High	No
	Merits: Makes decisions in an autonomous way, considers multiple criteria.					
	Demerits: Complexity increases if additional input parameters are considered.					
Game Theory	Strong	Yes	Medium	Medium	High	No
	Merits: Efficient resource management.					
	Demerits: Additional decision parameters are required in practice to ensure better quality of service.					
Reputation	Medium	Yes	Medium	Medium	Medium	No
	Merits: Faster VHD decision-making.					
	Demerits: Reputation sustainability needs to be addressed in greater depth.					

Table 2.1 shows a comparison of the salient features of different existing vertical handover decision strategies for heterogeneous wireless networks (Kassar et al. 2008; Charilas and Panagopoulous 2010; Zekri et al. 2012; Wang and Kuo 2013).

Inference: Through the literature survey on vertical handover decision of heterogeneous wireless networks, it can be concluded that, VHD is essential for seamless communication of MNs. Despite extensive work available in the literature on VHD, seamless communication of MNs for better QoS is still a challenging issue in the research community.

2.3 Multiple Attribute Decision Making approach for VHD

Section 2.2 presented multiple attribute decision making as one of the suitable methods for VHD in heterogeneous wireless networks because of its support for multiple attributes with minimized complexity. Since, the handover decision in heterogeneous wireless networks depends on multiple heterogeneous attributes such as network performance, users' demands, applications expectations and device capabilities, so, there is a need for optimized VHD.

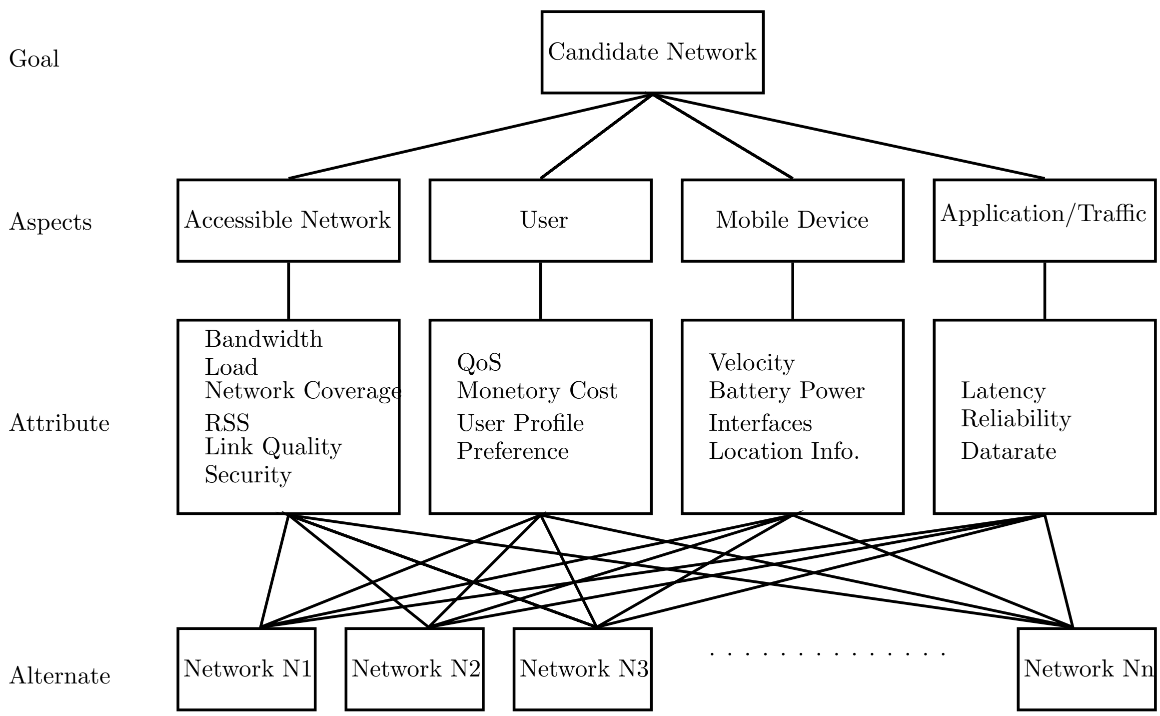


Figure 2.1: Hierarchical system of candidate network selection in MADM

Figure 2.1 shows the hierarchical system of candidate network selection in heterogeneous wireless networks using classical MADM methods (Ozdemir and Saaty 2006; Nikou and Mezei 2013; Aragonés-Beltrán et al. 2014). As shown in Figure 2.1, one of the inputs to classical MADM is attributes or selection criteria m of network, user, application and device. The second input is accessible heterogeneous wireless networks n with m attributes (a_{ij}) of network, application, user and the device.

The following subsection presents in detail the classical MADM methods: TOPSIS, SAW, MEW, and GRA and their related works.

2.3.1 Classical MADM Methods

Figure 2.2 illustrates the sequential steps of networks (alternates) ranking (selection) of state-of-the-art four classical MADM methods: TOPSIS, SAW, MEW and GRA (Stevens-Navarro and Wong 2006; Kuo et al. 2008; Stevens-Navarro et al. 2012; Wang and Kuo 2013; Drissi and Oumsis 2015).

As shown in Figure 2.2, TOPSIS, SAW, MEW and GRA are primarily dependent on the attributes normalization (Çelen 2014) and weight calculation methods (Wang and Kuo 2013) during network ranking. Some of the popularly used attributes normalization methods in classical MADM are: (i) Vector Normalization (ii) Sum Normalization and (iii) Max-Min Normalization. Similarly, weight of the attributes can be computed by (i) Entropy (Lin 1991) and (ii) Variance (Wang and Kuo 2013) for objective attributes and (iii) Analytical Hierarchy Process (AHP) for subjective attributes (Saaty 1990; Charilas and Panagopoulous 2010; Wang and Kuo 2013).

As shown in Figure 2.2, attributes normalization is the essential step of classical MADM methods to present the attributes: bandwidth, delay, energy consumption, etc., of different unit: bits per sec (bps), millisecond (msec), mWatt (mWatt), etc., in dimensionless for common comparisons (see Table 1.2 of Section 1.2 of Chapter 1). The attributes weight calculation methods compute the importance (common to all alternates) of the attributes, either by using all available network attributes value (Objective method: Entropy and Variance) or by using inputs from the decision maker (Subjective method: AHP). The objective method of attributes weight computation uses the objective (precise) attributes value of network versus attribute, whereas, the subjective attributes weight computation method uses the linguistic value.

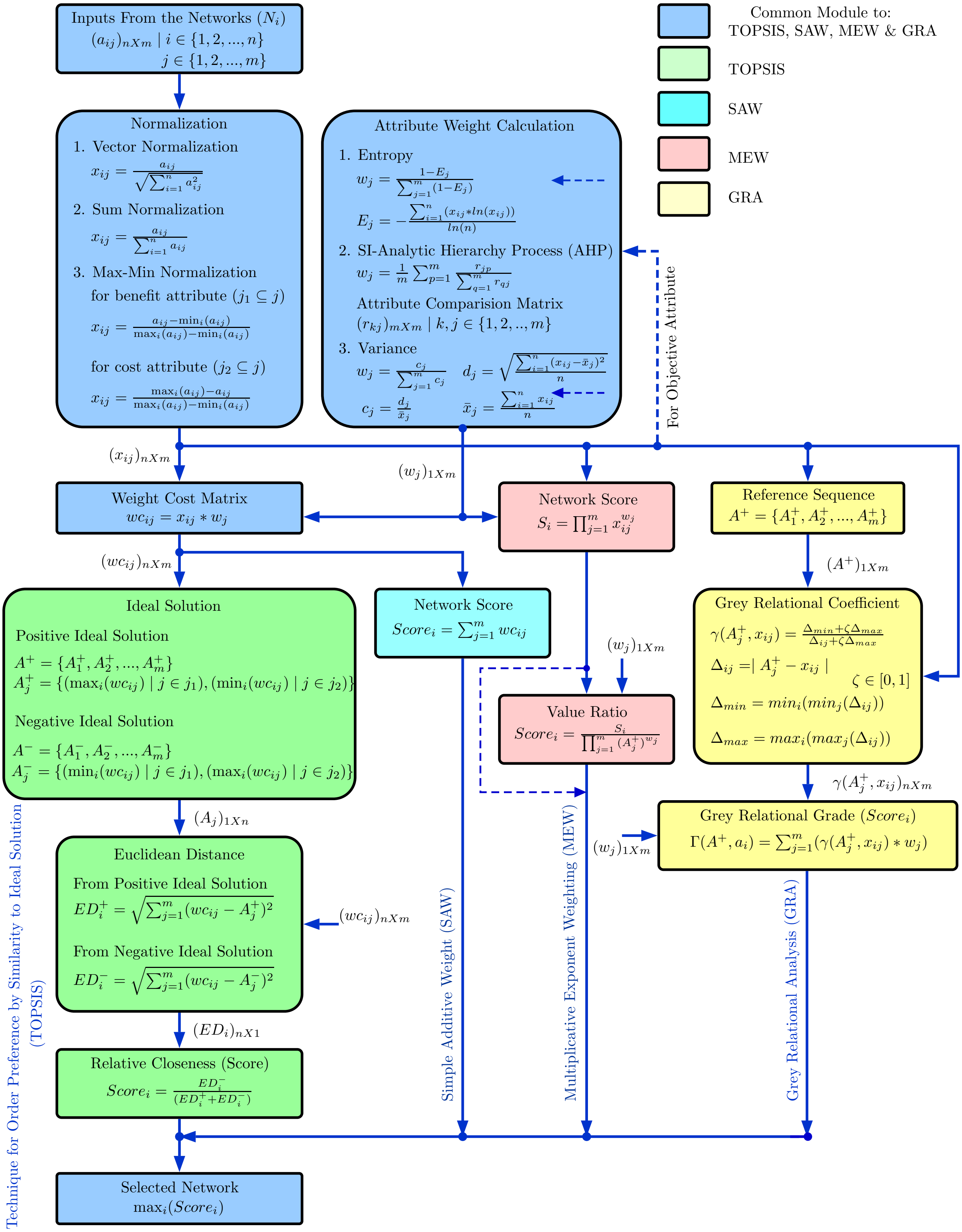


Figure 2.2: The classical MADM methods: TOPSIS, SAW, MEW and GRA

The remaining steps of network ranking in classical MADM methods such as TOPSIS, SAW, MEW and GRA as shown in Figure 2.2 are unique to the respective classical MADM methods as listed below:

- TOPSIS (Stevens-Navarro and Wong 2006; Stevens-Navarro et al. 2012; Wang and Kuo 2013; Drissi and Oumsis 2015): This approach of the classical MADM method - TOPSIS select the network for handover during vertical handover decision in heterogeneous wireless networks, by computing the score of the individual networks accessible to mobile node. The selection of network for handover using computed score of the individual network depends on its closeness to the positive and negative ideal solution. Minimum closeness to the positive ideal solution, maximum is the score and vice-versa for the negative ideal solution.

  - *Weight Cast Matrix* (wc_{ij}): Computes the product of the normalized network versus attribute x_{ij} and their respective attributes weight w_j.
  - *Ideal Solution* (A^+ *and* A^-): Computes the positive and negative ideal value of the attributes using the weight cost matrix.
  - *Euclidean Distance* (ED^+ *and* ED^-): Computes the separations from the positive (best) and negative (worst) value of the attributes among networks.
  - *Relative Closeness (*$Score_i$*)*: Computes the closeness to the positive value of the attributes among networks. The score of a network in TOPSIS can be computed by,

$$Score_i = \frac{\sqrt{\sum_{j=1}^{m}(x_{ij} * w_j - A_j{}^+)^2}}{(\sqrt{\sum_{j=1}^{m}(x_{ij} * w_j - A_j{}^+)^2} + \sqrt{\sum_{j=1}^{m}(x_{ij} * w_j - A_j{}^-)^2})} \tag{2.1}$$

  where, a_{ij} - network versus attribute, x_{ij} - normalised a_{ij}, w_j - weight of attribute j, and $A_j{}^+$ and $A_j{}^-$ represent the positive and negative ideal solutions respectively.

- SAW (Stevens-Navarro and Wong 2006; Stevens-Navarro et al. 2012; Wang and Kuo 2013; Drissi and Oumsis 2015): This is one of the simplest classical MADM methods. SAW computes the score of the individual network, by the summation of product of normalized individual network versus attribute with the respective attributes weight.

  - *Weight Cast Matrix* (wc_{ij}): Computes the product of the normalized network versus attribute x_{ij} and their respective attributes weight w_j.
  - *Network Score (Score$_i$)*: Computes the score of individual networks by adding their respective network weight cost matrix entries.

$$Score_i = \sum_{j=1}^{m} x_{ij} * w_j \tag{2.2}$$

- MEW (Stevens-Navarro and Wong 2006; Stevens-Navarro et al. 2012; Wang and Kuo 2013; Drissi and Oumsis 2015): It computes the score of the individual network, by the product of individual network versus attribute to the power of the respective attributes weight.

  - *Network Score* ($Score_i$): Computes the score of the individual networks by the weighted product of their respective normalized network versus attribute.
  - *Value Ratio*: Ratio of the individual network score to the weighted product of the positive ideal value of the attributes.

$$Score_i = \prod_{j=1}^{m} {x_{ij}}^{w_j} \tag{2.3}$$

- GRA (Stevens-Navarro and Wong 2006; Kuo et al. 2008; Wang and Kuo 2013): It computes the score of the individual networks using grey relational coefficient and positive ideal solutions.

  - *Reference Sequence* (A^+): Computes the positive ideal value of the attributes using normalized network versus attribute.
  - *Grey Relational Coefficient* ($\gamma({A_j}^+, x_{ij})$): Describes the similarities between networks and the reference sequence.

– *Grey Relational Grade* ($\Gamma(A^+, a_i)$): Computes the correlation between the reference sequence and the comparability sequence.

$$Score_i = \sum_{j=1}^{m} (\gamma({A_j}^+, x_{ij}) * w_j) \tag{2.4}$$

where, $\gamma({A_j}^+, x_{ij})$ represents the grey relational coefficient and ${A_j}^+$ represents the positive ideal solution.

In Equations (2.1) - (2.4), x_{ij} - the normalized value of network versus attribute (a_{ij}), w_j - the weight of the attribute j. Where, $i = 1, 2, ..., n$ networks and $j = 1, 2, ..., m$ attributes.

As shown in Equations (2.1) - (2.4), the major drawbacks with classical MADM methods are:

- Dependency of classical MADM methods on attributes normalization and weight calculation methods substantially influences the ranking of the networks. Further, this results in an uncertainty in selecting the appropriate attributes normalization and weight calculation methods with respect to a specific classical MADM method.

- The way the attributes are normalized or the weight are calculated depends on the relation between one network's attributes and those of the others existing in the network selection list. The outcome of this dependency is the rank reversal problem with classical MADM methods (Wang and Luo 2009). The rank reversal problem is the reversal of the relative ranking of the networks during the removal and insertion of network in the network selection list.

To address the drawbacks of classical MADM methods, Zhang (2004), developed handover decision using the fuzzy MADM method. The input data is fuzzy in nature, but the TOPSIS, SAW, AHP and DEA methods are finally used for ranking the alternates. Hence, their approach did not address the rank reversal problem.

Stevens-Navarro and Wong (2006), discussed handover metrics (bandwidth, latency, reliability, power, price, security and availability) and the different traffic classes (conversational, streaming, interactive and background). Further, the authors simulated the classical MADM methods, but did not address the unreliability in network ranking due to existing attributes normalization and weight computation methods.

Wang and Binet (2009), proposed a new subjective attributes weighting method referred to as TRigger-based aUtomatic Subjective weighTing (TRUST). The major drawback of their proposed approach is that the important attributes usually obtain a maximum weight and the unimportant attributes obtain a weight of 0, resulting in neglect of all unimportant attributes.

Wang and Luo (2009), demonstrated the rank reversal problem of the Analytical Hierarchy Process (AHP) along with the other classical MADM methods: TOPSIS and SAW. The main reason identified by the authors for the rank reversal in MADM is its dependency on the attributes normalization method. The authors concluded by stating that normalization cannot prevent the rank reversal problem.

Chamodrakas and Martakos (2012), developed an energy efficient utility function-based fuzzy TOPSIS for network selection, thereby addressing the rank reversal problem. Their method is based on the trade-off between performance and energy consumption. The major drawback of this method is its dependency on attributes weight calculation using linguistic value.

Wang and Kuo (2013), presented an analytical framework used for modelling network selection in the classical MADM methods: TOPSIS, SAW, GRA and ELECTRE. The authors listed the key attributes (benefit and cost) used for the network selection problem along with the different subjective and objective attributes normalization and weight computation methods.

Yang and Tseng (2013), proposed a novel approach for attributes rating referred to as Weighted Rating of Multiple Attributes (WRMA), which relies on TOPSIS for network ranking. Similar to AHP, the major drawbacks of WRMA are the decision maker's competency involved in identifying the application level priority, and its dependency on TOPSIS.

Table 2.2 shows a comparison between the different classical MADM methods with respect to procedure- and application- based merits and demerits (Stevens-Navarro and Wong 2006; Trestian et al. 2012; Wang and Kuo 2013).

Table 2.2: Comparison of classical MADM methods

MADM Method	Merits		Demerits	
	Procedure-Based	Application-Based	Procedure-Based	Application-Based
SAW	Easy to understand, easy to implement and support for multiple attributes.	Good performance for interactive applications.	Poor-valued attributes can be outweighed by a very good value of another attribute (Trestian et al. 2012), unreliable ranking and rank reversal problem (Wang and Luo 2009).	Poor performance for data-intensive applications.
TOPSIS	Simple and comprehensive, scalable, high efficiency, high flexibility, and accurate results.	Good performance for interactive and background applications (Piamrat et al. 2011).	Imprecise data cannot be handled, unreliable ranking and rank reversal problems.	Poor performance for applications heavily dependent on bandwidth and delay (Piamrat et al. 2011).
MEW	Medium implementation complexity and the least sensitive method.	Good performance for interactive applications (Drissi and Oumsis 2015).	Penalizes alternatives with poor-valued attributes more heavily, unreliable ranking and rank reversal problem.	Poor performance for data-intensive applications.
ELECTRE	Integrates subjective assessments with numerical data.	Satisfactory performance for data-intensive applications.	Complicated, uses pairwise comparisons, unreliable ranking and rank reversal problem.	Poor performance for voice applications (Stevens-Navarro et al. 2012).
AHP-GRA	Integrates subjective appraisals with numerical statistics, supports multiple attributes with precise solutions.	Good performance for bandwidth and delay applications.	Complicated, uses pairwise comparisons, the length of the process increases with the number of levels, unreliable ranking and rank reversal problem.	Poor performance for interactive and background applications (Piamrat et al. 2011).

Inference: Based on the literature survey on MADM approaches, it can be concluded that, network selection unreliability and the rank reversal problems are the major issues in all MADM approaches available in the literature. Hence, there is a need to improve network selection reliability and the elimination of the rank reversal problem of classical MADM methods.

2.4 Attributes Weight Computation Method - AHP

As it has been presented in Section 2.3 of Chapter 2, unreliable weight of the attributes is one of the reasons for the unreliable selection of the network using MADM based VHD in heterogeneous wireless networks. Wang and Kuo (2013); Zardari et al. (2014), presented the different approaches for calculating the attributes weight. Table 2.3 summarizes the different attributes weight calculation methods with their strengths and weaknesses (Wang and Kuo 2013; Zardari et al. 2014).

Among the available attributes weight calculation approach, Analytical Hierarchy Process (AHP) is one of the more popularly used attributes weight computation and alternative (network) ranking methods. Saaty (1990), introduced a multi-criteria decision making approach-Analytical Hierarchy Process with the principles and philosophy of the theory with its properties and applications. AHP is one of the pairwise comparison, attributes weight calculation approach of Multiple Attribute Decision Making aid to select the candidate network for seamless handover in an overlay heterogeneous wireless networks. AHP uses the reciprocal matrix input from the decision maker in computing attributes weight, which are accepted into the network ranking if the consistency ratio is less than or equal to 0.1 (Saaty 1990).

The major problem with AHP is in the competency of the decision maker while producing the reciprocal matrix, which may lead to unreliable attributes weight. Further, Saaty (2003) addressed the issues with the inconsistent positive reciprocal pairwise comparison matrix and the importance of eigenvector. The author also proposed the three ways to improve the consistency of judgement. This section presents AHP based attributes weight computation and the related work on different variants of AHP addressing the advantages and limitations.

Table 2.3: Attributes weight calculation methods

Category/Method	Approach	Strengths	Weaknesses
Objective Attribute			
Entropy	Based on mathematical models.	No decision makers' involvement, simple and straightforward, reliable, resolves the inherent conflict between the attributes.	Neglects the subjective judgement information, needs attribute normalization.
CRiteria Importance Through Inter-criteria Correlation (CRITIC)			
Mean Weight			
Standard Deviation			
Statistical Variance Procedure			
Subjective Attribute			
Simple Multi-attribute Rating Technique (SMART)	Based on the decision maker's pairwise comparison between all attributes	Useful when the decision maker is unable to rank the alternatives holistically and directly with respect to an attribute. Transparent, easy to calculate and the results are clear. Useful for assigning weight representing the relative importance of attributes.	Depends on the competency of the decision maker. Complexity increases with the number of attributes. Insufficient and imprecise. Uncertain about attributes.
Analytical Hierarchy Process (AHP)			
SIMOS (Zardari et al. (2014))			
Delphi Method (Zardari et al. (2014))			

2.4.1 Analytical Hierarchy Process

Following are the steps followed in AHP for weight calculation of m decision making attributes.

Step 1: Deriving the reciprocal matrix (R): It represents the pairwise comparison or importance relationship of attributes m as perceived by the decision maker. A manually derived reciprocal matrix by the decision maker is given by Equation (2.5) as follows;

$$R = r_{kj}, \text{ where } k, j = 1, 2, ..., m \text{ attributes} \tag{2.5}$$

with the following conditions:

(i) $r_{kj} = \frac{1}{r_{jk}}$

(ii) $r_{kj} = 1$, if $k = j$

The pairwise comparisons r_{kj} of attributes k and j are mapped to any one of the linguistic value $\in \{1, 3, 5, 7, 9\}$ to denote the importance of k attribute over j as equal, moderate, strong, demonstrated and extreme respectively and is inverse for vice-versa. Accordingly, the total number of manual comparisons among m attributes required to complete the reciprocal matrix manually by the decision maker is computed as $m(m-1)/2$.

Step 2: Computation of eigenvector:

$$w_j = \frac{1}{m} \sum_{k=1}^{m} \frac{r_{jk}}{\sum_{x=1}^{m} r_{xk}} \tag{2.6}$$

where $j = 1, 2, 3, ..., m$ with $\sum_{j=1}^{m} w_j = 1$.

This step computes the weight or eigenvector of m attributes using Equation (2.6) for the reciprocal matrix presented using Equation (2.5).

Step 3: Consistency of eigenvector: This is the additional and compulsory step for checking the consistency or reliability of the calculated attributes weight w_j or eigenvector in Step 2 and is measured using the consistency ratio ≤ 0.1 given by

$$\text{Consistency ratio} = \frac{\text{Consistency Index (CI)}}{\text{Random Consistency Index (RI)}} \tag{2.7}$$

Where

$$\text{Consistency Index (CI)} = \frac{\lambda_{max} - m}{(m-1)} \tag{2.8}$$

In Equation (2.8) λ_{max} is the largest eigenvalue computed in Step 2 in relation to the reciprocal matrix of Step 1 and is calculated by,

$$\lambda_{max} = \sum_{j=1}^{m}(w_j * \sum_{k=1}^{m} r_{kj}) \tag{2.9}$$

Further, in Equation (2.7), Random Consistency Index (RI) is the constant derived from a large sample of randomly generated reciprocal matrices using the scale $\frac{1}{9}$, $\frac{1}{8}$, . . , 1, . . . , 8, 9. The constant RI for a number of attributes 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 13 is given as 0.52, 0.89, 1.11, 1.25, 1.35, 1.40, 1.45, 1.49, 1.51, 1.54 and 1.56 respectively (Tzeng and Huang 2011).

Finally, the calculated weight of attributes w_j using Equation (2.6) is acceptable if the consistency ratio computed for w_j in relation to reciprocal matrix is less than or equal to 0.1. Failure of condition (consistency ratio $\leq$ 0.1) results in repeating Steps 1-3 for the consistent eigenvector. Accordingly, lower the consistency ratio $\leq$ 0.1 the higher is the consistency or reliability of the calculated weight of attributes.

Additionally, for consistent eigenvector (consistency ratio $\leq$ 0.1), the supplementary requirement of reciprocal matrix is:

(i) $r_{kj} = \frac{r_{kx}}{r_{jx}}$ or $r_{kj} = \frac{r_{xj}}{r_{xk}}$ for any $j, k, x = 1, 2, ..., m$

resulting into:

(i) $\lambda_{max} = m$

(ii) $r_{kj} = \frac{w_k}{w_j}$ for any $j, k = 1, 2, ..., m$

(iii) $\sum_{j=1}^{m} r_{kj} * w_j = \lambda_{max} * w_k$ for any $j, k = 1, 2, ..., m$

Inferences: Computing attributes weight in AHP and satisfying the condition of consistency ratio less than or equal to 0.1 while manually computing the reciprocal matrix is challenging for the decision maker.

To address the drawbacks of AHP, Zhang (2004), proposed fuzzy based MADM to deal with the imprecise information of criteria and user preference. The author compared SAW, TOPSIS and Max-Min method with respect to subjective and objective attributes. The weight of the attributes based on the subjective value for video and download applications are used for ranking the alternatives.

Bernasconi et al. (2010), provided theoretical based proof and results to consider AHP as a reliable decision making procedure in terms of the modern theory of subjective measurement of the attributes. Sekitani and Yamaki (1999), provided the logical justification for the eigenvalue method by means of optimization/equilibrium models in AHP. Tan et al. (2014), proposed fuzzy AHP where pairwise comparison of the attributes by the decision maker is presented with triangular fuzzy numbers.

Ning and Zhang (2012), proposed Multiple Attribute Decision Making-Access Selection (M-AS) which uses AHP in the weight calculation of the different requirements of the real-time and non-real time services and TOPSIS for ranking the available networks. Simulations were carried for the WLAN and WCDMA and the results were compared with the Utility Function-Access Selection (UFAS).

Saaty and Vargas (2012), addressed the seven pillars of the AHP such as; (i) Ratio scales, proportionality, and normalized ratio scales, (ii) Reciprocal paired comparisons: Relative, Absolute, (iii)Sensitivity of the principal right eigenvector, (iv) Homogeneity and clustering, (v) Synthesis that can be extended to dependence and feedback, (vi) Rank preservation and reversal, (vii) Group judgements.

Tzeng and Huang (2011); Saaty and Vargas (2012), summarized the MADM approaches: Analytic Hierarchy process (AHP), Simple Additive Weight, Technique for Order Preferences by Similarity to an Ideal Solution (TOPSIS), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), ELimination Et Choice Translating REality (ELECTRE), Preference Ranking Organization METHods for Enrichment Evaluations (PHOMETHEE), Grey Relational Analysis (GRA) and Fuzzy Integral Techniques.

Table 2.4 illustrates the summary of AHP's related work with their advantages and limitations.

Inference: Based on the literature survey on AHP, it can be concluded that, involvement of the decision makers during the computation of reciprocal matrix results in unreliable attributes weight indicated by the consistency ratio greater than 0.1. Hence, there is a need for improving the attributes weight for the reliable ranking of network in a MADM based VHD in HWNs.

Table 2.4: Comparisons of AHP Variants

AHP Variant	Approach	Advantages	Limitations
AHP (Saaty 1990; Sekitani and Yamaki 1999; Bernasconi et al. 2010; Saaty and Vargas 2012)	Pairwise comparison of attributes.	Consistent, Structured and Intuitive	Uncertainty of the decision makers' judgement, the effect of the decision makers' competency is huge and higher the number of alternatives implies a large number of comparisons.
Fuzzy AHP (Javanbarg et al. 2012; Mosadeghi et al. 2015)	Pairwise comparison of attributes with inevitably fuzziness in human judgement and preference, particularly for intangible items.	Useful for consistent and inconsistent attributes and eliminates aggregation and ranking procedures.	Reliability of attributes is not considered efficiently.
AHPSort (Ishizaka et al. 2012)	Sorts alternatives into predefined ordered categories before applying AHP.	Minimum pairwise comparisons and useful in any number of attributes.	Uses AHP for selection after alternate sorting and dependency of limiting profile on decision maker competency.
Z-AHP (Azadeh et al. 2013)	Uses Z-number to deal with linguistic decision making problems.	Z-number has more ability to describe the knowledge of human, Z-number can describe both restraint and reliability, and tolerate vagueness and uncertainty of human judgements.	Competency of decision maker in identifying criteria and sub-criteria and measure of reliability.

2.5 Simulation of Heterogeneous Wireless Networks using NS2

This section of the chapter presents the work related to the results analysis of NS2's simulation of wired, and wireless homogeneous and heterogeneous wireless networks. Table 2.5 summarize available tools for NS2's simulation and trace file analysis of single WiFi interfaced MNs in homogeneous wired and wireless networks. To the best of our knowledge, there is no tool available for NS2 in the literature to simulate heterogeneous interfaces MNs in heterogeneous wireless networks. Correspondingly, the remaining part of this section presents existing work in NS2 for simulating heterogeneous wireless networks.

Table 2.5: NS2 trace file analysis tools for homogeneous networks

Sl. No.	Contribution	Remarks
1	TCP Performance Evaluation Tool [1]	The tool developed cannot only be used for high-speed TCP protocols, but also be used for other purposes such as changes in congestion control mechanisms. After analysing the NS2 trace file, results are presented in both textual and graphical formats.
2	TRAFIL (Bouras et al. 2013)	Developed a trace file analysis and simulation tool for single interface MNs in homogeneous wired/wireless networks.
3	Trace Analyser [2]	Analyses the NS2 trace file for common network statistics. It supports homogeneous networks, but lacks in presenting the results in graphical form.
4	NS2 Visual Trace Analyser [3]	Analyses the trace file of homogeneous wired and wireless network simulation. It supports graphical and statistical analysis of the simulation.
5	JTran [4]	Supports NS2 trace file analysis of both wired and wireless homogeneous networks simulation.
6	NsGTFA (Ibrahim et al. 2015)	Windows-based NS2 GUI trace file analyser developed using VC++.

[1] TCP Performance Evaluation Tool. Available: `http://netlab.cs.ucla.edu/tcpsuite/`

[2] The Trace File analysis tool - Trace Analyser. Available: `http://trace-analyzer.sourceforge.net/`

[3] NS2 Visual Trace Analyser. Available: `https://nsvisualtraceanalyzer.wordpress.com/`

[4] A java-based ns2 wireless trace analyser. Available: `http://sites.google.com/site/ns2trana/`

Pontes et al. (2008), addressed the handover management aspects in the integration of 802.11 WLAN and 802.16 WMAN. Firstly, the authors presented basic integration issues of WLAN and WMAN such as applications and cost, architecture and operation modes, coverage and data rate, and QoS support. Secondly, the authors presented integration solutions for WLAN and WMAN, using upper layer protocols and 3GPP. Thirdly, the authors presented the IEEE 802.21 - Media Independent Handover to facilitate handover and interoperability between IEEE 802 and cellular.

Chen et al. (2009), presented the integration of the Telecommunication Networks Group (TKN) WiFi module with the NIST WiMAX module to improve transmission QoS guarantees. Further, the authors demonstrated that the stated integration would improve system performance in terms of throughput, delay, jitter and packet loss rate through the NS2 simulation. The major issues with their proposed work are the scalability and design of the result analysis script.

Marques et al. (2010), presented NIST's IEEE 802.21-Media Independent Handover (MIH) implementation in NS2 with intercommunication between WiFi and WiMAX. The authors simulated NS2's distribution provided by NIST for reliability and scalability with different number of MNs. Finally, the authors concluded that NIST's contribution in simulating HWNs is one of NS2's beneficial distributions to the research community. The major limitations of their paper is the lack of design details of multiple MNs heterogeneous wireless networks simulation and the result analysis script.

Shi et al. (2010), proposed an improved horizontal and vertical handover scheme which reduces the handover latency for seamless service between WiFi and WiMAX networks. Further, the authors evaluated the proposed scheme using NIST's NS2 distribution. The major drawback of this paper is the lack of design details of the NS2 simulation and result analysis script.

Inference: Based on the existing literature survey, it is found that there is no NS2 trace file analysis tool for result analysis of the simulation of heterogeneous interfaced MNs in heterogeneous wireless networks. This motivated us to design a tool referred to as ES-UDP for the simulation and result analysis of heterogeneous wireless networks.

2.6 Deployment of MIPv6 Testbed

Analytical, simulation and testbed are the three different ways available for justifying any proposed solutions to the research community. Each of these approaches are characterised by complexity, cost, time and the nature of results. The main objectives of the thesis is to analytically demonstrate the proposed solutions: SI-AHP and SI-MAAR. Additionally, the thesis addressed the challenges of simulation and testbed approaches of heterogeneous wireless networks. Hence, ES-UDP is developed for simulating heterogeneous wireless networks in NS2. Similarly, for the HWNs testbed result analysis, a MIPv6 (TCP/IP's network layer protocol for handover execution in homogeneous and HWNs) based framework is proposed in this thesis. This section of the chapter presents, in brief, the survey conducted with respect to MIPv6 testbed deployment. Even though extensive research papers are available addressing MIPv6 testbed deployment, they all lack in the presentation of the MIPv6 testbed deployment in detail with testing checkpoints and debugging procedures.

Chua et al. (1999), presented the Mobile IPv4 implementation in the Linux kernel. Ruchala and Zielinski (2006), measured the data streaming QoS during handover in MIPv6 testbed. However, the major drawback of their paper is the lack of information to deploy the MIPv6 testbed and the unavailability of the Mobile IP for Linux (MIPL) used for the testbed deployment. Similarly, Haseeb and Kurup (2007), deployed the MIPv6 testbed using MIPL implementation to study performance metrics, but the drawback of their paper is the lack of testbed deployment with debugging information. Azzuhri et al. (2008), also presented the deployment of MIPv6 testbed with the lack of testbed deployment and configuration details. Montavont et al. (2007), presented the shortcomings of the MIPv6 implementation in Linux compared to FMIPv6, using testbed. The major issues addressed by the authors are resolved in the current implementation of MIPv6.

Inference: Hence, the existing literature either used the older version of MIPL by addressing the drawbacks of MIPv6 implementation, or failed to provide easy, cost-effective and detailed information to deploy the MIPv6 testbed. This motivated us to build a simple and cost-effective Linux-based MIPv6 testbed with detailed deployment information, testing checkpoints and debugging procedures.

Table 2.6: A Summary of Literature Survey on Mobility Management, VHD and MADM

Heuristic	Contribution	Remarks
Siddiqui and Zeadally (2006)	Survey Paper	Mobility management, heterogeneous wireless networks key features, its challenges, different type of handovers and their metrics.
Nasser et al. (2006)		
Kassar et al. (2008)		
Charilas and Panagopoulous (2010)		
Yan et al. (2010)		Categories of VHD algorithms.
Márquez-Barja et al. (2011)		MIH in system discovery, along with VHD open research issues.
Zekri et al. (2012)		VHD Solutions
Xenakis et al. (2014)		Mobility management for femtocells in LTE-A.
Stevens-Navarro and Wong (2006)	Survey and Simulation	Handover metrics and simulation of classical MADM methods.
Wang and Kuo (2013)		Theory behind the classical MADM methods. Detailed list of subjective and objective attributes.
Wang and Luo (2009)	Verification	Demonstrated the rank reversal problem in SAW, TOPSIS, MEW and DEA.
Chamodrakas and Martakos (2012)	New TOPSIS	Energy Efficient Fuzzy TOPSIS.
Wang and Binet (2009)	Weight computation method of the attributes.	TRigger-based aUtomatic Subjective weighTing (TRUST) method.
Yang and Tseng (2013)		Five steps of an attributes weight computation method referred to as Weighted Rating of Multiple Attributes (WRMA).
Zhang (2004)	New MADM	Fuzzy MADM.
He et al. (2011)	New VHD method	VHD method based on MN classification.
Ahuja et al. (2014)		Received signal strength, distance and outage probability-based VHD method.
Wen and Hung (2015)		Energy Efficient VHD method.
Khloussy et al. (2015)		Markov Decision Process (MDP)-based VHD method.

2.7 Outcome of Literature Survey

Table 2.6 summarizes the literature survey carried out related to mobility management (Section 2.1), VHD (Section 2.2) and classical MADM methods (Section 2.3).

Based on the literature survey carried out in the individual areas of heterogeneous wireless networks, such as, mobility management, vertical handover decision, MADM methods, AHP, simulation of heterogeneous wireless networks and deployment of MIPv6 testbed, the following observations were made:

- 4G heterogeneous wireless networks is the future communication technology with additional features and applications over the conventional communication technologies: 3G, 2G and 1G.
- Optimized mobility management in heterogeneous wireless networks is one of the essential criteria for seamless communication of MNs with an uninterrupted service.
- Vertical handover decision is a major challenge in mobility management for its optimization in the seamless communication of MNs.
- Many VHD approaches are available with different complexity, reliability and flexibility. MADM is one of the VHD approaches which is designed for multiple attributes with minimum complexity.
- The major issues with the available MADM methods are, network rank unreliability and the rank reversal problem.
- AHP results in unreliable attributes weight, because of manual computation of reciprocal matrix by the decision makers.
- Simulation of heterogeneous wireless networks using NS2 imposes the issues such as, simulation script for multiple interface, multiple nodes and result analysis of simulation results.
- Insufficient information, cost and time are the major issues for deploying MIPv6 testbed to study handover execution in heterogeneous wireless networks.

2.8 Summary

This chapter of the thesis presented, an overview of recent work in the areas of heterogeneous wireless networks mobility management, attributes weight computation, VHD-making and support for simulation of heterogeneous wireless networks using the network simulator NS2. Further, this chapter also presented the state-of-the-art classical MADM methods: TOPSIS, SAW, MEW, and GRA addressing their major drawbacks such as network selection unreliability and the rank reversal problem. Additionally, state-of-the-art AHP method of attributes weight computation is presented with its drawback of unreliable attributes weight.

The following chapter numerically demonstrates the issues of classical MADM methods, sigmoidal function based approach of selecting the network and simulation of heterogeneous wireless networks.

Chapter 3

Mobility Management in Heterogeneous Wireless Networks

This chapter of the thesis numerically substantiates the unreliability in network ranking and the rank reversal problem of the classical MADM methods: TOPSIS, SAW, MEW and GRA addressed in Section 2.3.1 of Chapter 2. Additionally, this chapter presents the comparative analysis of sigmoidal utility functions based network selection in heterogeneous wireless networks. Further, the challenges for the research community in using network simulator NS2 [1] for simulation of heterogeneous wireless networks. Finally, the last section presents the proposed NS2 evaluation suite of User Datagram Protocol (UDP) applications.

3.1 Analysis of Classical MADM Methods

This section of the chapter presents an extensive MATLAB simulations carried out to numerically demonstrate the network rank (selection) unreliability and the rank reversal problem of the classical MADM methods: TOPSIS, SAW, MEW and GRA (see Figure 2.2 in Section 2.3.1 of Chapter 2). The remaining part of this section is detailed as follows:

- Subsection 3.1.1: Effect of the different attributes normalization and weight calculation methods for common networks and the corresponding attributes value referred to as network versus attribute (a_{ij}, where $i = 1, 2, ..., n$ networks and $j = 1, 2, ..., m$ attributes) on the network rank and score in TOPSIS, SAW, MEW and GRA.

[1] Network Simulator - NS2. Available: `http://www.isi.edu/nsnam/ns/`

- Subsection 3.1.2: The rank reversal problem for 1,000 different combinations of a_{ij} against different pairs of attributes normalization and weight calculation methods of TOPSIS, SAW, MEW and GRA.

In Subsections 3.1.1 and 3.1.2, a MATLAB simulation is carried out to demonstrate the unreliability in network rank and the rank reversal problem of classical MADM methods with the following three cases:

- Case 1 - removal of network N_4 from the network selection list $\{N_1, N_2, N_3, N_4\}$, resulting in $\{N_1, N_2, N_3\}$
- Case 2 (Normal) - with four networks $\{N_1, N_2, N_3, N_4\}$
- Case 3 - inserting a new network N_5 into the network selection list $\{N_1, N_2, N_3, N_4\}$, resulting in $\{N_1, N_2, N_3, N_4, N_5\}$

In the simulations, attributes of TOPSIS, SAW, MEW and GRA methods are normalized with the Vector, Sum and Max-Min normalization methods. Similarly, attributes weight (w_j, where $j = 1, 2, ..., m$ attributes) is computed using the Entropy, AHP and Variance methods.

3.1.1 Effect of Different Attributes Normalization and Weight Calculation Methods on Classical MADM

To demonstrate numerically the network selection unreliability in the classical MADM methods: TOPSIS, SAW, MEW and GRA, a MATLAB simulation is carried out with five heterogeneous wireless networks (N_1, N_2, N_3, N_4 and N_5) each with six attributes (four benefit attributes and two cost attributes) in three different cases: Case 1, Case 2 and Case 3. The attributes in MADM methods can be benefit attributes (i.e., the higher the attribute value, the better is the network rank and score) or cost attributes (i.e., the lower the attribute value, the better is the network rank and score). The benefit attributes in VHD's network selection can be bandwidth, signal-to-noise ratio, throughput, etc., and the cost attributes can be packet delay, packet loss, monetary cost, energy consumption, etc. (Wang and Kuo 2013). Heterogeneity of the five networks is accomplished in the MATLAB simulation using a different range of values for the six attributes with respect to the individual networks.

Table 3.1: MATLAB simulation parameters

Simulation Case			Network (Alternate)	Network vs. Attribute (a_{ij})					
				Benefit				Cost	
Case 1	**Case 2**	**Case 3**		**1**	**2**	**3**	**4**	**5**	**6**
N_1			Network 1 (N_1)	30	31	47	30	9.75	33
N_2			Network 2 (N_2)	60	57	10	118	3.75	37
N_3			Network 3 (N_3)	22600	91	50	106	8.25	16
	N_4		Network 4 (N_4)	45000	1	50	94	3.75	5
		N_5	Network 5 (N_5)	55000	161	128	104	3	10
AHP (Attributes Linguistic Value)				M-5	L-3	VL-1	M-5	H-7	L-3

Table 3.1 enumerates the MATLAB simulation parameters for a combination of network and the corresponding attribute value (a_{ij}) used in simulation of classical MADM methods. Additionally, Table 3.1 illustrates the linguistic value of the six attributes (Very Low (VL)-1, Low (L)-3, Medium (M)-5, High (H)-7 and Very High (VH)-9) (Chamodrakas and Martakos 2012) used in the AHP method for deriving the reciprocal matrix.

Table 3.2 shows the attributes weight computed using the Entropy, AHP and Variance methods after normalizing the attributes with the Vector, Sum and Max-Min normalization methods with respect to a_{ij} as shown in Table 3.1 with the condition $\sum_{j=1}^{m} w_j = 1$ and $w_j \geq 0$. As illustrated in Figure 2.2 (see Section 2.3.1 of Chapter 2), attributes weight computation in the Entropy and Variance methods depends on the normalized value of the attributes, resulting in variation in attributes weight with changes in attributes normalization method.

As shown in Table 3.2, Sl. Nos.: (1, 2) and (8, 9, 10) indicate the variation in attributes weight computed using the Entropy method with the Vector and Sum normalization methods respectively. However, Entropy with the Vector (Sl. No.: 3) and Max-Min (Sl. No.: (15, 16, 17)) normalization method results in an invalid attributes weight ($w_j = \infty$ or $w_j < 0$). In the Entropy attributes weighting method, a few of the attributes with vector normalization (Sl. No.: 3) result in entropy $E_j > 1$, which leads to $w_j < 0$. Also, in Max-Min normalization (Sl. Nos.: (15, 16, 17)), the Entropy weighting method computes $w_j = \infty$, since $x_{ij} = 0$ for some attributes,

Table 3.2: Attributes weight in different attributes normalization and weight Methods

Sl. No.	Normalization	Weight Method	Case	Attributes Weight					
				Benefit				Cost	
				1	2	3	4	5	6
1	Vector	Entropy	1	0.461429	0.09974	0.137427	0.12054	0.093301	0.08756
2			2	0.436522	0.22816	0.085489	0.06464	0.059212	0.12598
3			3	-	-	-	-	-	-
4		AHP	-	0.170455	0.05682	0.034091	0.17045	0.511364	0.05682
5		Variance	1	0.406652	0.1191	0.147529	0.13312	0.101723	0.09187
6			2	0.301955	0.20182	0.118236	0.10707	0.115139	0.15578
7			3	0.238596	0.20928	0.175534	0.08932	0.125051	0.16221
8	Sum	Entropy	1	0.683413	0.05532	0.10231	0.08011	0.043524	0.03532
9			2	0.469046	0.21932	0.076826	0.05879	0.057001	0.11901
10			3	0.363999	0.23759	0.144743	0.04775	0.072814	0.13311
11		AHP	-	0.170455	0.05682	0.034091	0.17045	0.511364	0.05682
12		Variance	1	0.406652	0.1191	0.147529	0.13312	0.101723	0.09187
13			2	0.301955	0.20182	0.118236	0.10707	0.115139	0.15578
14			3	0.238596	0.20928	0.175534	0.08932	0.125051	0.16221
15	Max-Min	Entropy	1	-	-	-	-	-	-
16			2	-	-	-	-	-	-
17			3	-	-	-	-	-	-
18		AHP	-	0.170455	0.05682	0.034091	0.17045	0.511364	0.05682
19		Variance	1	0.243252	0.1477	0.122146	0.12284	0.175762	0.18829
20			2	0.233195	0.15913	0.122312	0.12598	0.167662	0.19172
21			3	0.204371	0.18171	0.182122	0.11437	0.150567	0.16686

leading to $\ln(x_{ij}) = \infty$. Further, as shown in Table 3.2, Sl. Nos.: (5, 12, 19), (6, 13, 20) and (7, 14, 21) indicate the variation in attributes weight computed using the Variance method with Vector, Sum and Max-Min normalization for Case 1, 2 and 3 respectively. However, in AHP (Sl. Nos.: 4, 11, 18), the computed weight of the attributes remains the same, since AHP is independent of attributes normalization methods.

Tables 3.3 - 3.6 illustrate the variation in network rank and score in the TOPSIS, SAW, MEW and GRA methods respectively, for different pairs of attributes normalization and weight calculation methods in three different cases (Case 1, Case 2 and Case 3) with respect to a_{ij} as shown in Table 3.1.

Table 3.3: TOPSIS - Variations in the network rank and score with respect to different attributes normalization and weight methods for three different cases

Sl. No.	Normalization	Weight Method	Case	Rank 1		Rank 2		Rank 3		Rank 4		Rank 5	
				Network	Score	Network	Score	Network	Score	Network	Score	Network	Score
1	Vector	Entropy	1	3	0.93549	2	0.14781	1	0.13511				
2			2	4	0.68547	3	0.58474	2	0.23008	1	0.14786		
3			3	-	-	-	-	-	-	-	-	-	-
4		AHP	1	2	0.58919	3	0.5375	1	0.05808				
5			2	4	0.84568	2	0.60097	3	0.41233	1	0.07084		
6			3	5	0.9587	4	0,79522	2	0.62209	3	0.33257	1	0.04222
7		Variance	1	3	0.92255	2	0.17762	1	0.15802				
8			2	4	0.64613	3	0.61784	2	0.29342	1	0.19548		
9			3	5	0.94831	4	0.49166	3	0.47081	2	0.24837	1	0.16952
10	Sum	Entropy	1	3	0.98587	1	0.04945	2	0.044				
11			2	4	0.74193	3	0.554477	2	0.18298	1	0.11301		
12			3	5	0.96889	4	0.53852	3	0.45771	2	0.18211	1	0.12758
13		AHP	1	3	0.63237	2	0.47289	1	0.05003				
14			2	4	0.84653	2	0.52713	3	0.43157	1	0.06834		
15			3	5	0.96158	4	0.78351	2	0.57765	3	0.33806	1	0.04495
16		Variance	1	3	0.94948	2	0.12175	1	0.11089				
17			2	4	0.67772	3	0.59436	2	0.25629	1	0.16714		
18			3	5	0.95274	4	0.49365	3	0.46885	2	0.23363	1	0.16368
19	Max-Min	Entropy	1	-	-	-	-	-	-	-	-	-	-
20			2	-	-	-	-	-	-	-	-	-	-
21			3	-	-	-	-	-	-	-	-	-	-
22		AHP	1	3	0.76024	1	0.67479	2	0.25106				
23			2	3	0.72708	1	0.67844	4	0.29119	2	0.25306		
24			3	3	0.72778	1	0.67573	5	0.31135	4	0.29564	2	0.27969
25		Variance	1	3	0.64518	1	0.45311	2	0.41142				
26			2	3	0.6234	1	0.48327	4	0.47981	2	0.44017		
27			3	5	0.62394	3	0.49841	1	0.41948	2	0.39432	4	0.38963

Attributes normalization with respect to different weight calculation methods for three different cases of MATLAB simulation as shown in Tables 3.3 - 3.6 are as follows:

- Attribute Vector normalization with respect to weight calculation methods: Entropy, AHP and Variance are shown by Sl. Nos.: 1-3, 4-6 and 7-9 respectively;
- Attribute Sum normalization with respect to weight calculation methods: Entropy, AHP and Variance are shown by Sl. Nos.: 10-12, 13-15 and 16-18 respectively;
- Attribute Max-Min normalization with respect to weight calculation methods: Entropy, AHP and Variance are shown by Sl. Nos.: 19-21, 22-24 and 25-27 respectively.

Following are the pairwise entries in Table 3.3 illustrating the network rank unreliability with the TOPSIS method:

- *Vector normalization with the Entropy, AHP and Variance methods*:
  Sl. Nos. - (1, 4) and (4, 7) in Case 1; Sl. Nos. - (2, 5) and (5, 8) in Case 2; and Sl. No. - (6, 9) in Case 3.
- *Sum normalization with the Entropy, AHP and Variance methods*:
  Sl. Nos. - (10, 13) and (10, 16) in Case 1; Sl. Nos. - (11, 14) and (14, 17) in Case 2; and Sl. Nos. - (12, 15) and (15, 18) in Case 3.
- *Max-Min normalization with the Entropy, AHP and Variance methods*:
  Sl. No. - (24, 27) in Case 3.

Inference:

- In the TOPSIS method, the Entropy weighting method is most suitable for the Sum normalization method.
- The dependency of TOPSIS on attributes normalization methods results in an unreliable network rank and score, despite AHP being independent of the normalized attributes.
- The TOPSIS method with the Vector and Max-Min normalization methods are suitable for both AHP and Variance methods, but not to the Entropy method.

Table 3.4: SAW - Variations in the network rank and score with respect to different attributes normalization and weight methods for three different cases

Sl. No.	Normalization	Weight Method	Case	Rank 1		Rank 2		Rank 3		Rank 4		Rank 5	
				Network	Score	Network	Score	Network	Score	Network	Score	Network	Score
1	Vector	Entropy	1	3	0.80559	1	0.26762	2	0.24849				
2			2	3	0.54219	4	0.50275	2	0.27283	1	0.2421		
3			3	-	-	-	-	-	-	-	-	-	-
4		AHP	1	3	0.6876	1	0.48132	2	0.34336				
5			2	3	0.56185	1	0.45833	4	0.40263	2	0.31967		
6			3	3	0.48881	1	0.4309	5	0.40273	4	0.33001	2	0.28792
7		Variance	1	3	0.78867	1	0.29101	2	0.27431				
8			2	3	0.54606	4	0.44077	2	0.3261	1	0.31775		
9			3	5	0.59427	3	0.3924	4	0.2897	1	0.28595	2	0.26754
10	Sum	Entropy	1	3	0.81315	1	0.09795	2	0.0889				
11			2	4	0.36831	3	0.34922	2	0.15147	1	0.131		
12			3	5	0.37219	3	0.20921	4	0.1857	1	0.11713	2	0.11578
13		AHP	1	3	0.49026	1	0.29621	2	0.21353				
14			2	3	0.32384	1	0.25089	4	0.24885	2	0.17642		
15			3	3	0.24954	5	0.21722	1	0.21565	4	0.17421	2	0.14338
16		Variance	1	3	0.64576	1	0.18254	2	0.1717				
17			2	3	0.33776	4	0.29393	2	0.18828	1	0.18003		
18			3	5	0.33438	3	0.21344	4	0.16198	1	0.14974	2	0.14046
19	Max-Min	Entropy	1	-	-	-	-	-	-	-	-	-	-
20			2	-	-	-	-	-	-	-	-	-	-
21			3	-	-	-	-	-	-	-	-	-	-
22		AHP	1	2	0.70667	3	0.59323	1	0.04236				
23			2	4	0.89669	2	0.71729	3	0.4888	1	0.05758		
24			3	5	0.964	4	0.78633	2	0.64498	3	0.41164	1	0.02845
25		Variance	1	3	0.85143	2	0.36293	1	0.14885				
26			2	4	0.80652	3	0.67501	2	0.39281	1	0.19015		
27			3	5	0.95573	4	0.61281	3	0.4896	2	0.31192	1	0.11203

Table 3.4 illustrates the following pairwise unreliable network rank entries with the SAW method:

- *Vector normalization with the Entropy, AHP and Variance methods*:
  Sl. Nos. - (2, 5) and (5, 8) in Case 2; and Sl. No. - (6, 9) in Case 3.

- *Sum normalization with the Entropy, AHP and Variance methods*:
  Sl. No. - (11, 14, 17) in Case 2; and Sl. Nos. - (12, 15) and (15, 18) in Case 3.

- *Max-Min normalization with the Entropy, AHP and Variance methods*:
  Sl. No. - (22, 25) in Case 1; Sl. No. - (23, 26) in Case 2; and Sl. No. - (24, 27) in Case 3.

Inference:

- In the SAW method, the Entropy weighting method is most suitable for the Sum normalization method.

- The dependency of SAW on attributes normalization methods results in an unreliable network rank and score, despite AHP being independent of the normalized attributes.

- The SAW method with the Vector and Max-Min normalization methods are suitable for both AHP and Variance methods, but not Entropy.

Table 3.5 illustrates the following pairwise unreliable network rank entries with the MEW method:

- *Vector normalization with the Entropy, AHP and Variance methods*:
  Sl. Nos. - (1, 4) and (4, 7) in Case 1; Sl. Nos. - (2, 5) and (5, 8) in Case 2; and Sl. No. - (6, 9) in Case 3.

- *Sum normalization with the Entropy, AHP and Variance methods*:
  Sl. Nos. - (10, 13) and (13, 16) in Case 1; Sl. Nos. - (11, 14) and (14, 17) in Case 2; and Sl. Nos. - (12, 15) and (15, 18) in Case 3.

- *Max-Min normalization with the Entropy, AHP and Variance methods*: This is not applicable with respect to network ranking.

Table 3.5: MEW - Variations in the network rank and score with respect to different attributes normalization and weight methods for three different cases

Sl. No.	Normalization	Weight Method	Case	Rank 1		Rank 2		Rank 3		Rank 4		Rank 5	
				Network	Score	Network	Score	Network	Score	Network	Score	Network	Score
1	Vector	Entropy	1	3	0.76785	2	0.03854	1	0.0299				
2			2	3	0.51737	4	0.20422	2	0.0325	1	0.02277		
3			3	-	-	-	-	-	-	-	-	-	-
4		AHP	1	3	0.66615	1	0.18502	2	0.15946				
5			2	3	0.55178	4	0.29427	1	0.15325	2	0.13208		
6			3	3	0.47271	5	0.33944	4	0.2521	1	0.13129	2	0.11315
7		Variance	1	3	0.75138	2	0.0508	1	0.0407				
8			2	3	0.52122	4	0.1942	2	0.06884	1	0.05615		
9			3	5	0.5087	3	0.37982	4	0.12928	2	0.06609	1	0.06334
10	Sum	Entropy	1	3	0.74857	2	0.01078	1	0.00708				
11			2	3	0.33517	4	0.14229	2	0.01759	1	0.01204		
12			3	5	0.32365	3	0.20468	4	0.07241	2	0.1777	1	0.01478
13		AHP	1	3	0.44696	1	0.12414	2	0.10699				
14			2	3	0.3188	4	0.17002	1	0.08854	2	0.07631		
15			3	3	0.24449	5	0.17556	4	0.13039	1	0.06791	2	0.05852
16		Variance	1	3	0.569	2	0.03847	1	0.03082				
17			2	3	0.32233	4	0.1201	2	0.04257	1	0.03473		
18			3	5	0.2789	3	0.20824	4	0.07088	2	0.03624	1	0.03472
19	Max-Min	Entropy	1	-	-	-	-	-	-				
20			2	-	-	-	-	-	-	-	-		
21			3	-	-	-	-	-	-	-	-	-	-
22		AHP	1	-	-	-	-	-	-				
23			2	-	-	-	-	-	-	-	-		
24			3	-	-	-	-	-	-	-	-	-	-
25		Variance	1	-	-	-	-	-	-				
26			2	-	-	-	-	-	-	-	-		
27			3	-	-	-	-	-	-	-	-	-	-

Inference:

- Sl. Nos.: (19 - 27) indicate that the MEW method is not suitable for Max-Min normalization irrespective of attributes weight calculation methods.
- In MEW, irrespective of the attributes normalization method, the rank of networks remains the same for the Entropy and Variance methods.
- In MEW, Entropy attributes weight method is suitable for the Sum normalization method.
- The dependency of MEW on attributes normalization methods results in an unreliable network rank and score, despite the AHP method being independent of the normalized attributes.

Table 3.6 illustrates the following pairwise unreliable network rank entries with the GRA method:

- *Vector normalization with the Entropy, AHP and Variance methods*:
  Sl. Nos. - (1, 4) and (4, 7) in Case 1; Sl. Nos. - (2, 5) and (5, 8) in Case 2; and Sl. No. - (6, 9) in Case 3.
- *Sum normalization with the Entropy, AHP and Variance methods*:
  Sl. Nos. - (10, 13) and (13, 16) in Case 1; Sl. Nos. - (11, 14) and (14, 17) in Case 2; and Sl. Nos. - (12, 15) and (15, 18) in Case 3.
- *Max-Min normalization with the Entropy, AHP and Variance methods*:
  Sl. No. - (23, 26) in Case 2; and Sl. No. - (24, 27) in Case 3.

Inference:

- The GRA with the Entropy weighting method is most suitable for the Sum normalization method.
- The dependency of GRA on attributes normalization methods results in an unreliable network rank and score, despite the AHP method being independent of the normalized attributes.

Table 3.6: GRA - Variations in the network rank and score with respect to different attributes normalization and weight methods for three different cases

Sl. No.	Normalization	Weight Method	Case	Rank 1		Rank 2		Rank 3		Rank 4		Rank 5	
				Network	Score	Network	Score	Network	Score	Network	Score	Network	Score
1	Vector	Entropy	1	3	0.94671	2	0.54198	1	0.48796				
2			2	4	0.83878	3	0.70874	2	0.50004	1	0.44717		
3			3	-	-	-	-	-	-	-	-	-	-
4		AHP	1	2	0.82125	3	0.77147	1	0.50018				
5			2	4	0.92536	2	0.81308	3	0.65975	1	0.48238		
6			3	5	0.96581	4	0.80555	2	0.74336	3	0.58354	1	0.4428
7		Variance	1	3	0.94168	2	0.56382	1	0.50138				
8			2	4	0.84625	3	0.73745	2	0.56643	1	0.48328		
9			3	5	0.95733	4	0.67062	3	0.55727	2	0.50268	1	0.41449
10	Sum	Entropy	1	3	0.98026	2	0.47377	1	0.45819				
11			2	4	0.85811	3	0.70886	2	0.51332	1	0.467		
12			3	5	0.97124	4	0.65366	3	0.53935	2	0.45064	1	0.4044
13		AHP	1	2	0.83737	3	0.83498	1	0.59308				
14			2	4	0.93656	2	0.82178	3	0.70633	1	0.54302		
15			3	5	0.97022	4	0.81678	2	0.75005	3	0.0646	1	0.4693
16		Variance	1	3	0.95857	2	0.60255	1	0.55599				
17			2	4	0.86033	3	0.75773	2	0.59415	1	0.52225		
18			3	5	0.96132	4	0.67535	3	0.56596	2	0.50728	1	0.4265
19	Max-Min	Entropy	1	-	-	-	-	-	-	-	-	-	-
20			2	-	-	-	-	-	-	-	-	-	-
21			3	-	-	-	-	-	-	-	-	-	-
22		AHP	1	3	0.75514	1	0.71473	2	0.49259				
23			2	1	0.72445	3	0.67571	4	0.52317	2	0.4983		
24			3	1	0.70647	3	0.63574	5	0.58227	2	0.50427	4	0.47193
25		Variance	1	3	0.78956	1	0.58959	2	0.56083				
26			2	3	0.69192	1	0.61532	4	0.60986	2	0.58277		
27			3	5	0.76724	2	0.5433	1	0.53628	3	0.5354	4	0.47268

- The GRA with the Vector and Max-Min normalization methods are suitable for both AHP and Variance methods, but not the Entropy method.

Additionally, Tables 3.3 - 3.6 illustrates the variations in the computed score of individual network in all pairs of attributes normalization with respect to weight calculation methods in TOPSIS, SAW, MEW and GRA methods.

Ultimately, this subsection numerically demonstrated (see Tables 3.3 - 3.6) the network rank unreliability of the classical MADM methods: TOPSIS, SAW, MEW and GRA. Subsequently, the following subsection demonstrates the second major limitation of the classical MADM methods i.e., the rank reversal problem.

3.1.2 The Rank Reversal Problem of Classical MADM

The second major challenging issue of the classical MADM methods is the rank reversal problem. As explained in Section 2.3.1 of Chapter 2 of the thesis, the rank reversal problem of classical MADM methods leads to the reversal of the relative ranking of the networks if an alternative network is removed from or inserted into the candidate networks selection list. The same Tables 3.3, 3.4 and 3.6 of Subsection 3.1.1 are used to illustrate the rank reversal problem of the classical MADM methods: TOPSIS, SAW and GRA respectively (**Note:** Table 3.5 of MEW shows no rank reversal problem entries for a_{ij} shown in Table 3.1.).

Table 3.3 illustrates the following entries with the rank reversal problem in the TOPSIS method:

- Sl. Nos.: 10 (Case 1) and 11 (Case 2) present the removal of network N_4 in Case 2 that results in the ranking of the other three networks (Case 1) as $Rank_{N_3} > Rank_{N_1} > Rank_{N_2}$ instead of $Rank_{N_3} > Rank_{N_2} > Rank_{N_1}$
- Sl. Nos.: 13 (Case 1) and 14 (Case 2) present the removal of network N_4 in Case 2 that results in the ranking of the other three networks (Case 1) as $Rank_{N_3} > Rank_{N_2} > Rank_{N_1}$ instead of $Rank_{N_2} > Rank_{N_3} > Rank_{N_1}$
- Sl. Nos.: 26 (Case 2) and 27 (Case 3) present the insertion of a new network N_5 in Case 2 with better network attributes that results in the ranking of the networks (Case 3) as $Rank_{N_5} > Rank_{N_3} > Rank_{N_1} > Rank_{N_2} > Rank_{N_4}$ instead of $Rank_{N_5} > Rank_{N_3} > Rank_{N_1} > Rank_{N_4} > Rank_{N_2}$

Table 3.4 illustrates the following entries with the rank reversal problem in the SAW method:

- Sl. Nos.: 1 (Case 1) and 2 (Case 2) present the removal of network N_4 in Case 2 that results in the ranking of the other three networks (Case 1) as $Rank_{N_3} > Rank_{N_1} > Rank_{N_2}$ instead of $Rank_{N_3} > Rank_{N_2} > Rank_{N_1}$

- Sl. Nos.: 7 (Case 1) and 8 (Case 2) present the removal of network N_4 in Case 2 that results in the ranking of the other three networks (Case 1) as $Rank_{N_3} > Rank_{N_1} > Rank_{N_2}$ instead of $Rank_{N_3} > Rank_{N_2} > Rank_{N_1}$

- Sl. Nos.: 8 (Case 2) and 9 (Case 3) present the insertion of a new network N_5 in Case 2 with better network attributes that results in the ranking of the networks (Case 3) as $Rank_{N_5} > Rank_{N_3} > Rank_{N_4} > Rank_{N_1} > Rank_{N_2}$ instead of $Rank_{N_5} > Rank_{N_3} > Rank_{N_4} > Rank_{N_2} > Rank_{N_1}$

- Sl. Nos.: 10 (Case 1) and 11 (Case 2) present the removal of network N_4 in Case 2 that results in the ranking of the other three networks (Case 1) as $Rank_{N_3} > Rank_{N_1} > Rank_{N_2}$ instead of $Rank_{N_3} > Rank_{N_2} > Rank_{N_1}$

- Sl. Nos.: 11 (Case 2) and 12 (Case 3) present the insertion of a new network N_5 in Case 2 with better network attributes that results in the ranking of the networks (Case 3) as $Rank_{N_5} > Rank_{N_3} > Rank_{N_4} > Rank_{N_1} > Rank_{N_2}$ instead of $Rank_{N_5} > Rank_{N_4} > Rank_{N_3} > Rank_{N_2} > Rank_{N_1}$

- Sl. Nos.: 16 (Case 1) and 17 (Case 2) present the removal of network N_4 in Case 2 that results in the ranking of the other three networks (Case 1) as $Rank_{N_3} > Rank_{N_1} > Rank_{N_2}$ instead of $Rank_{N_3} > Rank_{N_2} > Rank_{N_1}$

- Sl. Nos.: 17 (Case 2) and 18 (Case 3) present the insertion of a new network N_5 in Case 2 with better network attributes that results in the ranking of the networks (Case 3) as $Rank_{N_5} > Rank_{N_3} > Rank_{N_4} > Rank_{N_1} > Rank_{N_2}$ instead of $Rank_{N_5} > Rank_{N_3} > Rank_{N_4} > Rank_{N_2} > Rank_{N_1}$

Table 3.6 illustrates the following entries with the rank reversal problem in the GRA method:

- Sl. Nos.: 22 (Case 1) and 23 (Case 2) present the removal of network N_4 in Case 2 that results in the ranking of the other three networks (Case 1) as $Rank_{N_3} > Rank_{N_1} > Rank_{N_2}$ instead of $Rank_{N_1} > Rank_{N_3} > Rank_{N_2}$
- Sl. Nos.: 23 (Case 2) and 24 (Case 3) present the insertion of a new network N_5 in Case 2 with better network attributes that results in the ranking of the networks (Case 3) as $Rank_{N_1} > Rank_{N_3} > Rank_{N_5} > Rank_{N_2} > Rank_{N_4}$ instead of $Rank_{N_1} > Rank_{N_3} > Rank_{N_5} > Rank_{N_4} > Rank_{N_2}$.
- Sl. Nos.: 26 (Case 2) and 27 (Case 3) present the insertion of a new network N_5 in Case 2 with better network attributes that results in the ranking of the networks (Case 3) as $Rank_{N_5} > Rank_{N_2} > Rank_{N_1} > Rank_{N_3} > Rank_{N_4}$ instead of $Rank_{N_5} > Rank_{N_3} > Rank_{N_1} > Rank_{N_4} > Rank_{N_2}$

Table 3.7: The rank reversal problem for 1,000 different combinations of network vs. attribute (a_{ij}) in TOPSIS, SAW, MEW and GRA

Sl. No.	Normalization	Weight Method	Total No. of a_{ij}	Classical MADM Methods							
				No. of Invalid a_{ij}				a_{ij} with the rank reversal problem			
				TOPSIS	SAW	MEW	GRA	TOPSIS	SAW	MEW	GRA
1	Vector	Entropy	1,000	981	981	981	981	9	13	6	16
2		AHP		0	0	0	0	578	587	0	564
3		Variance		0	0	0	0	496	706	261	594
4	Sum	Entropy		0	0	0	0	456	676	280	570
5		AHP		0	0	0	0	671	645	0	622
6		Variance		0	0	0	0	487	700	261	583
7	Max-Min	Entropy		1000	1000	1000	1000	-	-	-	-
8		AHP		15	15	717	15	261	350	33	503
9		Variance		15	15	717	15	654	489	32	748

To study the rank reversal problem's detrimental effect on the classical MADM methods: TOPSIS, SAW, MEW and GRA, an extensive MATLAB simulation is carried out on the randomly generated 1,000 different combinations of a_{ij}. Table 3.7 shows the number of invalid a_{ij} and the number of a_{ij} with the rank reversal problem.

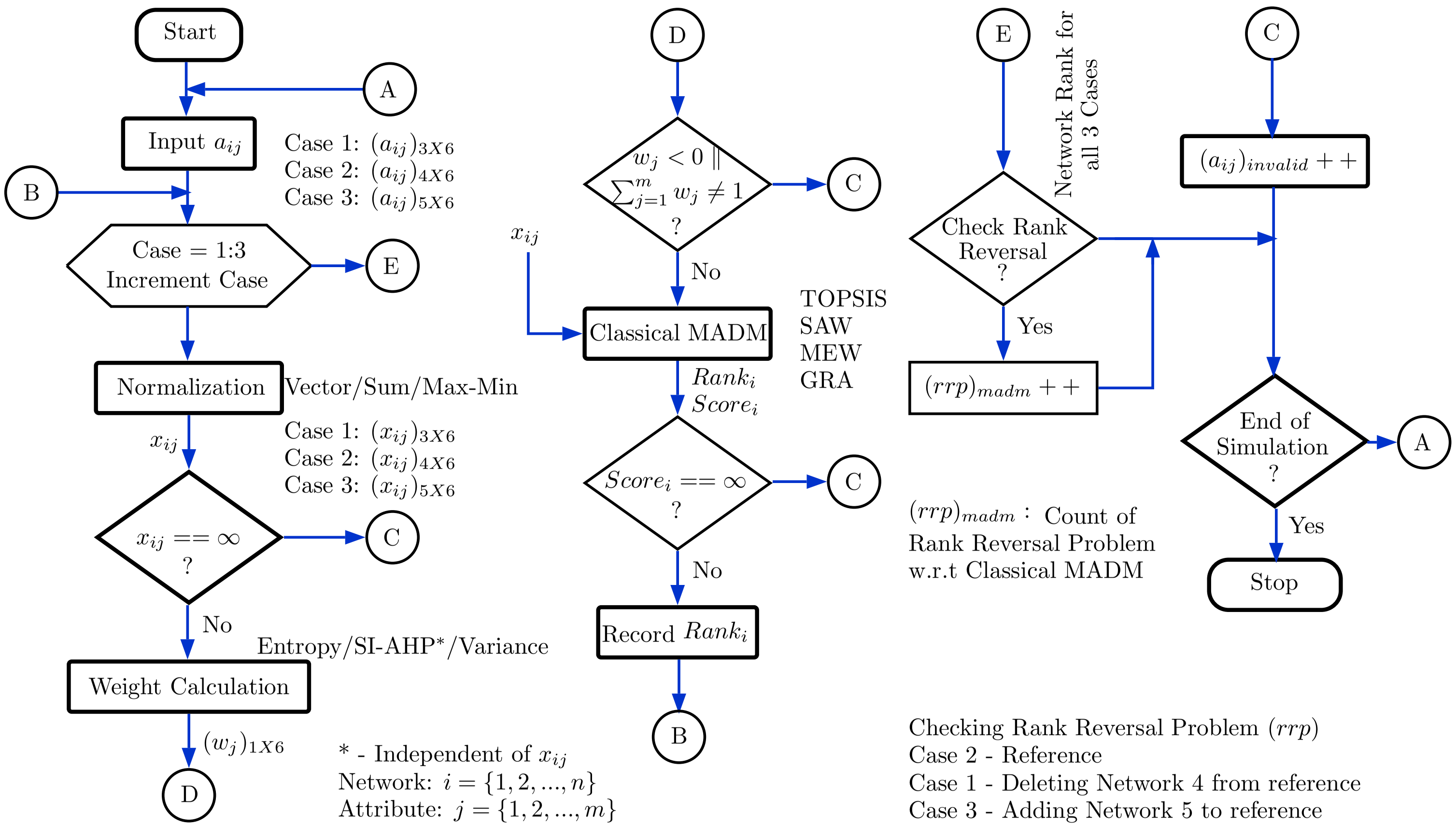


Figure 3.1: Flowchart for counting the rank reversal problem of the classical MADM methods for 1,000 different a_{ij}

Figure 3.1 illustrates the flowchart used to study the rank reversal problem's detrimental effect (invalid a_{ij} and a_{ij} with the rank reversal problem) on the classical MADM methods illustrated in Table 3.7. As shown in Figure 3.1, an invalid a_{ij} represents the a_{ij} with $x_{ij} = \infty$ (Max-Min Normalization) or $w_j < 0$ (Entropy) or $Score_i = \infty$ (MEW ranking). In Table 3.7, the number of combinations of a_{ij} with the rank reversal problem is computed for the valid a_{ij}, if the rank reversal exists in Case 2 and Case 1 or Case 2 and Case 3.

As illustrated in Table 3.7, the rank reversal problem is observed in all the four classical MADM methods with the different pairs of attributes normalization and weight calculation methods.

Inference: Dependency of the classical MADM methods on attributes normalization and weight calculation methods, and the interdependence between one network attribute and the others, will cause an unreliable network ranking and the rank reversal problem.

Finally, Section 3.1 numerically justified the issues: ranking unreliability and the rank reversal problem of the classical MADM methods mentioned in Section 2.3.1 of Chapter 2.

3.2 Analysis of Sigmoidal Utility Function based Handover in Heterogeneous Wireless Networks

The sigmoidal utility function is one of the approaches evolved in network selection during handover decisions in heterogeneous wireless networks. Satisfaction (utility) of user and application with respect to a selected network is a key factor of the utility function in selecting the network for handover. Many variations of a sigmoidal utility function with merits and demerits are proposed in the literature for network selection in heterogeneous wireless networks (Nguyen-Vuong et al. 2013). The objective of this section of the chapter is to compare and analyse the performances of some of the popularly used sigmoidal utility functions during handover decision in heterogeneous wireless networks using MATLAB. Further, common issues pertaining to these functions are addressed.

3.2.1 Variations of Sigmoidal Functions

A sigmoidal (S) function is essentially a single-attribute utility function. It is used for network selection during handover in heterogeneous wireless networks because of its desirable properties: twice-differentiability, monotonicity, concavity and convexity (Nguyen-Vuong et al. 2013).

Equations (3.1)-(3.4) represent the more popularly used sigmoidal utility functions (Chamodrakas and Martakos 2012; Abid et al. 2012; Nguyen-Vuong et al. 2013). In Equations (3.3) and (3.4), x_α and x_β represent the lower and upper limits of the network attribute a_j, where $j = 1, 2, ..., m$ attributes.

The shape of the S in the sigmoidal function depends on the constant parameters ζ (steepness of the S shape) and x_m (center of the S shape, where the utility with respect to the network attribute a_j is 0.5).

$$u_1(a_j) = \frac{1}{1 + e^{\zeta(x_m - a_j)}} \tag{3.1}$$

$$u_2(a_j) = \frac{\left(\frac{a_j}{x_m}\right)^\zeta}{1 + \left(\frac{a_j}{x_m}\right)^\zeta} \tag{3.2}$$

$$u_3(a_j) = \begin{cases} 0 & \text{if } a_j < x_\alpha; \\ \dfrac{\left(\frac{a_j - x_\alpha}{x_m - x_\alpha}\right)^\zeta}{1 + \left(\frac{a_j - x_\alpha}{x_m - x_\alpha}\right)^\zeta} & \text{if } x_\alpha \leq a_j \leq x_m; \\ 1 - \dfrac{\left(\frac{x_\beta - a_j}{x_\beta - x_m}\right)^\gamma}{1 + \left(\frac{x_\beta - a_j}{x_\beta - x_m}\right)^\gamma} & \text{if } x_m < a_j \leq x_\beta; \\ 1 & \text{if } a_j > x_\beta \end{cases} \tag{3.3}$$

$$u_4(a_j) = \begin{cases} 0 & \text{if } a_j < x_\alpha; \\ \dfrac{1}{1 + e^{\left(\frac{\zeta(x_m - a_j)}{a_j - x_\alpha}\right)}} & \text{if } x_\alpha \leq a_j \leq x_m; \\ 1 - \dfrac{1}{1 + e^{\left(\frac{\gamma(a_j - x_m)}{x_\beta - a_j}\right)}} & \text{if } x_m < a_j \leq x_\beta; \\ 1 & \text{if } a_j > x_\beta \end{cases} \tag{3.4}$$

where $x_\alpha \leq a_j \leq x_\beta < \infty$

$$\zeta \geq max\left(\frac{2(x_m - x_\alpha)}{x_\beta - x_m}, 2\right) \tag{3.5}$$

and

$$\gamma = \frac{\zeta(x_\beta - x_m)}{x_m - x_\alpha} \tag{3.6}$$

Figure 3.2, shows the variations in the shape of S with respect to the variations in ζ(zeta) derived using Equation (3.5) for $a_j \in \{1, 2, ..., 100\}$. The constant ζ is varied for values 2, 4, 6 and 10. Moreover, Figure 3.2 illustrates the sensitivity of sigmoidal functions represented by Equations (3.1)-(3.4) for the variations of constant ζ and attribute a_j. As shown in Figure 3.2, Equation (3.1) is highly sensitive, whereas Equation (3.2) is less sensitive compared to the Equations (3.3) and (3.4) with respect to ζ and a_j. The sensitivity of sigmoidal functions as shown in Figure 3.2 represents how quickly utility varies for the variations of constant ζ and attribute a_j.

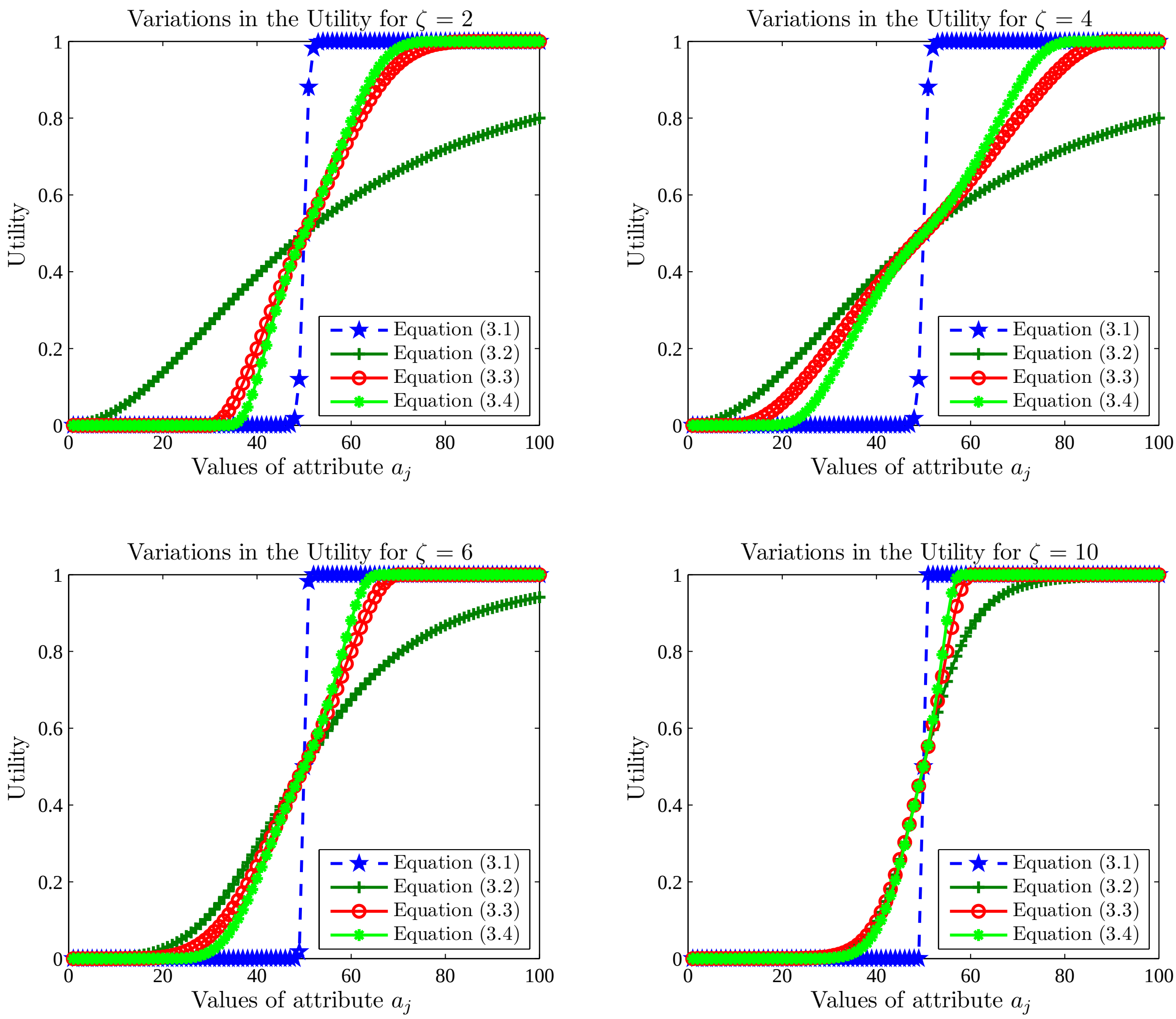


Figure 3.2: Utility of sigmoidal functions for different ζ and a_j

Inference: Equation (3.1) is useful for applications (real-time) which are more sensitive to variations in network attributes, whereas Equations (3.2)-(3.4) are useful for applications such as web browsing.

Subsection 3.2.2 compare and analyse, Equations (3.1)-(3.3) with respect to their influence in network selection during handover decision in heterogeneous wireless networks. (**Note:** Equation (3.4) is not considered in further discussion, since it follows Equation (3.3) for the variation of ζ and a_j.)

3.2.2 Network Selection using Sigmoidal Function

The satisfaction $u(a_j)$ of the user and an application for the variation of ζ and a_j with respect to a network are the key factor for network selection using sigmoidal functions. The higher the satisfaction during the handover decision, the better is the network for handover and vice-versa. Since, network selection in heterogeneous wireless networks depends on multiple attributes, single-attribute sigmoidal utility function (Equations (3.1)-(3.3)) is always used with the classical MADM methods such as Simple Additive Weighting (SAW) or Multiplicative Exponent Weighting (MEW) to compute the satisfaction score of the networks (Stevens-Navarro et al. 2008, Tzeng and Huang 2011). Equations (3.7) and (3.8) represent SAW and MEW respectively, for computing the final satisfaction score of network i with respect to m attributes. Figure 2.2 (see Section 2.3.1 of Chapter 2) illustrates the detailed steps followed in ranking the networks using the classical MADM methods: SAW and MEW.

$$\text{Score}_i = \sum_{j=1}^{m} w_j * U_{ij} \tag{3.7}$$

$$\text{Score}_i = \prod_{j=1}^{m} U_{ij}^{w_j} \tag{3.8}$$

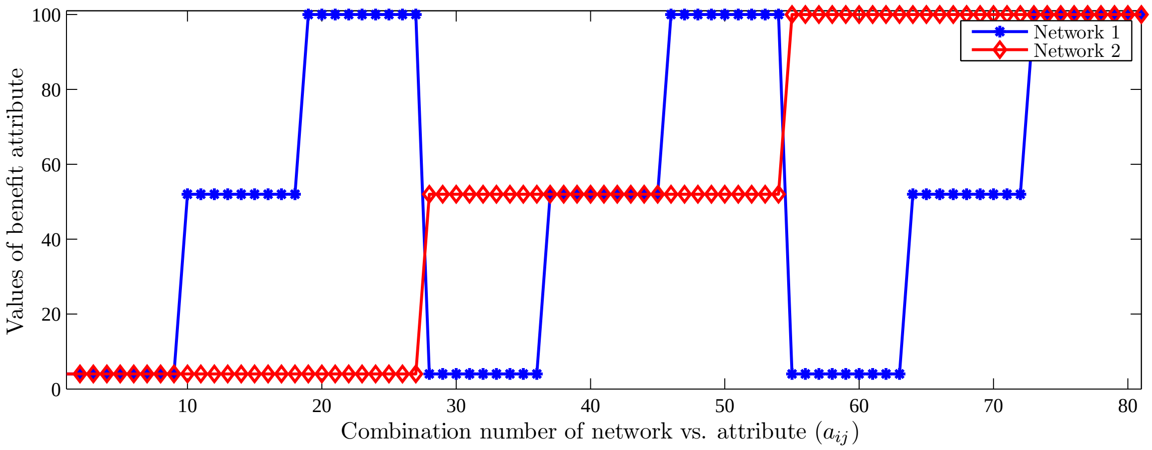
where U_{ij} represents the utility of network i with respect to attribute j and is given as follows,

$$U_{ij} = \begin{cases} u_{ij}(a_{ij}) & \text{if } j \text{ is the benefit attribute;} \\ 1 - u_{ij}(a_{ij}) & \text{if } j \text{ is the cost attribute} \end{cases} \tag{3.9}$$

$$\text{Selected network for handover} = \max_i \text{Score}_i \tag{3.10}$$

where network: $i = 1, 2, .., n$ and attribute: $j = 1, 2, ..., m$, with weight w_j.

A Results and Analysis



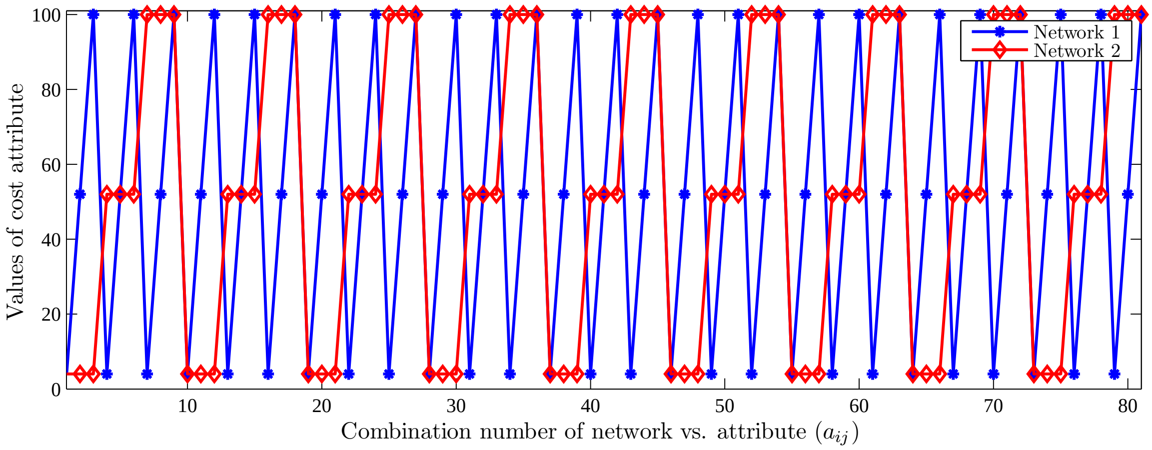


Figure 3.3: Variations in networks' benefit and cost attribute

To compare and analyse the influence of different sigmoidal functions (Equations (3.1)-(3.3)) on network selection, a MATLAB simulation is carried out with the following parameters. (**Note:** To justify the results, a simulation is carried out for two networks with two attributes each.)

- Number of networks: two (N_1 and N_2).
- Number of attributes: two (benefit (b_1) and cost (c_1) attributes).
- As shown in Figure 3.3, b_1 and c_1 attributes value are varied from 4 to 100 in steps of 48 (b_1, $c_1 \in \{4, 52, 100\}$ for network N_1 and network N_2), resulting in 81 different combinations of network versus attribute (a_{ij}). Each of these attributes with respect to network are varied one at a time.

- Weight of the attributes are varied to $\{w_{b_1}, w_{c_1}\} \in \{\{0.0, 1.0\}, \{0.2, 0.8\}, \{0.4, 0.6\}, \{0.6, 0.4\}, \{0.8, 0.2\}, \{1.0, 0.0\}\}$ with the condition $\sum_{j=1}^{2} w_j = 1$ and $w_j \geq 0$.

- Finally, $\{x_\alpha, x_m, x_\beta\} \in \{\{10, 50, 90\}, \{10, 50, 70\}, \{20, 50, 60\}, \{0, 50, 60\}\}$.

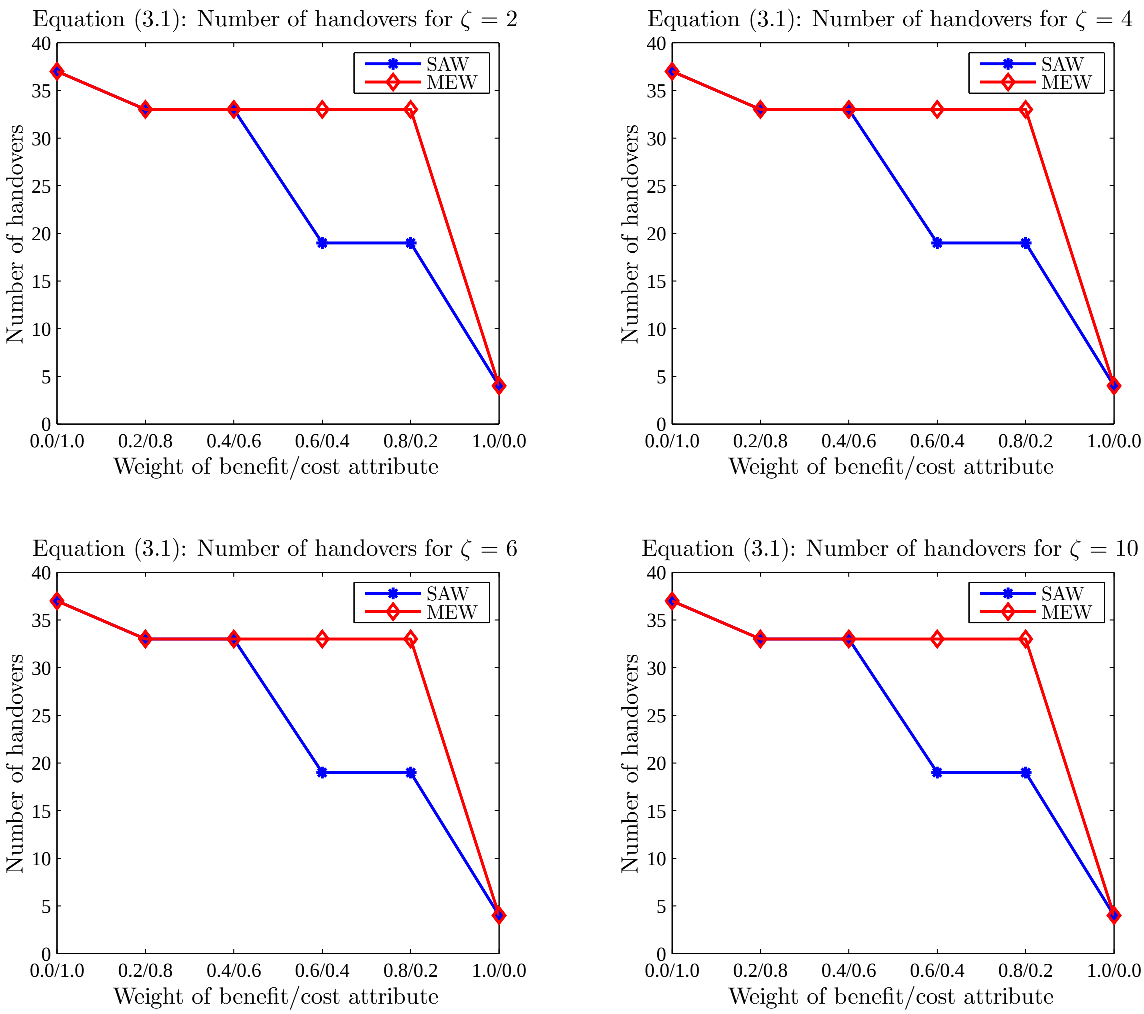


Figure 3.4: Number of handovers for different w_j and ζ in Equation (3.1)

Figures 3.4 - 3.6, illustrate the number of handovers (i.e., cumulative value for 81 different combinations of network versus attribute for a particular attributes weight) for the variations of w_{b_1} and w_{c_1}, and ζ. As shown in Figures 3.4 - 3.6, increase in weight of the benefit attribute (i.e., decrease in weight of the cost attribute) decreases the number of handovers because of minimum variations in the benefit attribute between the two networks (see Figure 3.3). Similarly, when the weight of the cost attribute is more than that of the benefit attribute, the final utility score of both networks depends on cost attribute of the network. Since, the cost attribute of both the networks varies continuously as shown in Figure 3.3, it results in maximum number of handovers and vice-versa for the benefit attribute.

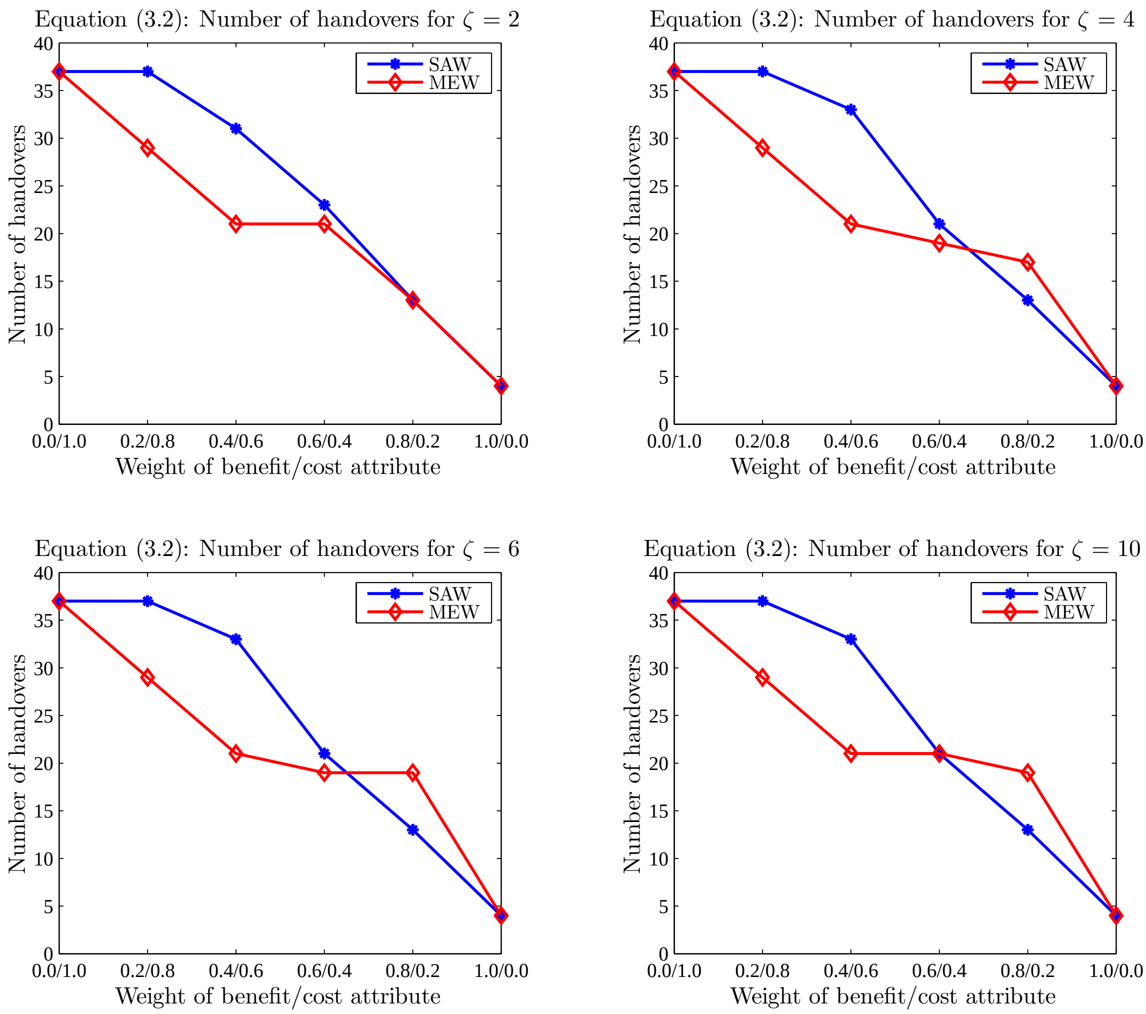


Figure 3.5: Number of handovers for different w_j and ζ in Equation (3.2)

Inference on Figure 3.4:

- There is no effect of constant ζ and weight of benefit and cost attributes variations on a number of handovers in SAW and MEW. The number of handovers in SAW remains same for different values of ζ and variations of benefit and cost attributes weight. The same is true for MEW.

- SAW is less sensitive compared to MEW for the variation of attributes weight, since the number of handovers in SAW is less than MEW as weight of cost attribute decreases.

- Number of handovers in SAW decrease in the case of less variation in values of the higher weighted attributes.

- Number of handovers are less in the case of a single attribute with less variation (benefit attribute) and vice-versa for a single attribute with more variations. Only with benefit attribute ($w_1 = 1$ and $w_2 = 0$) number of handovers are 5 and only with cost attribute ($w_1 = 0$ and $w_2 = 1$) number of handovers are 36, according to the variation in values of benefit and cost attributes of the networks as shown in Figure 3.3.

Inference on Figure 3.5:

- There is a less effect of constant ζ variations on a number of handovers in SAW compared to MEW. The total number of handovers in MEW varies for the variations of ζ.

- MEW is less sensitive compared to SAW for the variations of attributes weight, since the number of handovers in MEW is less than SAW for weight of cost attribute higher than benefit attribute.

- Number of handovers in SAW and MEW decreases in the case of fewer variations in values of the highest weighted attributes.

- Number of handovers are less in the case of a single attribute with less variation (benefit attribute) and vice-versa for a single attribute with more variations. Only with benefit attribute ($w_1 = 1$ and $w_2 = 0$) number of handovers are 4 and only with cost attribute ($w_1 = 0$ and $w_2 = 1$) number of handovers are 36, according to the variation in values benefit and cost attribute of the networks as shown in Figure 3.3.

Inference on Figure 3.6:

- There is a less effect of constant ζ variations on a number of handovers in SAW compared to MEW. As the values of ζ vary, the number of handovers in MEW also varies.

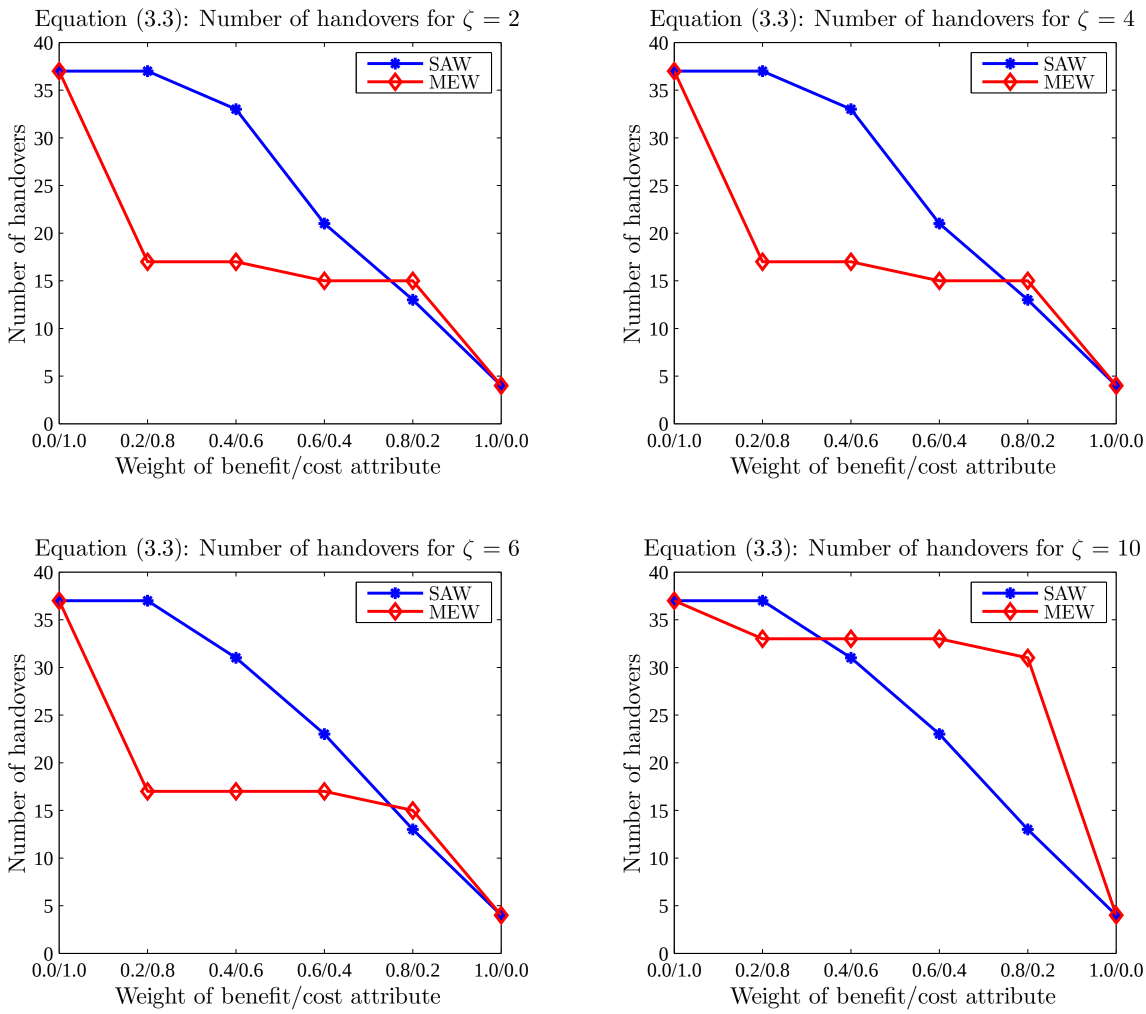


Figure 3.6: Number of handovers for different w_j and ζ in Equation (3.3)

- SAW is more sensitive compared to MEW for the variation of attributes weight and smaller value of ζ, since the number of handovers in SAW is more than MEW. Whereas, MEW is more sensitive than SAW for $\zeta = 10$.

- Number of handovers in SAW decrease in the case of less variation in values of the highest weighted attributes.

- Number of handovers are less in the case of a single attribute with less variation (benefit attribute) and vice-versa for a single attribute with more variations. Only with benefit attribute ($w_1 = 1$ and $w_2 = 0$) number of handovers are 5 and only with cost attribute ($w_1 = 0$ and $w_2 = 1$) number of handovers are 36, according to the variation in values benefit and cost attribute of the networks as shown in Figure 3.3.

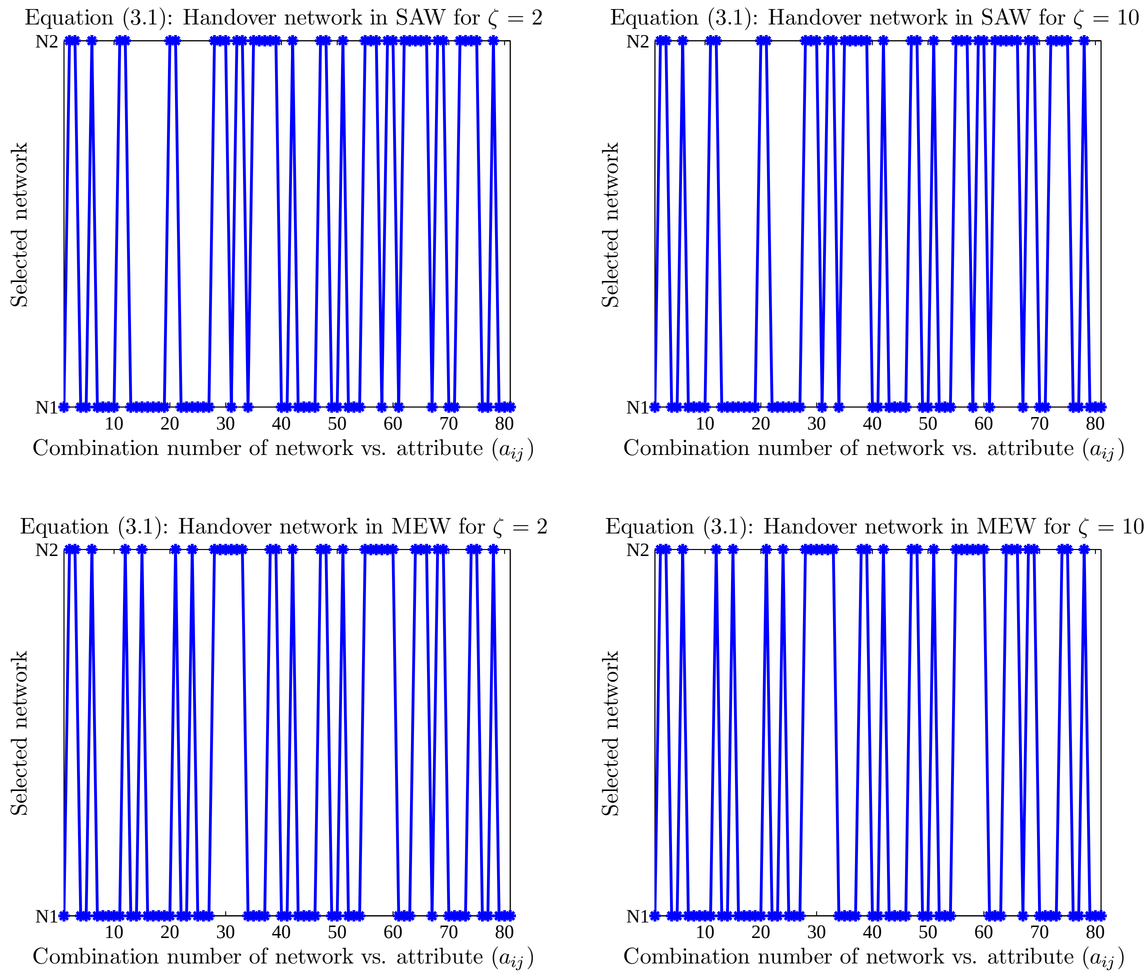


Figure 3.7: Equation (3.1): Selected network for $\{w_{b_1}, w_{c_1}\} = \{0.4, 0.6\}$

Further, to analyse the effect of ζ of sigmoidal functions on the handover decision process, a MATLAB simulation is carried out for $\{w_{b_1}, w_{c_1}\} = \{0.4, 0.6\}$ with the $\zeta \in \{2, 10\}$. Figures 3.7 - 3.9 shows the selected network N_1 and N_2 for 81 different combinations of network versus attribute (a_{ij}) as shown in Figure 3.3. In Figures 3.7 - 3.9, the comparison is among SAW for different ζ and MEW for different ζ.
Dots in Figures 3.7 - 3.9 represents,

- Selected network for handover,
- Change in the handover decision between network N_1 and N_2 for a combination number (1 to 81) of network versus attribute (a_{ij}) as shown in Figure 3.3.

As shown in Figure 3.7 for Equation (3.1), the variation in the utility of a network is sensitive only for smaller ranges of inputs. The change in selected network for handover and the combination number (1 to 81) of network versus attribute (a_{ij}) the change occurred is same ($\sim$33) for $\zeta = \{2, 10\}$ in both SAW and MEW. Similar result illustrated in Figure 3.7 can also be observed in Figure 3.4.

Similarly, Figure 3.8 for Equation (3.2) shows the similar selected network for handover to the similar combination number of network versus attribute (a_{ij}) in SAW and MEW for $\zeta = 2$ and 10. However, in SAW for $\zeta = 2$ and 10, the variations in selected network for handover exists for few combinations of network versus attributes (a_{ij}) (between 10 to 15). This variations results during the benefit attribute of network N_1 is higher than those of network N_2.

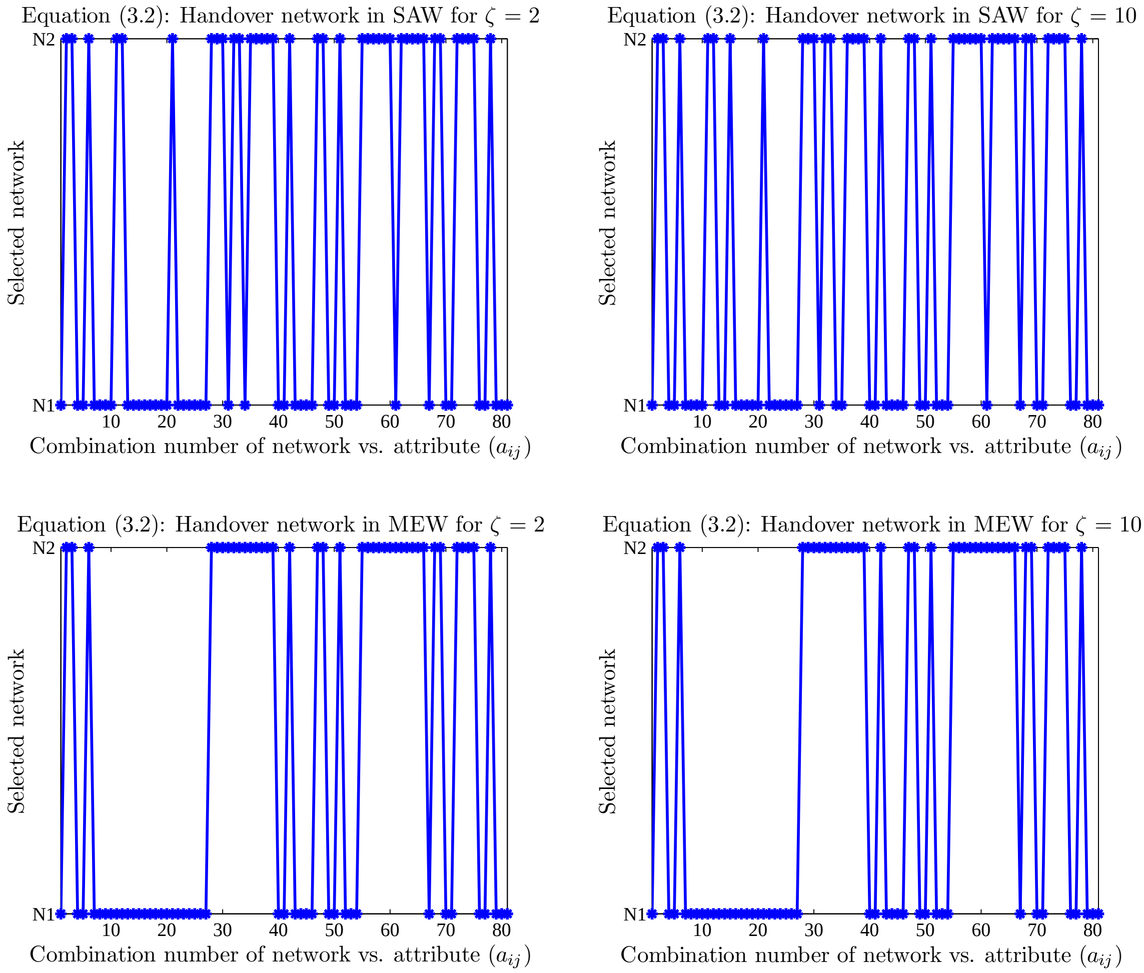


Figure 3.8: Equation (3.2): Selected network for $\{w_{b_1}, w_{c_1}\} = \{0.4, 0.6\}$

As shown in Figure 3.9 for Equation (3.3), the selected network for handover is almost same in SAW for $\zeta = 2$ and 10, but there is a lot of variation in the selected network in MEW. According to Equation (3.3), MEW is more sensitive to higher ζ compared to SAW.

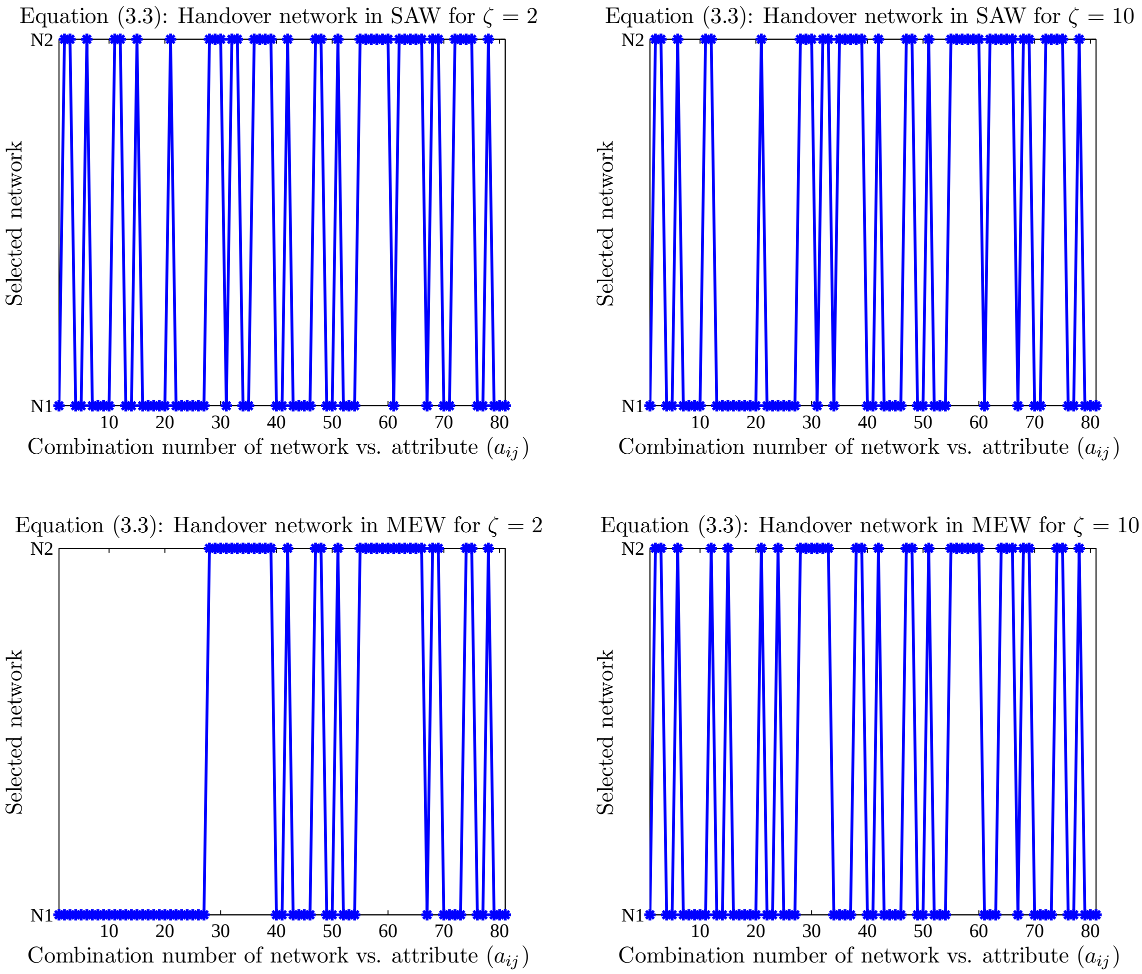


Figure 3.9: Equation (3.3): Selected network for $\{w_{b_1}, w_{c_1}\} = \{0.4, 0.6\}$

Inference: Sigmoidal function based handover decision is inevitably influenced by the variations in sigmoidal function constant ζ and attributes weight w_j.

3.3 Analysis of NS2 Simulations of Heterogeneous Wireless Networks

The major hurdles for the research community with respect to heterogeneous wireless networks are the implementation and verification of innovative ideas.

Table 3.8: Comparisons of system modelling methodologies

Method	Merits	Demerits
Analytical	Cost-effective and provides an abstract view of component interaction.	Not feasible for large and complex systems, too many assumptions leading to inaccurate results.
Simulation	Cost-effective, simple, easy to implement, utilizes less abstraction, and feasible for large and complex systems.	Too many details resulting in an unmanageable simulation.
Testbed	Realistic results and actual system modelling.	Time consuming and expensive.

There are three different methodologies to implement and verify innovative ideas, namely Analytical, Simulation and Testbed (Jain 2015; Rahman et al. 2009; Imran et al. 2010; Fernandez et al. 2012). Table 3.8 illustrates the merits and demerits of the Analytical, Simulation and Testbed approaches.

As shown in Table 3.8, simulation is a cost-effective, simple and an easy methodology to implement a system. Accordingly, many researchers rely on the simulation-based approach to the implementation and verification of innovative networking ideas (Heidemann et al. 2001). Many commercial and open source network simulators exist in the literature, such as NS2 [2](Issariyakul and Hossainp 2011), NS3 [3], OMNeT++ [4], OPNET [5], QualNet [6], J-Sim [7], etc. (Weingartner et al. 2009; Marques et al. 2010; Bilalb et al. 2013). Table 3.9 illustrates some of the open source network simulators with their properties (Lessmann et al. 2008; Monika and Shekhar 2014).

[2]Network Simulator - NS2. Available: `http://www.isi.edu/nsnam/ns/`
[3]Network Simulator - NS3. Available: `https://www.nsnam.org/`
[4]OMNet++. Available: `http://www.omnetpp.org/`
[5]OPNET. Available: `http://www.opnet.com/`
[6]QualNet. Available: `http://www.scalable-networks.com/products/`
[7]J-Sim. Available: `http://www.j-sim.org/`

Table 3.9: Comparisons of open source network simulators

Criterion	**Open Source Simulator**			
	NS2	**NS3**	**OMNET++**	**J-Sim**
Interface	C++, OTcl	C++, Python	C++	Java, Tcl
User Support	Excellent	Excellent	Good	Excellent
Applicability	Net./Sys.	Net./Sys.	Net./Sys.	Net.
Mobility	Yes	Yes	No	Yes
GUI	Limited	Limited	Good	Limited
Scalability	Small	Large	Small	Moderate

Amongst all network simulators available in the literature, NS2 and NS3 are most popularly used by the research community to implement and verify innovative networking ideas (Sirisena et al. 2006; Orfanus et al. 2008). Hence, this subsection focuses on the use of the network simulator NS2. Moreover, NS3 has been yet to support simulation of heterogeneous wireless networks. Many contributions of the research community in the area of wired and wireless networks in NS2 are available in the literature [8]. One amongst them is heterogeneous wireless networks, which is the future of wireless communication systems or next generation wireless networks.

The National Institute of Science and Technology (NIST)(Wang et al. 1999) not only provided the Media Independent Handover (MIH) (De La Oliva et al. 2008; Eastwood et al. 2008; Lampropoulos et al. 2008) but also gave the Mobile IPv6 (MIPv6)-based NS2 distribution for simulating heterogeneous wireless networks (Marques et al. 2010). In order to verify simulation results of heterogeneous wireless networks (Fratu et al. 2011), researchers need to design their own NS2 trace file analysis scripts by using either AWK (Robbins 2015) or Perl, which is time consuming and tedious. The design of result analysis scripts for NS2's heterogeneous wireless networks simulation becomes more complicated because of the following issues:

- Mobile nodes with multiple heterogeneous wireless interfaces
- Change in the hierarchical address of the MNs interface during vertical handover (Márquez-Barja et al. 2011) in heterogeneous wireless networks.

[8] Network Simulator - NS2. Available: `http://www.isi.edu/nsnam/ns/`

These challenging issues motivated us to develop a user-friendly Graphical User Interface (GUI) -based suite for configuring and analysing heterogeneous wireless networks simulation and presenting the results in both textual and graphical format for performance analysis (Rumekasten 1994; Perrone et al. 2009).

This section of the chapter presents an Evaluation Suite for User Datagram Protocol (UDP) applications referred to as ES-UDP for heterogeneous wireless networks simulation in NS2. ES-UDP provides a GUI for configuring the WiFi and WiMAX interfaces of MNs simulated in heterogeneous wireless networks for UDP applications (Cheung et al. 2010). Further, ES-UDP provides both text and graphical results of handover, packets sent and received, throughput, packet delay and jitter extracted from the NS2 trace file.

The key ideas for developing the proposed ES-UDP tool are: (i) The Java-based GUI as a front-end for configuring the WiFi and WiMAX interfaces of MNs, WiFi Access Point and WiMAX Base Station resulting in an NS2 simulation script in heterogeneous wireless networks (ii) The ES-UDP analysis of the trace file of the NS2 simulation using AWK script to provide textual results (iii) The processing of textual results obtained through the AWK script by gnuplot (Williams et al. 2010) to present the results in the graphical format (iv) NS2's distribution provided by NIST is used at the back-end in ES-UDP for simulating HWNs.
The main contributions in this section are:

- Introduction to Evaluation Suite for User Datagram Protocol (ES-UDP).

- Simulation of heterogeneous wireless networks.

- Result analysis of both text and graphical results of handover, packets sent and received, throughput, packet delay and jitter of heterogeneous wireless networks simulated with respect to UDP applications.

The rest of the Section 3.3 is organized as follows: Subsection 3.3.1 introduce ES-UDP; Subsection 3.3.2 presents the simulation of four MNs with WiFi and WiMAX interfaces in heterogeneous wireless networks; Subsection 3.3.3 deals with Results and Analysis.

3.3.1 Evaluation Suite for User Datagram Protocol

The User Datagram Protocol (UDP) is one of TCP/IP's transport layer protocol stacks responsible for process-to-process communication in delay-sensitive applications such as real-time service (Cheung et al. 2010). The Evaluation Suite for UDP applications referred to as ES-UDP is used for the configuration and result analysis of the WiFi and WiMAX interfaces of MNs in heterogeneous wireless networks simulated using NS2.

Following is the list of performance parameters used in the analysis of NS2 simulation result in the development of ES-UDP:

Handover: This is the process of switching an MN's active communication to the new selected point of attachment during the movement of the MN away from the current accessing network. At the end of this process MN updates its new address referred to as Care of Address (CoA) using the Binding Update (BU) message to the Home Agent (HA) of its Home Network (HN) to which MN belongs and the node referred to as a Correspondent Node (CN) to which MN is communicating. The HA and CN respond to MN's BU messages using a Binding Acknowledgement (BA) message. In the NS2 trace file generated after the heterogeneous wireless networks simulation, a packet with *ifmngmt_red* symbolizes the BU and BA messages. Acknowledging the BU with a BA message is the next immediate event of the CN after receiving the BU from the MN. In the NS2 trace file of the heterogeneous wireless networks simulation, no other relation (packet id or sequence id) is maintained between the MN-sent BU packet to the CN and the CN-sent BA packet to the MN.

Packets Sent and Received: This is the average number of packets sent by the CN (source) to the individual MN (destination) and the average number of packets received by the individual MN's WiFi and WiMAX interfaces at a regular interval of simulation time (per unit of time). These facts are used to validate an individual MN's throughput.

Throughput: This is a measure of the size of the UDP packets received by the MN in a unit of time. In the NS2 trace file of the heterogeneous wireless networks simulation, upon the UDP packet received event, a particular MN is identified as a destination by referring its WiFi or WiMAX interface hierarchical address. Moreover, the MN's

WiFi or WiMAX interface is a destination that changes with the MN's handover to a WiFi or WiMAX network. In ES-UDP, the number of UDP packets received by the MN's WiFi and WiMAX interfaces at a regular interval of simulation time (per unit of time) is considered in the computation of the respective MN's throughput. The analysis of the throughput with respect to the selected WiFi or WiMAX network by the MN and the individual MN's WiFi and WiMAX interfaces can be analysed by using the handover statistics.

Packet Delay: This is the average delay of the packets received by the MN at a regular interval of simulation time (per unit of time). A computation similar to that used for an individual MN's throughput calculation is incorporated in the computation of an individual MN's packet delay, individual MN's packet delay with respect to the WiFi and WiMAX interfaces, and the packet delay with respect to an individual MN's selected network during the handover. Further, these statistics are used along with an individual MN's handover statistic for further analysis.

Jitter: This is the average variation in the packet delay at a regular interval of simulation time (per unit of time) with respect to an individual MN.

Table 3.10: ES-UDP's Simulation parameters (static)

Simulation Devices	Parameters
WiMAX Base Station (WiMAX-BS)	Total No.: 02 (WiMAX-BS1 and WiMAX-BS2) and Range: 500 m
WiFi Access Point (WiFi-AP)	Total No.: 02 (WiFi-AP1 and WiFi-AP2) and Range: 100 m
Mobile Node (MN) (Destination for UDP Packets)	Total No.: Any, Home Network: WiFi-AP1 is for odd numbered MN's WiFi interface, WiFi-AP2 is for even numbered MN's WiFi interface, WiMAX-BS1 is for odd numbered MN's WiMAX interface and WiMAX-BS2 is for even numbered MN's WiMAX interface.
Router	Total No.: 01
Correspondent Node (CN) (Source of UDP Packets)	Total No.: 01
Connecting Link	Duplex link, 100 Mbps, Propagation Delay: 15 ms, Drop Tail Queue

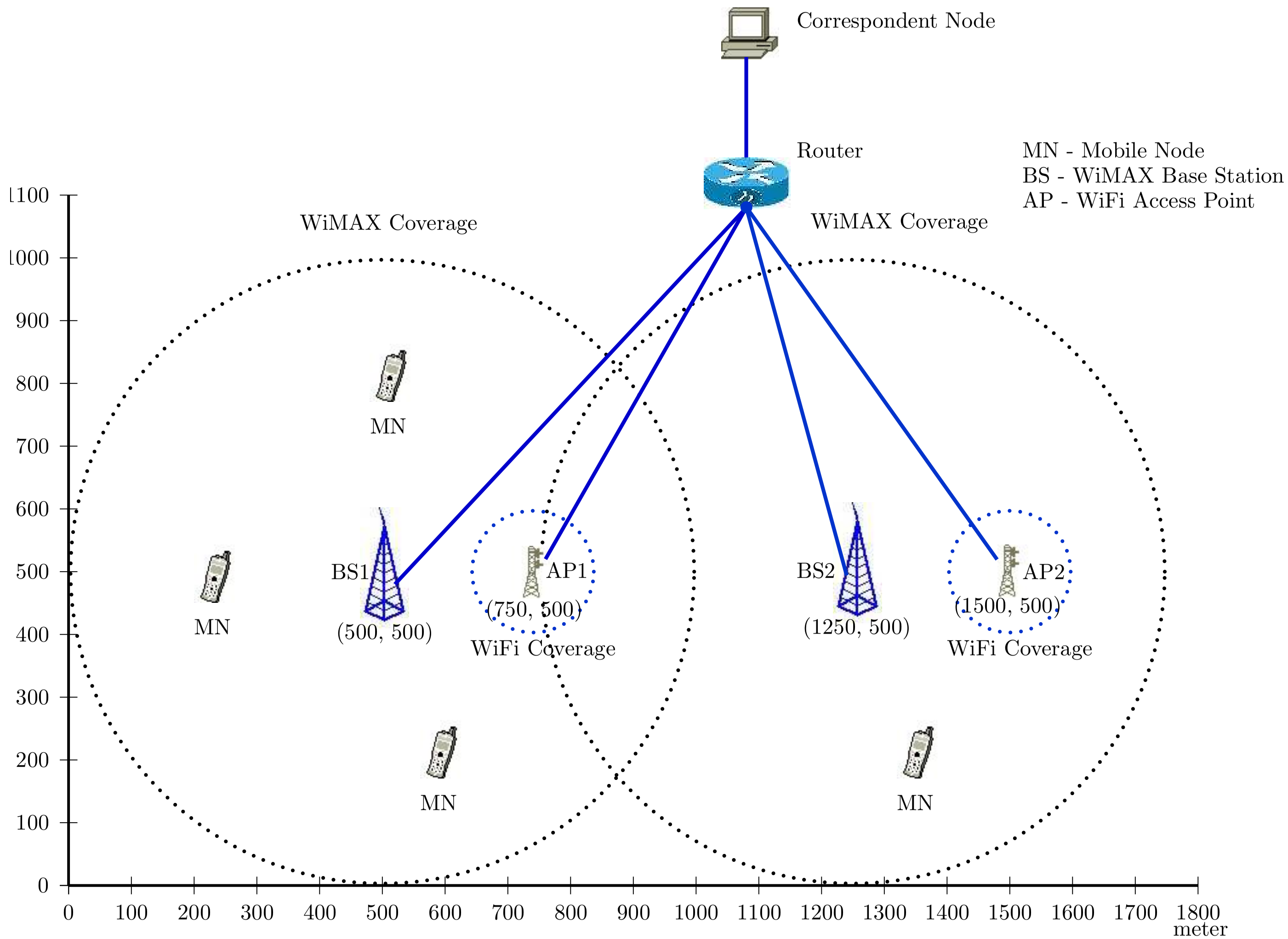


Figure 3.10: Heterogeneous wireless networks simulation topology for four mobile nodes

3.3.2 Simulation of WiFi and WiMAX Interface Mobile Nodes in Heterogeneous Wireless Networks

Figure 3.10 shows one of the scenarios of WiFi and WiMAX interfaced MNs in a heterogeneous wireless networks simulation in NS2 configured using ES-UDP. Table 3.10 illustrates some of the static parameters of the NS2 simulation script in ES-UDP's heterogeneous wireless networks simulation. The odd and even numbered MNs represent the order in which MNs are initialized in the simulation.

Table 3.11: ES-UDP's simulation parameters (dynamic)

Simulation Devices	**Parameters**
WiMAX Base Station (WiMAX-BS)	Position (X, Y and Z coordinates)
WiFi Access Point (WiFi-AP)	Position (X, Y and Z coordinates)
Mobile Node (MN)	Total number of mobile nodes, mobile node's initial and final position (X, Y and Z coordinates), interface of MN as an initial destination for the UDP application, speed, UDP packet size, and packet transmission rate.

Table 3.12: ES-UDP's heterogeneous wireless networks simulation parameters

Simulation Devices	**Parameters**
WiMAX Base Station (WiMAX-BS)	Position of WiMAX-BS1 and WiMAX-BS2 are (500, 500, 0) and (1250, 500, 0) respectively.
WiFi Access Point (WiFi-AP)	Position of WiFi-AP1 and WiFi-AP2 are (750, 500, 0) and (1500, 500, 0) respectively.
Mobile Node (MN)	Total number of mobile nodes are four, initial Position of four MNs are (250, 500, 0), (350, 500, 0), (450, 500, 0) and (550, 500, 0) respectively, final position of four MNs are (2000, 500, 0), (2025, 500, 0), (2050, 500, 0) and (2075, 500, 0) respectively, interface of four MNs as an initial destination for UDP packets are (i) WiMAX (see Figures 3.12(a) - 3.16(a)) and (ii) WiFi (see Figures 3.12(b) - 3.16(b)), speed of four MNs are 6, 11, 16 and 21 m/sec respectively, packet size 500 Bytes and packet transmission rate 0.001 sec.

Table 3.11 illustrates some of the dynamic parameters of the NS2 simulation script in ES-UDP's heterogeneous wireless networks simulation. The movement of the MNs in the simulation area is in a straight line with slope depending on the initial and the final locations of the MNs which is configured by the user. As per the current ES-UDP design, all MNs starts moving and the CN start to deliver the packets at 10 sec from the initialisation of the simulation.

3.3.3 Results and Analysis

This subsection presents the results and analysis with respect to the NS2 simulation topology shown in Figure 3.10 with the configuration parameters shown in Table 3.12.

ES-UDP generates both textual and graphical results of handover, packets sent and received, throughput, packet delay and jitter for an individual MN with respect to the configured simulation topology. Two scenarios (all MNs (i) WiMAX and (ii) WiFi interface as the initial UDP packet's destination) are considered to demonstrate ES-UDP's performance. The results shown in Figures 3.12 - 3.16 are obtained using NS2's distribution provided by NIST for HWNs simulation.

A Textual Results

Figure 3.11 shows ES-UDP's textual format of the NS2 simulation results of four MNs with WiFi and WiMAX interfaces in heterogeneous wireless networks.

Table 3.13 illustrates the interpretation of each column of ES-UDP's textual format results shown in Figure 3.11 and is common for any interface of the MNs as the initial destination of the UDP packets.

The second section of ES-UDP's textual results (where Column 1 and 2 are blank) shown in Figures 3.11(a) and 3.11(b) illustrates packets sent, received and dropped, throughput, packet delay and jitter after executing the last handover with respect to the individual MNs. Further, Column 6 represents the initial hierarchical addresses (dependent on the HN of the interfaces) of the WiFi and WiMAX interfaces of the individual MNs.

Handover Details												
Handover	Time	Node	Interface	ID	CoA	Packet Sent	Packet Received	Packet Dropped	BU Delay	Throughput	Packet Delay	Jitter
1	0.06	3	WiMAX	_14_	2.0.4	0	0	0	0.045115	0.00	0.000000	0.000000
2	0.06	1	WiMAX	_12_	2.0.2	0	0	0	0.045117	0.00	0.000000	0.000000
3	5.29	4	WiMAX	_15_	2.0.5	0	0	0	0.045115	0.00	0.000000	0.000000
4	5.30	2	WiMAX	_13_	2.0.3	0	0	0	0.045116	0.00	0.000000	0.000000
5	25.96	3	WiFi	_20_	4.0.3	17004	12158	0	0.045294	2860083.56	0.104132	0.001941
6	31.09	4	WiMAX	_15_	3.0.5	22132	21672	0	0.045116	3916983.87	0.055611	0.001137
7	31.61	3	WiMAX	_14_	2.0.4	5649	3478	2076	0.045117	2462895.03	0.094428	0.000509
8	43.73	3	WiMAX	_14_	3.0.4	12120	11681	0	0.045116	3855241.79	0.056925	0.001118
9	53.09	4	WiFi	_21_	5.0.4	22006	21956	0	0.045295	3990960.90	0.047973	0.000967
10	57.41	4	WiMAX	_15_	3.0.5	4319	2651	1573	0.045116	2455423.66	0.094294	0.000508
11	73.31	3	WiFi	_20_	5.0.3	29585	29535	0	0.045294	3993311.63	0.047866	0.000967
12	78.48	3	WiMAX	_14_	3.0.4	5167	3171	1997	0.045116	2454955.70	0.094372	0.000500
13	85.76	1	WiFi	_18_	4.0.1	76808	55980	0	0.045294	2915336.58	0.076852	0.001714
-	-	1	WiMAX	_12_	2.0.2	0	49	0	-	2153.85	0.049341	0.000947
-	-	1	WiFi	_18_	4.0.1	14192	8847	5251	0.045294	2493517.47	0.094719	0.000506
-	-	2	WiMAX	_13_	3.0.3	91000	47229	0	0.045115	2076000.00	0.072277	0.001468
-	-	2	WiFi	_19_	5.0.2	0	0	0	-	0.00	0.000000	0.000000
-	-	3	WiMAX	_14_	2.0.4	21475	11853	0	0.045294	2207776.48	0.051438	0.001087
-	-	3	WiFi	_20_	4.0.3	0	0	94	-	0.00	0.000000	0.000000
-	-	4	WiMAX	_15_	3.0.5	42543	9085	0	0.045117	854194.58	0.051797	0.001080
-	-	4	WiFi	_21_	5.0.4	0	0	95	-	0.00	0.000000	0.000000
					Total	364000	239345	11086	No Response Packets:			113569

(a) Simulation summary of four MNs WiMAX interface as an initial destination for UDP packets

Handover Details												
Handover	Time	Node	Interface	ID	CoA	Packet Sent	Packet Received	Packet Dropped	BU Delay	Throughput	Packet Delay	Jitter
1	25.98	3	WiFi	_20_	4.0.3	17022	27	16922	0.045294	6345.03	0.066997	0.000876
2	31.61	3	WiMAX	_14_	2.0.4	5630	2496	3134	0.045116	1773590.45	0.074022	0.000441
3	43.71	3	WiMAX	_14_	3.0.4	12104	11651	0	0.045116	3850515.65	0.050127	0.001022
4	53.11	4	WiFi	_21_	5.0.4	44156	29	44054	0.045295	2627.07	0.068285	0.000856
5	57.41	4	WiMAX	_15_	3.0.5	4301	1860	2441	0.045116	1729989.96	0.074012	0.000447
6	75.27	3	WiFi	_20_	5.0.3	31557	31509	0	0.045294	3993951.72	0.047766	0.000968
7	78.48	3	WiMAX	_14_	3.0.4	3208	1370	1838	0.045116	1708393.45	0.073832	0.000451
8	85.79	1	WiFi	_18_	4.0.1	76832	49	76702	0.045294	2551.03	0.066045	0.000663
-	-	1	WiMAX	_12_	2.0.2	14168	8845	5310	0.045294	2497176.74	0.094890	0.000509
-	-	1	WiFi	_18_	4.0.1	0	0	0	-	0.00	0.000000	0.000000
-	-	2	WiMAX	_13_	3.0.3	0	0	0	-	0.00	0.000000	0.000000
-	-	2	WiFi	_19_	5.0.2	91000	0	90954	-	0.00	0.000000	0.000000
-	-	3	WiMAX	_14_	2.0.4	21479	11852	0	0.045116	2207179.11	0.051379	0.001086
-	-	3	WiFi	_20_	4.0.3	0	0	73	-	0.00	0.000000	0.000000
-	-	4	WiMAX	_15_	3.0.5	42543	9049	0	0.045116	850809.77	0.052199	0.001081
-	-	4	WiFi	_21_	5.0.4	0	0	73	-	0.00	0.000000	0.000000
					Total	364000	78737	241501	No Response Packets:			43762

(b) Simulation summary of four MNs WiFi interface as an initial destination for UDP packets

Figure 3.11: ES-UDP's NS2 simulation results in textual format

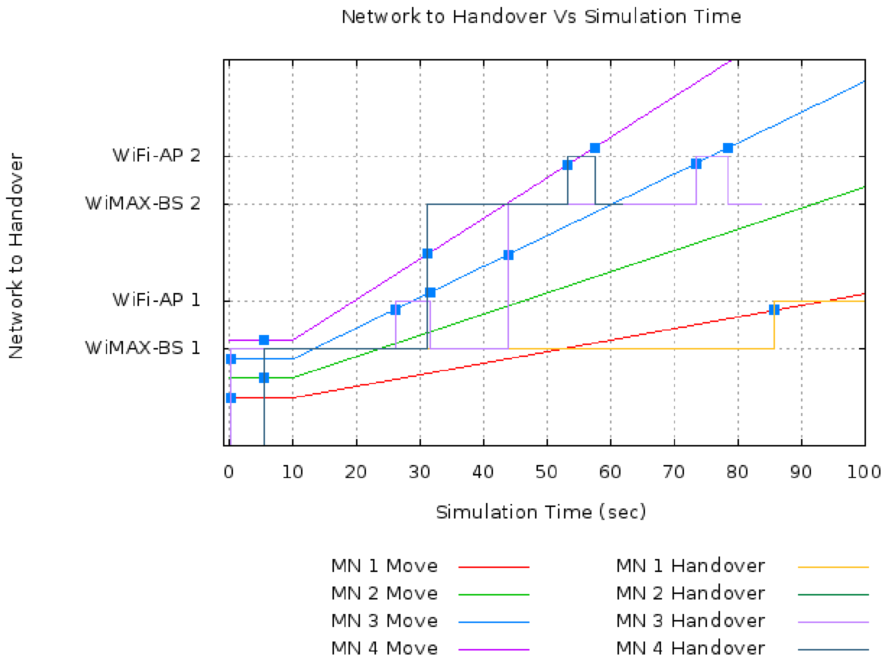
Table 3.13: Illustration of ES-UDP's textual format results

Column No.	Description
1	Sequence of handovers
2	Beginning (in terms of simulation time) of the execution of the handover
3	ID (used to identify the MN) of a particular MN executing the handover
4	Interface (WiFi or WiMAX) of the MN executing the handover
5	ID of the interface of the MN executing the handover
6	New hierarchical address (CoA) of MN's interface after executing the handover.
7	Total UDP packets sent to the MN (Column 3) by the CN between the end of the previous handover and the beginning of the current handover with respect to MN (Column 3)
8	Total UDP packets received by the MN (Column 3) sent by the CN between the end of the previous handover and the beginning of the current handover with respect to MN (Column 3)
9	Total UDP packets dropped, which is sent to the MN (Column 3) by CN between the end of the previous handover and the beginning of the current handover with respect to MN (Column 3)
10	Handover delay or Binding delay
11	Obtained throughput with respect to the MN (Column 3) between the end of the previous handover and the beginning of the current handover with respect to MN (Column 3)
12	Average delay of the UDP packets received by the MN (Column 3) sent by CN between the end of the previous handover and the beginning of the current handover with respect to MN (Column 3)
13	Average variation in the delay of the UDP packets received by the MN (Column 3) sent by the CN between the end of the previous handover and the beginning of the current handover with respect to MN (Column 3)

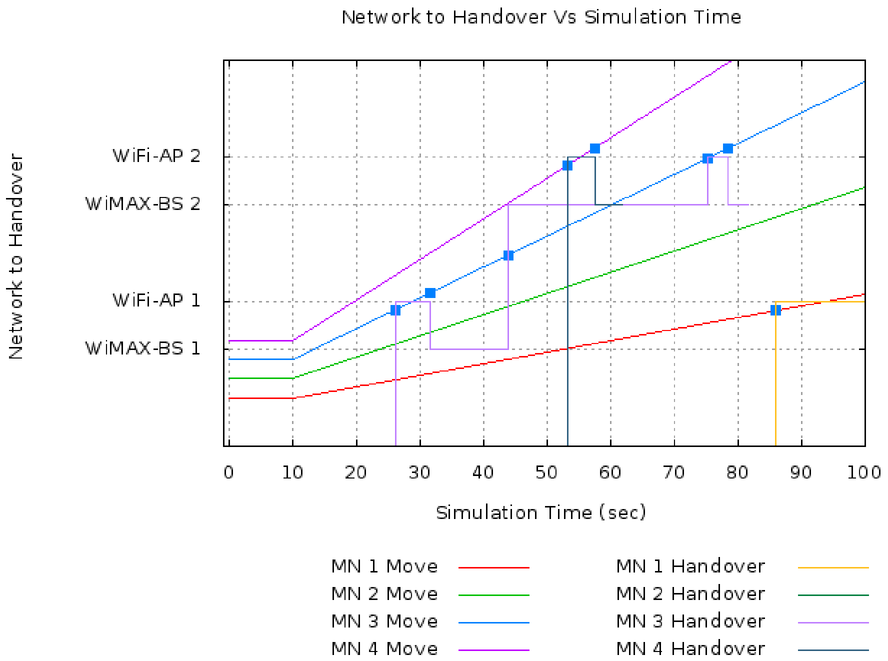
As shown in Figure 3.11, even though the total number of UDP packets sent by the CN to the individual MNs is 91,000, the average number of packets received in Figure 3.11(a) is 44% more than in Figure 3.11(b). Similarly, the average number of packets dropped in Figure 3.11(a) is 63% less than in Figure 3.11(b).

B Analysis of Individual MN Handovers

Figure 3.12 shows individual MNs' handover details (time of the handover and the selected network for handover) when the initial destination for the UDP application is an MN's WiMAX (see Figure 3.12(a)) and WiFi (see Figure 3.12(b)) interface.



(a) Movement and handover of four MNs for WiMAX interface as an initial destination for UDP packets



(b) Movement and handover of four MNs for WiFi interface as an initial destination for UDP packets

Figure 3.12: Movement and handover of four MNs for speed 6, 11, 16 and 21 m/sec respectively

As shown in Figure 3.12(a) (for all four MNs, WiMAX interface is the initial destination for the UDP application), since all the four MNs' initial locations are near to WiMAX-BS1, whether BS1 or BS2 is the home network for the WiMAX interface of MN, all four MN's handover to WiMAX-BS1. Further, when MNs enter the WiFi-AP1 coverage area, only MNs 1 and 3 handover to WiFi-AP1, since for the WiFi interfaces of MNs 1 and 3, WiFi-AP1 is the home network.

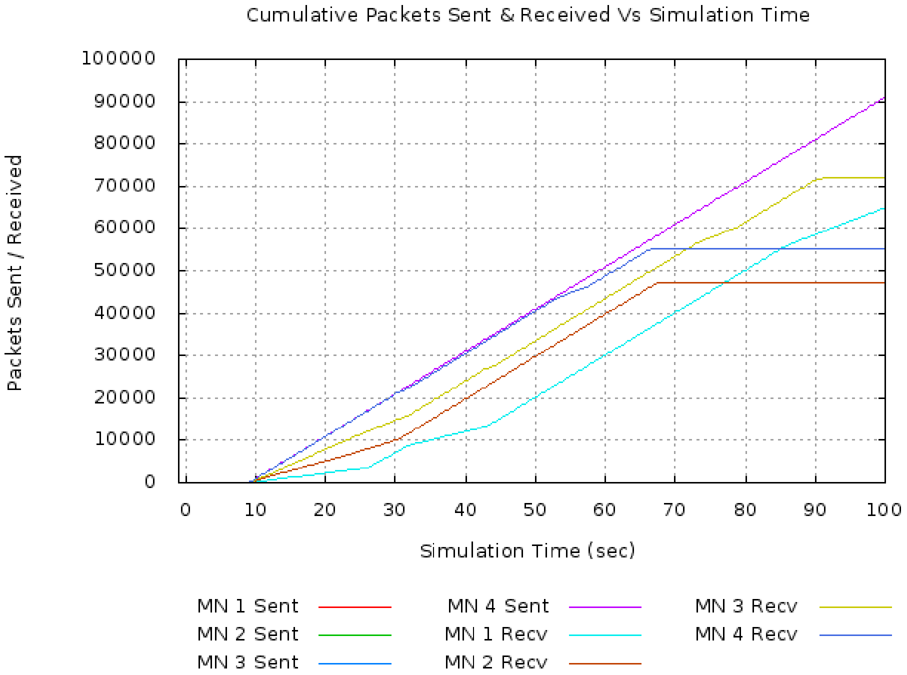
Similarly, as shown in Figure 3.12(b), when an MN's WiFi interface is the initial destination for the UDP application, each MN will first handover to the home network of its WiFi interface. According to the simulation results shown in Figure 3.12(b), MN-1 handovers to only WiFi-AP1 (since it came across only WiFi-AP1), MN-2 does not handover (due to NIST's distribution), MN-3 handovers in order to WiFi-AP1, WiMAX-BS1, WiMAX-BS2, WiFi-AP2 and WiMAX-BS2, and MN-4 to WiFi-AP2 and WiMAX-BS2.

As shown in Figure 3.12, dots on line represents MN's handover, handover time and selected network. Additionally, line represents speed, destination interface of MNs, and location of: MNs, APs and BSs.

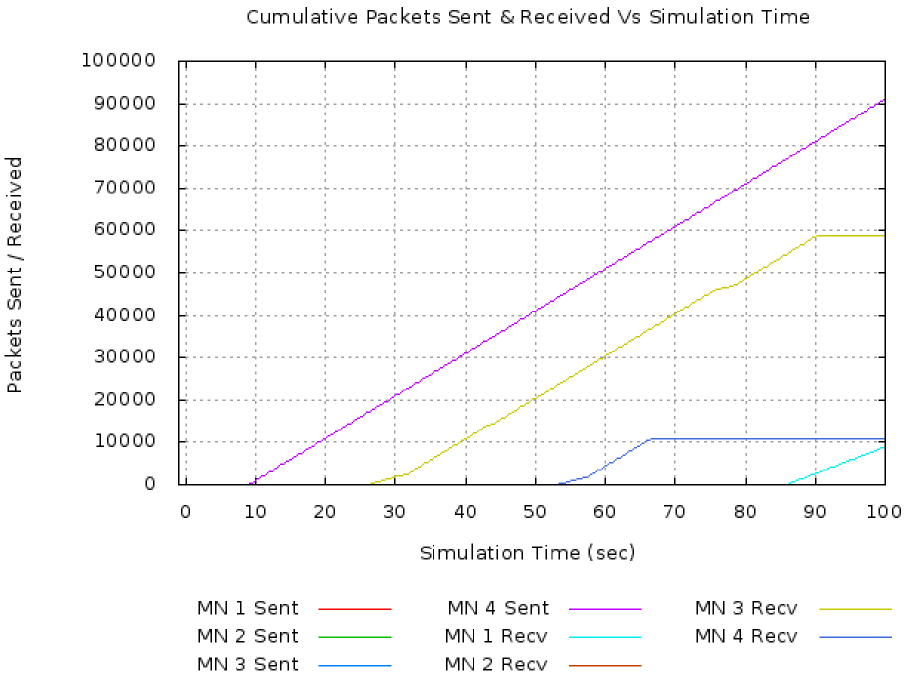
C Analysis of the MNs' Numbers of Packet Sent and Received

Figure 3.13 shows the cumulative number of UDP packets sent to and received by the individual MNs. As shown in Figure 3.13, the total number of packets sent to the individual four MNs are 91,000, whereas the cumulative number of packets received by the individual MNs varies with handover and selected network for handover. Following are the observations with respect to the UDP packets received by the individual MNs as shown in Figure 3.13(a) (for all four MNs, WiMAX interface is the initial destination for the UDP application):

- Since MN-1 is always with WiMAX-BS1, it receives all the UDP packets till the end of the simulation.
- MN-2 stops receiving packets after $\approx$ 68 sec of simulation time, since it leaves the coverage area of WiMAX-BS1 without any more handovers to other networks.
- MN-3 receives packets up till $\approx$ 90 sec of the simulation time, since it leaves the coverage area of WiMAX-BS2 at 90 sec.



(a) Packets sent to and received by four MNs for WiMAX interface as an initial destination for UDP



(b) Packets sent to and received by four MNs for WiFi interface as an initial destination for UDP

Figure 3.13: Packets sent to and received by four MNs for speed 6, 11, 16 and 21 m/sec respectively

- MN-4 receives packets up till ≈ 67 sec of the simulation time: because of its high speed (21 m/sec) it is with the available accessing networks only for a short duration.

Similarly, as shown in Figure 3.13(b) (for all four MNs, WiFi interface is the initial destination for the UDP application), only MNs 1, 3 and 4 receive the UDP packets. MN-1 receives fewer packets since it handovers only with WiFi-AP1 till the end of the simulation. MN-3 receives maximum packets because it handovers with the accessing networks at the beginning of the simulation.

D Analysis of the MNs' Throughput

Figure 3.14 shows the individual MN's throughput when the initial destination of the UDP application is MN's WiMAX (see Figure 3.14(a)) and WiFi (see Figure 3.14(b)) interface.

Following are the observations in Figure 3.14(a) when an individual MN's WiMAX interface is the UDP packet's destination:

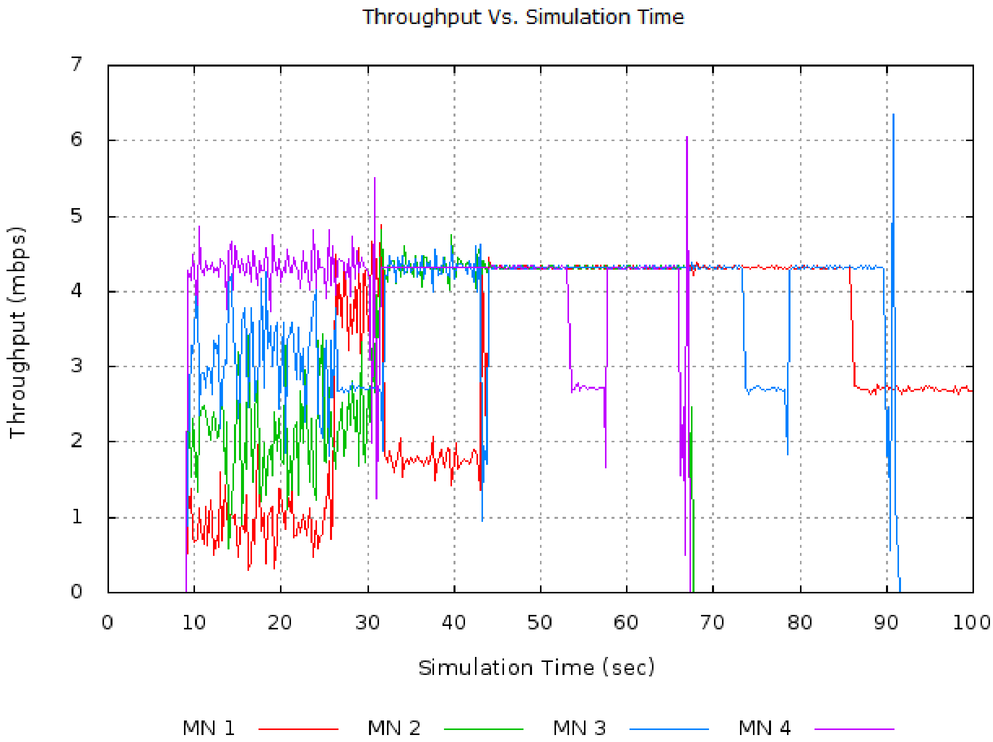
- A MN attains maximum throughput (WiMAX network 4.3 Mbps and WiFi network 2.8 Mbps) only when the number of MNs within the MN's current accessing the network is minimum.

- MN-1's maximum throughput with WiMAX-BS1 is during 43 sec - 86 sec. Similarly, with WiFi-AP1 is after 83 sec.

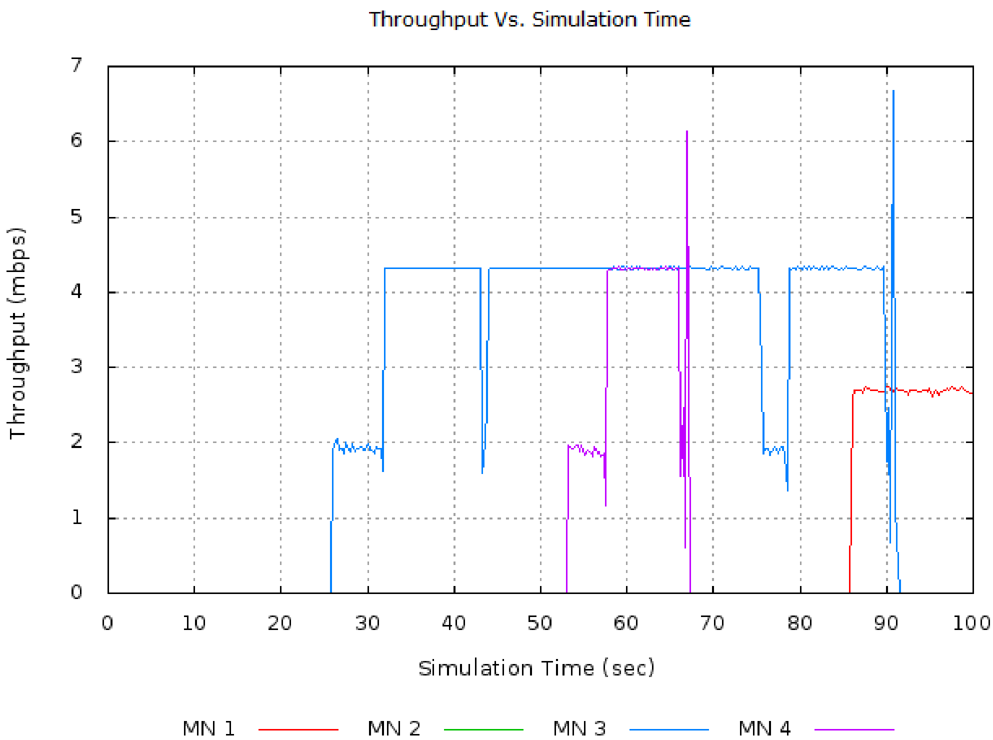
- MN-2's maximum throughput with WiMAX-BS1 is during 32 sec - 67 sec.

- In MN-3 and MN-4 the maximum throughput during the entire simulation continuously varies because of more number of handovers.

Similarly, Figure 3.14(b) illustrates (the MN's WiFi interface is the UDP packet's destination), MN-3 attains maximum throughput (WiMAX network 4.3 Mbps and WiFi network 2.8 Mbps) more number of times than MN-1 and MN-4. MN-1's and MN-3's maximum throughput is 2.8 Mbps and is 4.3 Mbps respectively during 58 sec - 67 sec.

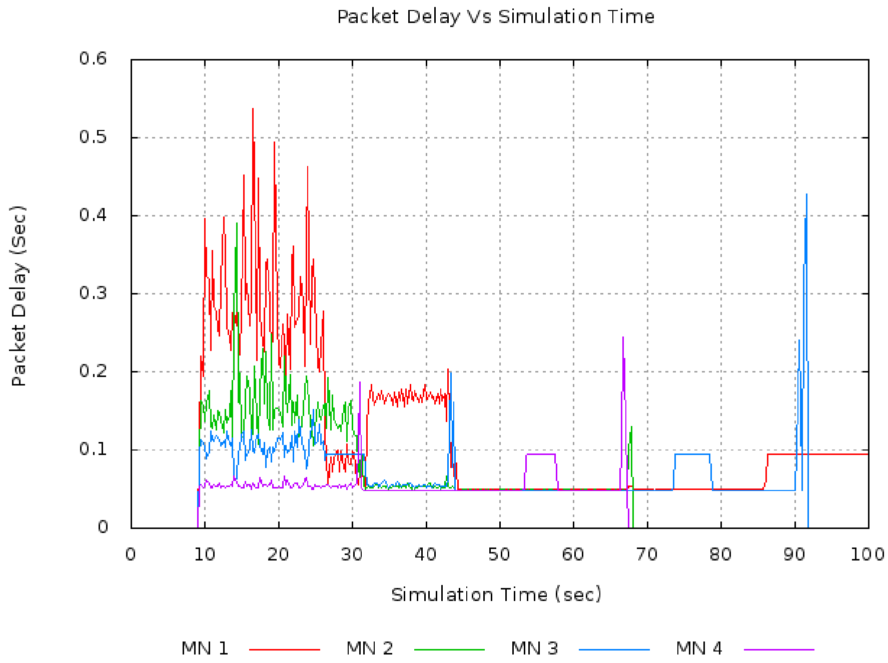


(a) Throughput of four MNs for WiMAX interface as an initial destination for UDP

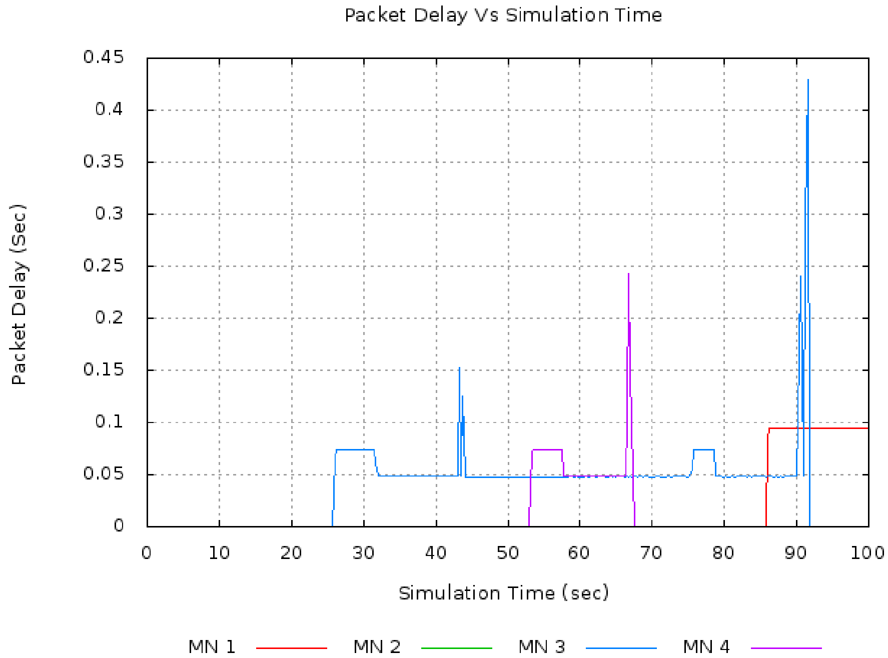


(b) Throughput of four MNs for WiFi interface as an initial destination for UDP

Figure 3.14: Throughput of four MNs for Speed 6, 11, 16 and 21 m/sec respectively

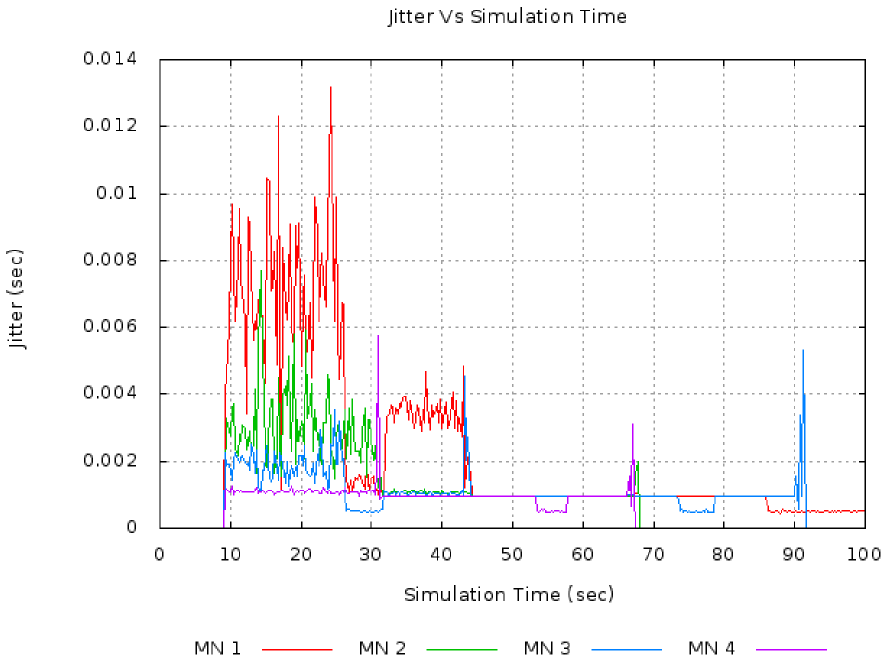


(a) UDP packet delay of four MNs for WiMAX interface as an initial destination for UDP packets

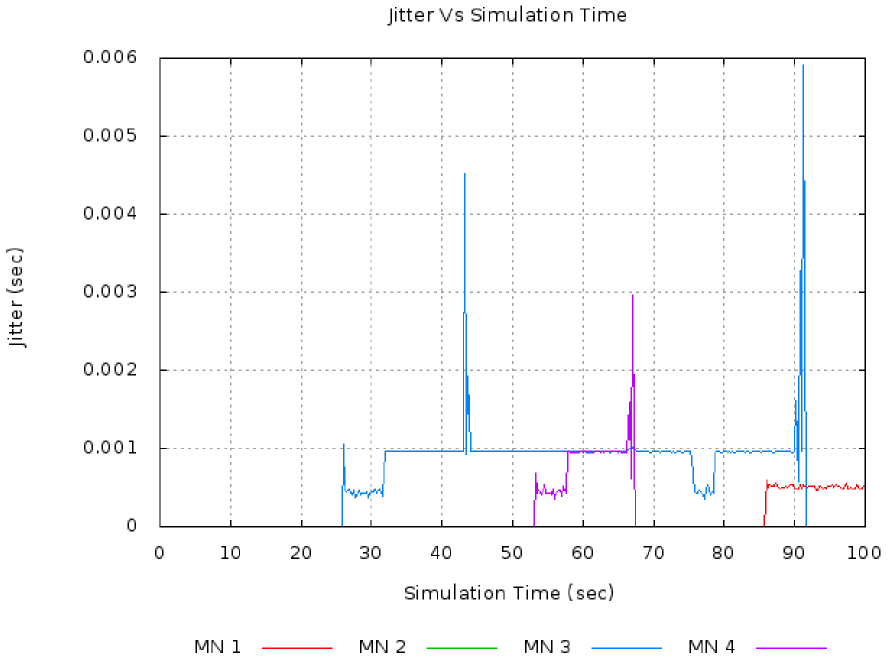


(b) UDP packet delay of four MNs for WiFi interface as an initial destination for UDP packets

Figure 3.15: UDP packet delay of four MNs for speed 6, 11, 16 and 21 m/sec respectively



(a) UDP packet jitter of four MNs for WiMAX interface as an initial destination for UDP packets



(b) UDP packet jitter of four MNs for WiFi interface as an initial destination for UDP packets

Figure 3.16: UDP packet jitter of four MNs for speed 6, 11, 16 and 21 m/sec respectively

E Analysis of the MNs' Packet Delay

Figure 3.15 shows the individual MN's variations in UDP packet delay when the initial destination of the UDP application is MN's WiMAX (see Figure 3.15(a)) and WiFi (see Figure 3.15(b)) interface.

Following are the observations in Figure 3.15(a) when an individual MN's WiMAX interface is the UDP packet's destination:

- Lower the throughput, greater is the packet delay and vice versa.
- Minimum packet delay is 0.05 sec and 0.1 sec when the MN's current accessing network is WiMAX and WiFi respectively.
- MN-1's minimum packet delay is during 43 sec - 86 sec, when MN-1 is the only MN under WiMAX-BS1.
- MN-2's minimum packet delay is with WiMAX-BS1, during 32 sec - 67 sec.
- In MN-3 and MN-4, minimum packet delay during the entire simulation continuously varies because of a more number of handovers.

Similarly, as shown in Figure 3.15(b) (the individual MN's WiFi interface is the UDP packet's destination), MN-3's average packet delay is less than the other two MNs' (MN-1 and MN-4).

F Analysis of the MNs' Jitter

Figure 3.16 shows the individual MN's variations in UDP packet jitter when the initial destination of the UDP application is MN's WiMAX (see Figure 3.16(a)) and WiFi (see Figure 3.16(b)) interface. As shown in Figure 3.16, the minimum jitter is 0.001 and less than 0.001 in WiMAX and WiFi network respectively.

3.4 Summary

This chapter of the thesis demonstrated the network ranking unreliability and the rank reversal problem of the classical MADM methods with an extensive MATLAB simulation. This chapter also presented a comparison and analysis of the three sigmoidal utility functions used for network selection in heterogeneous wireless networks.

The MATLAB simulation demonstrated the influence of the attributes weight and sigmoidal utility function constant in network selection. Additionally, it also presented NS2's first Evaluation Suite of the User Datagram Protocol referred to as ES-UDP for WiFi and WiMAX interfaced mobile nodes simulation in heterogeneous wireless networks. The designed suite support for configuration of simulation script and result analysis of handover, packets sent and received, throughput, delay and jitter.

The following chapter presents the proposed simplified and improved hierarchical analytical process for computing the reliable attributes weight.

Chapter 4

Simplified and Improved Analytical Hierarchy Process for Computing Reliable Attributes Weight in Heterogeneous Wireless Networks

4.1 Overview

As it has been numerically demonstrated in Section 3.1 of Chapter 3, weight calculation of the attributes is one of the main challenges of the classical MADM methods in selecting the networks during vertical handover decision in heterogeneous wireless networks. As shown in Table 2.3 (see Section 2.4 of Chapter 2) amongst all the available objective and subjective attributes weight computation methods, state-of-the-art Analytical Hierarchy Process (AHP) computes the attributes weight (w_j, where $j = 1, 2, ..., m$ attributes) using the perceived pairwise comparison of the attributes (r_{kj}, where $k, j = 1, 2, ..., m$ attributes)(Saaty 1990; Saaty 2006). Moreover, computed attributes weight using AHP of consistency ratio ≤ 0.1 is accepted further for selecting the network using classical MADM methods. The consistency ratio in AHP indicates the reliability of the computed attributes weight. The lower the consistency ratio, the higher is the reliability of the computed attributes weight. The consistency ratio of computed attributes weight higher than 0.1 results into unreliable selection of network during handover decision. Accordingly, the main challenging issue in AHP is, manual computation of the reciprocal matrix by the decision maker results in an inconsistency which is indicated by the consistency ratio being greater than 0.1 (Millet and Saaty 2000; Ozdemir 2005; Saaty and Begicevic 2010).

The reciprocal matrix in AHP computed by the decision maker illustrates the relational importance among the attributes. In manual pairwise comparisons of attributes to produce reciprocal matrix, the decision maker should be competent enough in identifying the relational differences between the attributes.

This chapter presents the proposed Simplified and Improved AHP referred to as SI-AHP for minimizing the involvement of the decision makers during the attributes weight computation. SI-AHP works on one-dimensional linguistic value of the attributes perceived by the decision maker with respect to application. Further, SI-AHP automatically computes the reciprocal matrix for the calculation of attributes weight. The linguistic value of the attributes are decided in relation to the application and not in comparison with other attributes. Additionally, with SI-AHP higher reliability in terms of the consistency ratio equal to 0 is achieved by computing the reciprocal matrix of pairwise comparison of any one of the attribute to the others. With the MATLAB simulation SI-AHP is evaluated for the consistency ratio of voice and download applications, and also for 78,125 different combinations of one-dimensional linguistic value of the seven attributes, i.e., bandwidth, signal-to-noise ratio, dwell time, seamlessness, price, battery consumption and latency. To summarize, the key contributions in this chapter are as follows:

- This is one of the first approach on simplified and improved AHP for the calculation of attributes weight with the minimal involvement of the decision maker.
- Further, this is the first approach with improved reliability and consistency of the computed attributes weight.

The remaining part of this chapter is organised as follows: Section 4.2 presents the proposed simplified and improved AHP; Section 4.3 illustrates the results and analysis of AHP and SI-AHP; Finally, Section 4.4 concludes with the summary.

4.2 Proposed Simplified and Improved Analytical Hierarchy Process

The major problem with the AHP approach described in Section 2.4.1 of Chapter 2 is manually computing the reciprocal matrix using the attributes relation with respect to the application. This requires sound knowledge of relational importance of attributes with respect to the application. The main objective of the proposed Simplified and Improved AHP (SI-AHP) is as follows:

- Simplifying AHP by minimizing the involvement of decision maker in computing the reciprocal matrix, resulting in consistency ratio ≤ 0.1 with the minimum weight computational time with higher reliability.
- Further improving the consistency or reliability of the calculated attributes weight by computing $r_{kj} = \frac{r_{1j}}{r_{1k}}$ with $r_{1j}, r_{1k} \in \{1/9,\ 1/7,\ 1/5,\ 1/3,\ 1,\ 3,\ 5,\ 7,\ 9\}$ with respect to first (any one) attribute relational importance to other $m-1$ attributes, where $j, k = 1, 2, ..., m$.

First, to simplify attributes weight computation procedure and to minimize the involvement of the decision maker following changes are incorporated in SI-AHP.

- Linguistic value 1, 3, 5, 7 and 9 of attributes in relation to the applications are redefined as very low, low, medium, high and very high respectively.
- Meaning of linguistic value of attributes are redefined to expectation of application with respect to attribute. For example, linguistic value of bandwidth with respect to voice application is medium, represent expectation of voice application from the selected network during handover is medium (Zhang 2004).
- Decision maker involvement is limited only upto defining the linguistic value of m attributes represented as l_j.

Further, in SI-AHP, Step 1 of AHP (see Section 2.4.1 of Chapter 2) is modified as:
Step 1: Deriving the reciprocal matrix R with the perceived one-dimensional vector l_j and is given by the Equation (4.1),

$$R = r_{kj} = \begin{cases} 1, & \text{if } l_k = l_j \\ l_k - l_j + 1, & \text{if } (l_k - l_j) > 0 \\ \frac{1}{l_j - l_k + 1}, & \text{if } (l_k - l_j) < 0 \end{cases} \tag{4.1}$$

where $j, k = 1, 2, ..., m$, with the condition $r_{kj} = \frac{1}{r_{jk}}$ for consistent eigenvector. $r_{kj} \in \{1/9,\ 1/7,\ 1/5,\ 1/3,\ 1,\ 3,\ 5,\ 7,\ 9\}$ depending on one-dimensional vector l_j defined by the decision maker.

Additionally, Steps 2-3 in SI-AHP follows the Step 2 (Computation of eigenvector - Equation (2.6)) and Step 3 (Consistency of eigenvector) of AHP (see Section 2.4.1 of Chapter 2).

Step 2: Equation (2.6) is applied to the reciprocal matrix derived using Equation (4.1) to compute the weight or eigenvector w_j of m attributes with the condition $\sum_{j=1}^{m} w_j = 1$.

Step 3: Verifying the eigenvector of Step 2 of section 4.2 using Equations (2.7) - (2.9) (see Section 2.4.1 of Chapter 2) for consistency ratio less than or equal to 0.1.

Some of the observations of SI-AHP:

Definition 1: Reciprocal matrix R is consistent if, $|l_k - l_j| = 0$ or $|l_k - l_j| \in$ any one $\{2, 4, 6, 8\}$ for all $j, k = 1, 2, .., m$.

Definition 2: For a consistent reciprocal matrix (consistency ratio ≤ 0.1), r_{kj} is a multiple of r_{xj} where $j, k, x = 1, 2, ..., m$ and $k \neq x$.

$$r_{kj} = \delta * r_{xj}, \text{ where } j, k, x = 1, 2, .., m \text{ and } x \neq \text{k} \tag{4.2}$$

where

$$\delta = \begin{cases} 1, & \text{if } l_k = l_x \\ l_k - l_x + 1, & \text{if } (l_k - l_x) > 0 \\ \frac{1}{l_x - l_k + 1}, & \text{if } (l_k - l_x) < 0 \end{cases} \tag{4.3}$$

The consistency of SI-AHP is further improved by deriving reciprocal matrix's r_{kj} using Equation (4.1) for $k = x$, where $x \in \{1, 2, ..., m\}$ and $j = 1, 2, ..., m$, and for $k \neq x$ as follows:

$$r_{kj} = \frac{r_{xj}}{r_{xk}}, \text{ where } j, k, x = 1, 2, ..., m \text{ and } k \neq x \tag{4.4}$$

resulting into:

- 100% consistency or reliability of the calculated attributes weight with $\lambda_{max} = m$ or consistency ratio $= 0$.

- $(m - 1)$ entries, automatically derives the reciprocal matrix.

4.3 Results and Analysis

The main difference between AHP and SI-AHP is the way the reciprocal matrix is computed. In AHP reciprocal matrix is computed manually by the decision maker with pairwise comparison of attributes with respect to the application. In SI-AHP, the decision maker inputs the perceived linguistic value of the attributes with respect to the application and the reciprocal matrix is derived either by using the Equation (4.1) or Equations (4.1) and (4.4). Further, to numerically compare SI-AHP with AHP, MATLAB simulation is carried out for the parameters shown in Table 4.1.

Table 4.1: MATLAB simulation parameters

Attribute	**Benefit Parameter:** (higher the value better is the rank of the network)	Bandwidth (Kbps), Signal-to-Noise Ratio (dB), Dwell Time (sec) and Seamlessness
	Cost Parameter: (lower the value better is the rank of the network)	Price ($), Battery Consumption (mWatt) and Latency (msec)

4.3.1 Consistency of AHP for Different Combinations of Reciprocal Matrix

This subsection demonstrates the consistency ratio of AHP for different combinations of manually derived reciprocal matrix. To derive different combinations of reciprocal matrix in MATLAB, each of the entries (r_{kj}) of 7 X 7 reciprocal matrix are varied for {1/9, 1/7, 1/5, 1/3, 1, 3, 5, 7, 9} for $j, k = 1, 2, ..., 7$ with the conditions $r_{jk} = \frac{1}{r_{kj}}$ and $r_{kj} = 1$ for $k = j$. This variations of r_{kj} results in 5,31,441 different combinations of reciprocal matrix.

Table 4.2 summarizes the numbers and % of different combinations of reciprocal matrix to a different range of values of the consistency ratio in AHP for total 5,31,441 combinations of reciprocal matrices. Following are the observations out of Table 4.2:

- 9 (0.0017%) combinations of reciprocal matrices with consistency ratio = 0.

- 2,139 (0.4024%) combinations of reciprocal matrices with 0 < consistency ratio ≤ 0.1.

Table 4.2: Consistency ratio of AHP for 5,31,441 different combinations of reciprocal matrix

Consistency Ratio	Reciprocal Matrix	
	No. of Combinations	% of Combinations
0	9	0.0017
> 0.00 to $<= 0.01$	0	0
> 0.01 to $<= 0.02$	29	0.0054
> 0.02 to $<= 0.03$	30	0.0056
> 0.03 to $<= 0.04$	52	0.0098
> 0.04 to $<= 0.05$	136	0.0256
> 0.05 to $<= 0.06$	118	0.0222
> 0.06 to $<= 0.07$	287	0.0540
> 0.07 to $<= 0.08$	350	0.0659
> 0.08 to $<= 0.09$	468	0.0880
> 0.09 to $<= 0.10$	669	0.1259
> 0.10	5,29,293	99.5958

- 5,29,293 (99.5958%) combinations of reciprocal matrices with consistency ratio > 0.1. Computed attributes weight or eigenvector for 5,29,293 combinations indicates inconsistent reciprocal matrix and the computed attributes weight are not useful in classical MADM methods.

Inference: Manually deriving the reciprocal matrix for consistency ratio less than or equal to 0.1 is a challenging task for the decision maker while using AHP for computing attributes weight.
Addressing the major drawback of AHP in this subsection, the following subsection demonstrates the effectiveness of SI-AHP over AHP.

4.3.2 Analysis of SI-AHP using Equation (4.1) to Voice and Download Applications Linguistic Attributes

This subsection demonstrates the consistency ratio of proposed SI-AHP method to voice and download application's linguistic attributes for reciprocal matrix derived using Equation (4.1).

Table 4.3: Attributes linguistic value of voice and download applications

Application	Voice		Download	
	Linguistic	**Value (l_j)**	**Linguistic**	**Value (l_j)**
Bandwidth	Medium	5	High	7
Signal-to-Noise Ratio	Low	3	Low	3
Dwell Time	High	7	Low	3
Seamlessness	High	7	Medium	5
Price	Medium	5	High	7
Battery Consumption	Low	3	Medium	5
Latency	High	7	Medium	5

Table 4.3 illustrates voice and download application's linguistic terms and values (Zhang 2004). The linguistic terms of voice and download applications shown in Table 4.3 indicates the attributes expectation of voice and download applications through the selected network during handover.

Table 4.4: Reciprocal matrix for voice application using Equation (4.1)

Attribute	BW	SNR	DT	SL	PR	BC	LA
Bandwidth (BW)	1	3	1/3	1/3	1	3	1/3
Signal-to-Noise Ratio (SNR)	1/3	1	1/5	1/5	1/3	1	1/5
Dwell Time (DT)	3	5	1	1	3	5	1
Seamlessness (SL)	3	5	1	1	3	5	1
Price (PR)	1	3	1/3	1/3	1	3	1/3
Battery Consumption (BC)	1/3	1	1/5	1/5	1/3	1	1/5
Latency (LA)	3	5	1	1	3	5	1

Further, applying Equation (4.1) on linguistic value l_j of voice and download applications shown in Table 4.3 results into the reciprocal matrix as shown in Table 4.4 and Table 4.5 respectively.

Finally, applying Steps 2-3 of Section 4.2 results in an eigenvector or attributes weight are as shown in Table 4.6 with the consistency ratio 0.0147 and 0.0149 for voice and download applications respectively.

Table 4.5: Reciprocal matrix for download application using Equation (4.1)

Attribute	**BW**	**SNR**	**DT**	**SL**	**PR**	**BC**	**LA**
Bandwidth (BW)	1	5	5	3	1	3	3
Signal-to-Noise Ratio (SNR)	1/5	1	1	1/3	1/5	1/3	1/3
Dwell Time (DT)	1/5	1	1	1/3	1/5	1/3	1/3
Seamlessness (SL)	1/3	3	3	1	1/3	1	1
Price (PR)	1	5	5	3	1	3	3
Battery Consumption (BC)	1/3	3	3	1	1/3	1	1
Latency (LA)	1/3	3	3	1	1/3	1	1

Table 4.6: Eigenvector for voice and download applications using Equation (4.1)

Attribute	**Eigenvector**	
	Voice	**Download**
Bandwidth	0.096885682	0.28506575
Signal-to-Noise Ratio	0.041662909	0.04519049
Dwell Time	0.240967606	0.04519049
Seamlessness	0.240967606	0.113162506
Price	0.096885682	0.28506575
Battery Consumption	0.041662909	0.113162506
Latency	0.240967606	0.113162506

Inference: Applying Equation (4.1) of SI-AHP on linguistic value of voice and download applications results in consistency ratio less than 0.1 for computed eigenvector.

4.3.3 Analysis of SI-AHP using Equations (4.1) and (4.4) to Voice and Download Applications Linguistic Attributes

This subsection demonstrates the consistency ratio of SI-AHP to voice and download application's linguistic attributes for reciprocal matrix derived using Equations (4.1) and (4.4). Additionally, in comparison to consistency ratio computed to voice and download applications in the previous subsection is further improved using Equations (4.1) and (4.4) of SI-AHP. To the linguistic attributes value of voice and download applications as shown in Table 4.3 a new eigenvector using Equations (4.1) and (4.4) are computed with the improved reliability. In this subsection, Equation (4.1) is used to derive r_{1j} of reciprocal matrix and for other entries of a reciprocal matrix of voice and download applications Equation (4.4) is used.

Table 4.7: Reciprocal matrix for voice application using Eqs. (4.1) and (4.4)

Attribute	**BW**	**SNR**	**DT**	**SL**	**PR**	**BC**	**LA**
Bandwidth (BW)	1	3	1/3	1/3	1	3	1/3
Signal-to-Noise Ratio (SNR)	1/3	1	1/9	1/9	1/3	1	1/9
Dwell Time (DT)	3	9	1	1	3	9	1
Seamlessness (SL)	3	9	1	1	3	9	1
Price (PR)	1	3	1/3	1/3	1	3	1/3
Battery Consumption (BC)	1/3	1	1/9	1/9	1/3	1	1/9
Latency (LA)	3	9	1	1	3	9	1

Table 4.8: Reciprocal matrix for download application using Eqs. (4.1) and (4.4)

Attribute	**BW**	**SNR**	**DT**	**SL**	**PR**	**BC**	**LA**
Bandwidth (BW)	1	5	5	3	1	3	3
Signal-to-Noise Ratio (SNR)	1/5	1	1	3/5	1/5	3/5	3/5
Dwell Time (DT)	1/5	1	1	3/5	1/5	3/5	3/5
Seamlessness (SL)	1/3	5/3	5/3	1	1/3	1	1
Price (PR)	1	5	5	3	1	3	3
Battery Consumption (BC)	1/3	5/3	5/3	1	1/3	1	1
Latency (LA)	1/3	5/3	5/3	1	1/3	1	1

Tables 4.7 and 4.8 illustrates the new reciprocal matrix derived to voice and download applications' linguistic attributes value (Table 4.3) using Equations (4.1) and (4.4).

Further, applying Steps 2 and 3 of Section 4.2 results in a consistency ratio of 0 (100% consistent reciprocal matrix) to voice and download applications with the eigenvector as shown in Table 4.9.

Table 4.9: Eigenvector for voice and download application using Eqs. (4.1) and (4.4)

Attribute	**Eigenvector**	
	Voice	**Download**
Bandwidth	0.085714286	0.294117647
Signal-to-Noise Ratio	0.028571429	0.058823529
Dwell Time	0.257142857	0.058823529
Seamlessness	0.257142857	0.098039216
Price	0.085714286	0.294117647
Battery Consumption	0.028571429	0.098039216
Latency	0.257142857	0.098039216

Inference: Applying Equations (4.1) and (4.4) of SI-AHP on l_j of voice and download applications results in consistency ratio equal to 0 for the computed eigenvector.

4.3.4 Analysis of SI-AHP for 78,125 Different Combinations of Linguistic Attributes

This subsection demonstrates the SI-AHP's stability of consistency ratio for 78,125 different combinations of attributes linguistic value (l_j) irrespective of applications. The linguistic attributes value of 78,125 combinations indicates 78,125 different combinations of reciprocal matrix using Equation (4.1), and Equations (4.1) and (4.4). To derive 78,125 different combinations of l_j, each of the attributes linguistic value are varied to 1, 3, 5, 7, and 9 one at a time. Few of the beginning combinations of l_j for seven attributes are; {1, 1, 1, 1, 1, 1, 1}, {3, 1, 1, 1, 1, 1, 1}, {5, 1, 1, 1, 1, 1, 1} and so on.

Table 4.10 summarizes the numbers and % of different combinations of attributes linguistics value l_j or reciprocal matrix for different consistency ratio. Using SI-AHP Equation (4.1), consistency ratio = 0 in 1,265 (%1.62) different combination of reciprocal matrices and 0 < consistency ratio < 0.08 for a remaining combination of the reciprocal matrices. With Equations (4.1) and (4.4), Table 4.10 shows 78,125 combinations of the reciprocal matrix with consistency ratio 0.

Table 4.10: Consistency ratio of SI-AHP for 78,125 different combinations of attributes linguistic value

Consistency Ratio	**Numbers and % of Combinations of l_j or R**			
	Using Equation (4.1)	**%**	**Using Equations (4.1) and (4.4)**	**%**
0	1,265	1.62	78,125	100
> 0.00 to $<= 0.01$	1,890	2.43	0	0
> 0.01 to $<= 0.02$	6,944	8.89	0	0
> 0.02 to $<= 0.03$	11,529	14.76	0	0
> 0.03 to $<= 0.04$	16,107	20.62	0	0
> 0.04 to $<= 0.05$	9,940	12.72	0	0
> 0.05 to $<= 0.06$	19,320	24.73	0	0
> 0.06 to $<= 0.07$	9,870	12.63	0	0
> 0.07 to $<= 0.08$	1,260	1.61	0	0
> 0.08 to $<= 0.09$	0	0	0	0
> 0.09 to $<= 0.10$	0	0	0	0
> 0.10	0	0	0	0

Inference: With the SI-AHP, involvement of the decision maker is limited to l_j and deriving the reciprocal matrix is done automatically with consistency ratio ≤ 0.1 using Equation (4.1) and consistency ratio $= 0$ with the Equations (4.1) and (4.4). Finally, use of SI-AHP results in 100% consistent and reliable eigenvector or attributes weight.

4.4 Summary

This chapter of the thesis presented the Simplified and Improved Analytical Hierarchy Process (SI-AHP) for computing consistent eigenvector or attributes weight. The main contribution of SI-AHP is in computing the consistent and reliable reciprocal matrix which satisfies the conditions for consistency ratio less than or equal to 0.1. With the MATLAB simulations, it is demonstrated that SI-AHP outperformed AHP in simplicity, reliability and consistency.

The following chapter presents the proposed simplified and improved multiple attributes alternate ranking method for VHD in heterogeneous wireless networks.

Chapter 5

Simplified and Improved Multiple Attributes Alternate Ranking Method for VHD in Heterogeneous Wireless Networks

5.1 Proposed SI-MAAR Method

As it has been presented in Chapter 3, the selection of candidate network during the Vertical Handover Decision (VHD) making process in heterogeneous wireless networks using classical MADM methods is predominantly decided by two steps, i.e., attributes normalization and weight calculation. This dependency in classical MADM methods results in an unreliable network selection (ranking) during VHD, and the rank reversal problem during the removal and insertion of the network in the network selection list.

This chapter of the thesis presents the proposed Simplified and Improved Multiple Attributes Alternate Ranking (SI-MAAR) method. The main objectives of the SI-MAAR method are:

- To eliminate the dependency of attributes normalization and weight calculation methods, thereby improving the reliability of network selection.
- To compute the network rank and score, which are independent of other network attributes, thereby avoiding the rank reversal problem.

Figure 5.1 shows the proposed SI-MAAR method of ranking the accessible heterogeneous wireless networks during the handover. The SI-MAAR accepts the expectation of the attributes e_j instead of weight of the attributes w_j. The e_j is depicted

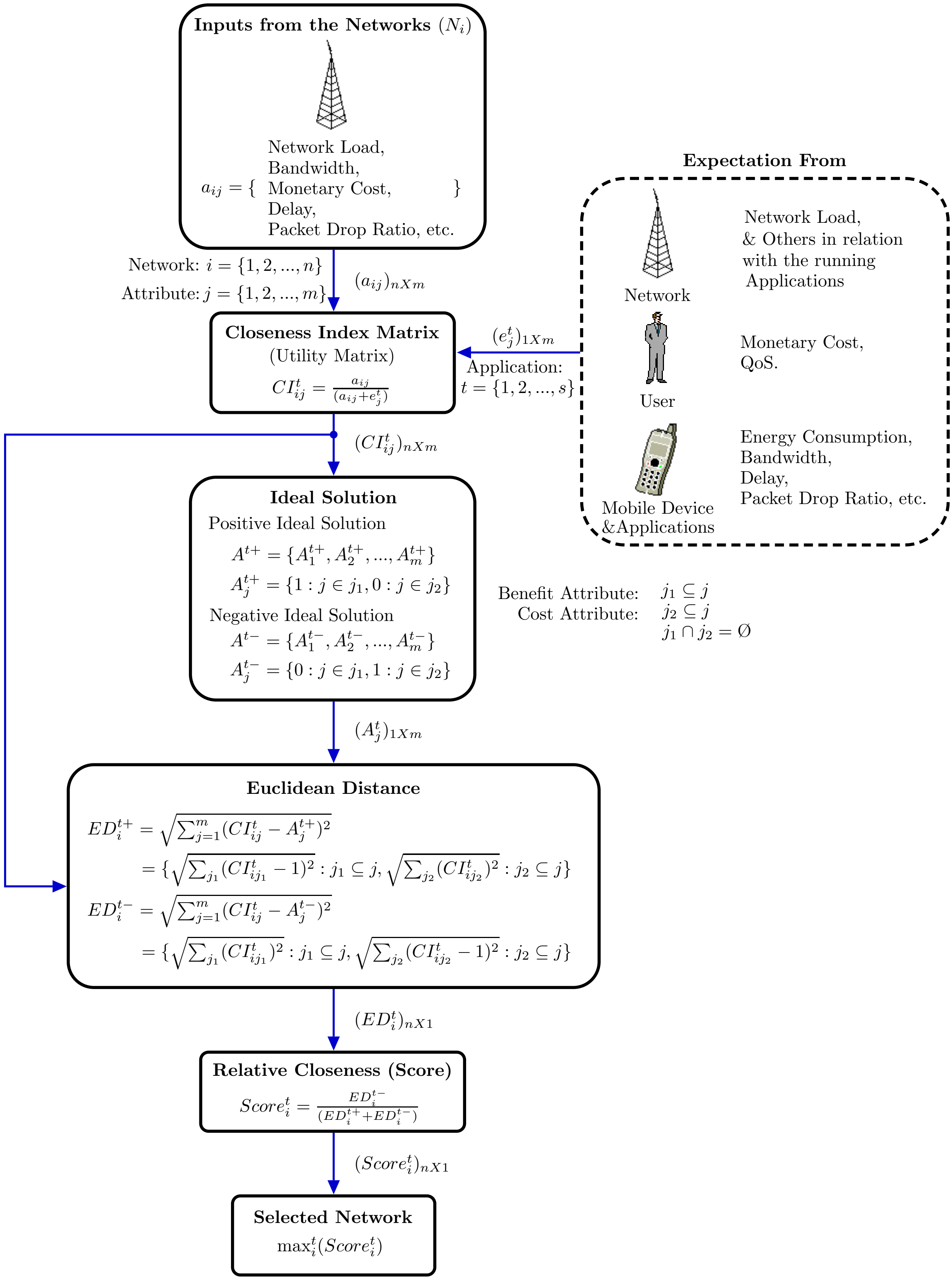


Figure 5.1: Proposed SI-MAAR method

based on the network, user, mobile device and application (t) (Chen et al. 2004; Cacheda et al. 2007). Further, e_j is used along with the networks and the corresponding attribute values a_{ij} in computing the Closeness Index matrix or Utility matrix. This step of the SI-MAAR method eliminates the dependency from the attributes normalization and weight calculation methods.

Closeness Index (CI) or Utility Matrix: It represents the closeness or utility (satisfaction) between the a_{ij} and e_j. The higher the difference between a_{ij} and e_j, the better is the CI of the network i with respect to the benefit attribute j, however the same is not true if the attribute j is the cost attribute. The CI between the a_{ij} and e_j is computed using the following equation:

$$CI_{ij} = \frac{a_{ij}}{(a_{ij} + e_j)}, \ i = 1, 2, 3, ..., n \text{ and } j = 1, 2, .., m. \tag{5.1}$$

where a_{ij} - network i versus attribute j, e_j - attribute j expectation of the network, user, mobile device or applications.

Observation 1: CI of a network is maximum to the benefit attributes of a network and vice-versa for the cost attributes.

Ideal Solution: It represents an ideal (best/worst) value of the attributes. To eliminate the dependency (the rank reversal problem) among the network attributes on the network ranking procedure, the best (positive) and the worst (negative) ideal value considered for the attributes are:

Positive Ideal Solution $(A^+) = \{A_1^+, A_2^+, ..., A_m^+\}$

Negative Ideal Solution $(A^-) = \{A_1^-, A_2^-, ..., A_m^-\}$

where

$$A_j^+ = \begin{cases} 1, & \text{for all benefit attributes} \\ 0, & \text{for all cost attributes} \end{cases} \tag{5.2}$$

$$A_j^- = \begin{cases} 0, & \text{for all benefit attributes} \\ 1, & \text{for all cost attributes} \end{cases} \tag{5.3}$$

Euclidean Distance: Euclidean distance is the distance measuring approach between two real valued vectors (D'Agostino and Dardanoni 2009). Minkowsky class of distance measure between two vectors v_1 and $\mathrm{v}_2 \in D^m$ is given by

$$d_m(\mathbf{v}_1, \mathbf{v}_2) = (\sum_{j=1}^{m} (v_{1j} - v_{2j})^p)^{1/p} \tag{5.4}$$

Euclidean Distance (ED) between two real valued vectors which satisfies the properties: Permutation Invariance, Extension Invariance, One dimensional value-sensitivity, Sub-vector Consistency and Monotonic Order Sensitivity with $p = 2$ in Equation (5.4) is given by (D'Agostino and Dardanoni 2009)

$$d_m(\mathbf{v}_1, \mathbf{v}_2) = \sqrt{\sum_{j=1}^{m}(v_{1j} - v_{2j})^2} \tag{5.5}$$

Euclidean distance with respect to the positive ideal solution (A^+) is:

$$ED_i^+ = \sqrt{\sum_{j=1}^{m}(CI_{ij} - A_j^+)^2} \tag{5.6}$$

Euclidean distance with respect to the negative ideal solution (A^-) is:

$$ED_i^- = \sqrt{\sum_{j=1}^{m}(CI_{ij} - A_j^-)^2} \tag{5.7}$$

where ED_i^+ and ED_i^- represent the Euclidean distance of the network i for the positive ideal (A^+) and the negative ideal (A^-) solution respectively.

Observation 2: The positive and negative ideal solutions shown in Equations (5.2) and (5.3) result in $ED_{y\in n}^+$ independent of $ED_{z\in n}^+$ and $ED_{y\in n}^-$ independent of $ED_{z\in n}^-$. This property of ED^+ and ED^- eliminates the rank reversal problem because of its independent nature.

Relative Closeness (RC): It represents the closeness of the network i to the positive and the negative Euclidean distance. The network's i, minimum distance with the positive and maximum distance with the negative Euclidean distance results in maximum score.

$$Score_i = \frac{ED_i^-}{(ED_i^+ + ED_i^-)} \tag{5.8}$$

Final Selection of the Network for Handover: Finally, the networks are ranked based on the relative closeness (score) and further, a network with the maximum score is selected by the MN for the handover in heterogeneous wireless networks.

$$\text{Selected Network for Handover} = \max_i(Score_i) \tag{5.9}$$

Table 5.1: MATLAB simulation parameters

Simulation Case			Network (Alternate)	Attribute (a_{ij})					
				Benefit ($j = 1, 2, 3, 4$)				Cost ($j = 5, 6$)	
Case 1	**Case 2**	**Case 3**		**1**	**2**	**3**	**4**	**5**	**6**
N_1			Network 1 (N_1)	30	31	47	30	9.75	33
N_2			Network 2 (N_2)	60	57	10	118	3.75	37
N_3			Network 3 (N_3)	22600	91	50	106	8.25	16
	N_4		Network 4 (N_4)	45000	1	50	94	3.75	5
		N_5	Network 5 (N_5)	55000	161	128	104	3	10
e_j				10030	61	77	148	3.75	73

5.2 Analysis of SI-MAAR for Reliability and the Rank Reversal Problem

To numerically check the rank reversal problem in SI-MAAR, a MATLAB simulation is carried out by computing the network rank and score for the parameters shown in Table 5.1. Further, to demonstrate the reliability in network rank and the elimination of rank reversal problem (reversal of the relative ranking of the networks if an alternative network is removed from or inserted into the candidate network selection list during the selection procedure) of the SI-MAAR, a MATLAB simulation is carried out with the following three cases:

- Case 1 - removal of network N_4 from the network selection list $\{N_1, N_2, N_3, N_4\}$, resulting in $\{N_1, N_2, N_3\}$
- Case 2 (Normal) - with four networks $\{N_1, N_2, N_3, N_4\}$
- Case 3 - inserting a new network N_5 into the network selection list $\{N_1, N_2, N_3, N_4\}$, resulting in $\{N_1, N_2, N_3, N_4, N_5\}$

Table 5.2 shows the network rank and score in relation to Table 5.1 for three different cases: Case 1, Case 2 and Case 3. As shown in Table 5.2, even after the removal of network N_4 in Case 1 or the insertion of network N_5 in Case 3 in relation to Case 2, there is no change in the network rank and score. The removal and insertion of the network in the network selection list in the proposed SI-MAAR method does not make any change in the rank and score of the networks. As shown in the Table 5.2, the score of network N_3 (0.5347) in Case 2 remains unchanged even after the removal of network N_4 in Case 1 or the insertion of network N_5 in Case 3 in relation to Case 2, and similarly with other networks.

Table 5.2: Ranking of the networks for the parameters shown in Table 5.1

Case	**Rank 1**		**Rank 2**		**Rank 3**		**Rank 4**		**Rank 5**	
	Network	Score	Network	Score	Network	Score	Network	Score	Network	Score
1	3	0.5347	2	0.3927	1	0.3409	-	-	-	-
2	3	0.5347	4	0.5063	2	0.3927	1	0.3409	-	-
3	5	0.6554	3	0.5347	4	0.5063	2	0.3927	1	0.3409

Table 5.3: Variations in the rank count of individual network for 1,000 different combinations of a_{ij} in Case 1, Case 2 and Case 3

Network	**Network (i) count in a particular Rank (r) for the particular Case (c) ($(Count_i)_r^c$)**											
	Case 1			**Case 2**				**Case 3**				
	Rank 1	Rank 2	Rank 3	Rank 1	Rank 2	Rank 3	Rank 4	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
N_1	177	483	340	16	175	471	338	2	19	175	467	337
N_2	88	310	602	4	91	305	600	0	8	92	300	600
N_3	735	207	58	174	568	200	58	36	176	533	197	58
N_4	-	-	-	806	166	24	4	280	544	148	24	4
N_5	-	-	-	-	-	-	-	682	253	52	12	1
Number of a_{ij} with the rank reversal problem = 0												

In order to check the existence of the rank reversal problem in SI-MAAR, extensive MATLAB simulation is carried out with 1,000 different combinations of a_{ij} used for computing Table 3.7 (see Section 3.1.2 of Chapter 3) and the fixed e_j shown in Table 5.1. Table 5.3 shows the variations in the network (N_1, N_2, N_3, N_4 and N_5) count in a particular rank for 3 different cases (Case 1, Case 2 and Case 3), where the number of invalid a_{ij} and the number of a_{ij} with the rank reversal problem is zero (**Note:** Figure 3.1 in Subsection 3.1.2 of Chapter 3 used for counting invalid a_{ij} and the rank reversal problem). Table 5.3 also illustrate the sensitivity of the SI-MAAR method for the variation of a_{ij}.

As shown in Table 5.3, $(Count_i)_r^c$ represents the count of network i in rank r for the Case c, where

Case 1 ($c = 1$, $n = 3$): $i = r = \{1, 2, 3\}$

Case 2 ($c = 2$, $n = 4$): $i = r = \{1, 2, 3, 4\}$

Case 3 ($c = 3$, $n = 5$): $i = r = \{1, 2, 3, 4, 5\}$

As shown in Table 5.3, $(Count_1)_r^1$ is 177, 483 and 340 representing the network N_1 count in rank 1, rank 2 and rank 3 respectively for Case 1, and so on for the other networks with the following conditions:

- $\sum_{r=1}^{n}(Count_i)_r^c$ = Number of combinations of a_{ij}
- $\sum_{i=1}^{n}(Count_i)_r^c$ = Number of combinations of a_{ij}

With respect to Table 5.3 following are some of the observations:

- For Case c, after removing the network i, the remaining $(n-1)$ networks' rank count, in a particular rank for Case $c-1$, can be computed as,

  $$(Count_i)_{r\neq 1}^c = [(Count_i)_{r+1}^{c+1} - (Count_i)_{r+1,r\neq n}^{c+1*}] + (Count_i)_r^{c+1*} \tag{5.10}$$

  $$(Count_i)_{r=1}^c = [(Count_i)_r^{c+1} + (Count_i)_{r+1}^{c+1}] - (Count_i)_{r+1}^{c+1*} \tag{5.11}$$

  where

  $\sum_{i=1}^{n} (Count_i)_{r,r\neq 1}^{c+1*} = \sum_{r=r}^{n} (Count_{n+1})_{r+1}^{c+1}$

  $\sum_{i=1}^{n} (Count_i)_1^{c+1*} = \sum_{r=2}^{n} (Count_{n+1})_{r+1}^{c+1}$, represents the rank r count of the network i of Case c which remains in the same rank r in Case $c-1$.

- For no rank reversal problem,

  $$(Count_i)_r^{c+1*} \geq 0 \tag{5.12}$$

Similarly, SI-MAAR is also verified for different e_j to study the rank reversal problem for the fixed a_{ij} (see Table 5.1). Table 5.4 shows the variations in the rank count of the networks for 1,000 different random combinations of e_j with the 0% rank reversal problem. The rank count of the individual networks shown in Table 5.4 follows the Equations (5.10) and (5.11), and Equation (5.12) for 0% of the rank reversal problem.

Table 5.4: Variations in the rank count of individual network for 1,000 different combinations of e_j and the common a_{ij} (see Table 5.1)in Case 1, Case 2 and Case 3

Network	Network (i) count in a particular Rank (r) for the particular Case (c) ($(Count_i)_r^c$)											
	Case 1			Case 2				Case 3				
	Rank 1	Rank 2	Rank 3	Rank 1	Rank 2	Rank 3	Rank 4	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5
N_1	0	1	999	0	0	1	999	0	0	0	9	991
N_2	0	999	1	0	8	991	1	0	8	237	754	1
N_3	1000	0	0	559	441	0	0	559	441	0	0	0
N_4	-	-	-	441	551	8	0	441	551	8	0	0
N_5	-	-	-	-	-	-	-	0	0	755	237	8
Number of a rank reversal problem for 1,000 different combinations of e_j = 0												

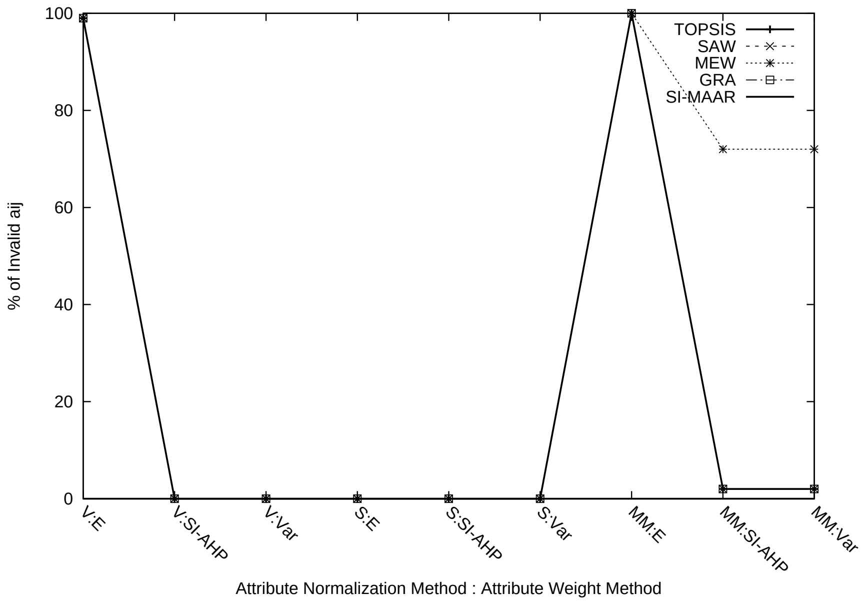


Figure 5.2: % of invalid a_{ij} of the classical MADM methods and SI-MAAR for 10,000 different combinations of a_{ij}

Note - S: Sum, V: Vector, MM: Max-Min Normalization and E: Entropy, SI-AHP, Var: Variance Weight Methods

In addition to above simulations, an extensive MATLAB simulation is also carried out to compare classical MADM methods (see Section 2.3.1 of Chapter 2) and SI-MAAR with respect to the percentage of invalid a_{ij} (see Figure 5.2), the percentage of a_{ij} with the rank reversal problem (see Figure 5.3) and the percentage of unreliable network ranking (see Figure 5.4) for 10,000 different combinations of a_{ij}. The percentage of a_{ij} with the rank reversal problem is computed against the valid number of a_{ij} (see Figure 3.1 in Section 3.1.2 of Chapter 3). Additionally, the percentage of unreliable network ranking is computed for (i) different attributes weight method with respect to the attributes normalization methods (see Figure 5.4) and (ii) attributes normalization method with respect to the attributes weight methods (see Figure 5.5).

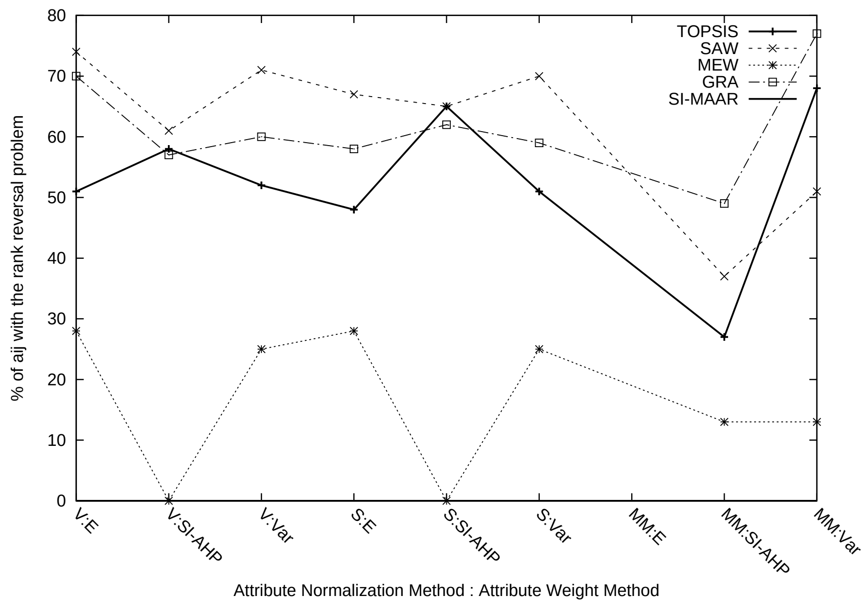


Figure 5.3: % of the rank reversal problem of SI-MAAR and the classical MADM methods for 10,000 different combinations of a_{ij}

Note - S: Sum, V: Vector, MM: Max-Min Normalization and E: Entropy, AHP, Var: Variance Weight Methods

As shown in Figure 5.2, the percentage of invalid a_{ij} (i.e., a_{ij} with $x_{ij} = \infty$) in the proposed SI-MAAR method is zero compared to the classical MADM methods. Similarly, Figure 5.3 illustrate, the percentage of the rank reversal problem with the proposed SI-MAAR method is zero compared to the classical MADM methods. As shown in Figure 5.3, among the classical MADM methods, the rank reversal problem is minimum in the MEW method.

Figure 5.4 illustrate the percentage of unreliable ranking of the classical MADM methods for 10,000 different combinations of a_{ij} with respect to the attributes weight method to the different attributes normalization methods. As shown in Figure 5.4, the percentage of unreliable ranking of the classical MADM methods is more than 97%, whereas, in the proposed SI-MAAR method, it is zero.

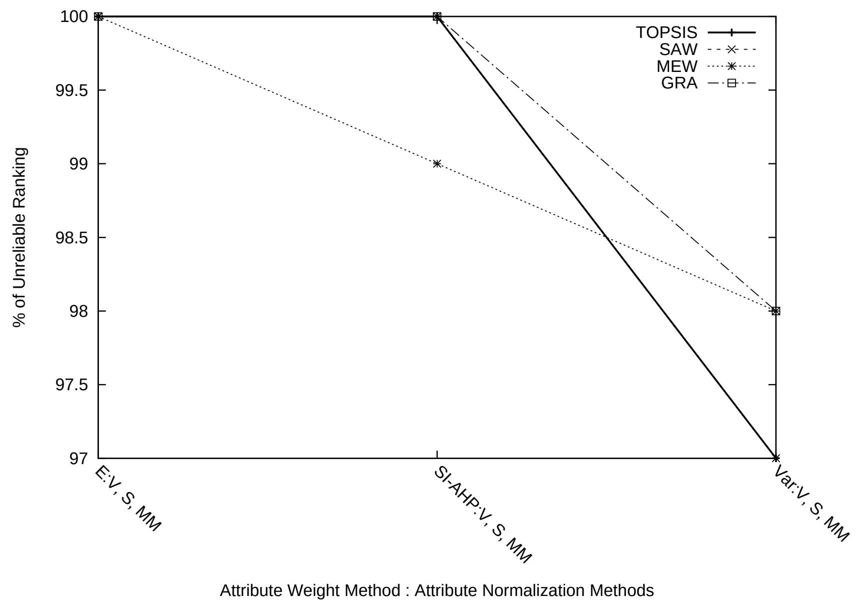


Figure 5.4: % of unreliable ranking of the MADM Methods for 10,000 different combinations of a_{ij} with respect to attribute weight to normalization methods

Note - S: Sum, V: Vector, MM: Max-Min Normalization and E: Entropy, AHP, Var: Variance Weight Methods

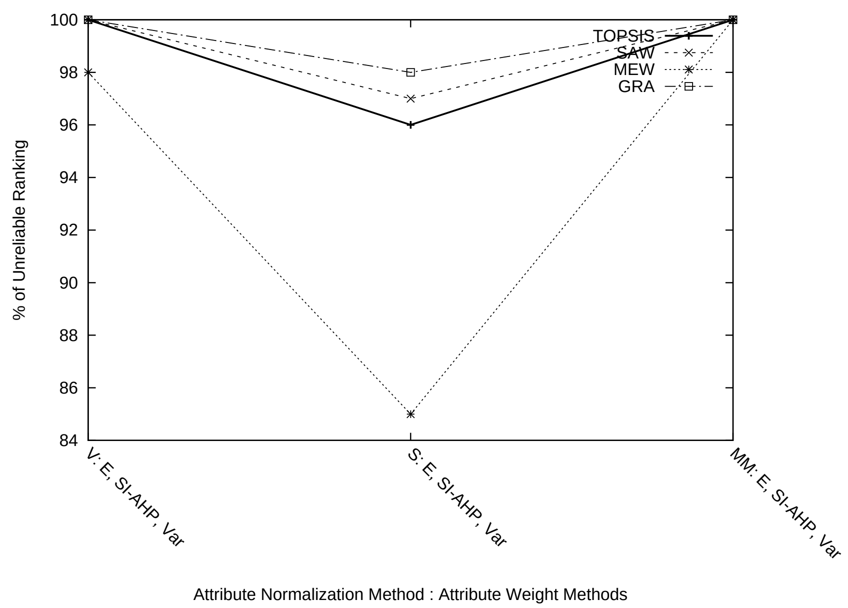


Figure 5.5: % of unreliable ranking of the MADM Methods for 10,000 different combinations of a_{ij} with respect to attribute normalization to weight methods

Note - S: Sum, V: Vector, MM: Max-Min Normalization and E: Entropy, AHP, Var: Variance Weight Methods

Similarly, Figure 5.5 illustrate the percentage of unreliable ranking of the classical MADM methods for 10,000 different combinations of a_{ij} with respect to the attributes normalization method to the different attributes weight methods. As shown in Figure 5.5, among the classical MADM methods, the percentage of unreliable ranking is less in the MEW method. Moreover, with the proposed SI-MAAR, the percentage of unreliable ranking is zero in comparison with the classical MADM methods.

As shown in Figure 5.1, the time complexity of computing closeness index matrix (CI_{ij}) and Euclidean distance (ED_i) is $O(n * m)$, whereas, ideal solution (A^+ and A^-) and relative closeness ($Score_i$) is $O(m)$ and $O(n)$ respectively. So, the worst case time complexity of the SI-MAAR for n networks of m attributes is $O(n * m)$. Hence, it has been showed that the SI-MAAR is the simplest and most improved network ranking method for VHD in HWNs. SI-MAAR is a simple method with minimum complexity and unambiguous network ranking steps when compared to the classical MADM methods. Moreover, the proposed SI-MAAR method completely eliminated unreliability in networks ranking and also, the rank reversal problem of the classical MADM methods.

5.3 Analysis of SI-MAAR for Objective and Subjective Attributes

Section 5.2 demonstrated, 100% reliable network ranking and 0% rank reversal problem of SI-MAAR. Additionally, this section demonstrates the performance of SI-MAAR for voice and download applications' objective e_j and subjective (linguistic) l_j attributes using MATLAB for the following parameters:

- Attributes: Six ($m = 6$) with benefit attributes - bandwidth (Kbps), signal-to-noise ratio (dB), dwell time (Sec), seamlessness and cost attributes - price ($) and battery consumption (mW). Tables 5.5 and 5.6 show the expected objective (Chen et al. 2004) and subjective (Zhang 2004) attributes with respect to voice and download applications.

- Number of networks: Four ($n = 4$) and Table 5.7 show the network versus attribute a_{ij} (Zhang 2004).

Table 5.5: Objective attributes of voice and download applications (e_j)

Application	**Bandwidth**	**Signal-to-Noise**	**Dwell Time**	**Seamlessness**	**Price**	**Battery Consumption**
Voice	50	30	1	1	5	1
Download	80	20	0.283	0.5	1	0.75

Table 5.6: Subjective attributes of voice and download applications (l_j)

Application /Attribute	**Bandwidth**	**Signal-to-Noise**	**Dwell Time**	**Seamlessness**	**Price**	**Battery Consumption**
Voice	Medium	Low	High	High	Medium	Low
Download	High	Low	Low	Medium	High	Medium

As shown in Figure 5.1, the expectation of the attributes e_j in SI-MAAR represents the specific requirements of MNs' ongoing applications during vertical handover decision in heterogeneous wireless networks. Moreover, expectation of attributes e_j in SI-MAAR method is also referred to as the objective attributes.
The following subsection 5.3.1 presents,

- Networks' ranking and ranking completion time of SI-MAAR to voice and download applications' expected objective attributes value (see Table 5.5) and network versus attribute a_{ij} (see Table 5.7)

Table 5.7: Network vs. Attribute (a_{ij})

Network	**Bandwidth**	**Signal-to-Noise**	**Dwell Time**	**Seamlessness**	**Price**	**Battery Consumption**
Network 1 (N_1)	30	80	0.909	1	10	0.5
Network 2 (N_2)	40	80	0.909	0.091	7	0.5
Network 3 (N_3)	80	20	0.283	0.909	1	1
Network 4 (N_4)	40	29	0.283	0.717	2	1

- Network selection sensitivity of SI-MAAR to voice application for variation of an individual network's individual attributes value one at a time in relation to network versus attribute a_{ij} (see Table 5.7).

- Network selection sensitivity of SI-MAAR to download application for variation of an individual network's individual attributes value one at a time in relation to network versus attribute a_{ij} (see Table 5.7).

- Network selection sensitivity of SI-MAAR for variation of individual attributes value one at a time of the expected objective attributes e_j of voice and download applications in relation to Table 5.5.

Similarly, subsection 5.3.2 presents,

- Comparison of SI-MAAR with the classical MADM methods: TOPSIS, SAW and GRA with respect to network ranking, ranking completion time and number of handover in 400 and 700 different combinations of subjective (linguistic) attributes.

- Network selection sensitivity of SI-MAAR and the classical MADM methods: TOPSIS, SAW and GRA for variation of individual attributes weight of voice application.

- Network selection sensitivity of SI-MAAR and the classical MADM methods: TOPSIS, SAW and GRA for variation of individual attributes weight of download application.

- Network selection sensitivity of SI-MAAR and the classical MADM methods: TOPSIS, SAW and GRA to voice and download applications for variation of an individual network's individual attribute's value one at a time in relation to network versus attribute a_{ij} (see Table 5.7).

5.3.1 Analysis for Expected Objective Attributes

Table 5.8 shows the networks' ranking and ranking completion time of SI-MAAR to voice and download application's expected objective attributes value e_j (see Table 5.5) and network versus attribute a_{ij} (see Table 5.7). As shown in Table 5.8, network N_3 is selected for handover during vertical handover decision for both voice and download applications.

Moreover, to study the network selection sensitivity of SI-MAAR to voice and download application's expected objective attributes e_j (see Table 5.5), individual

Table 5.8: Network rank and ranking completion time of SI-MAAR to voice and download application's expected objective attribute

Traffic	Metrics	Network			
		Network 1	**Network 2**	**Network 3**	**Network 4**
Voice	Ranking Score	0.5243	0.4287	0.6027	0.5382
	Rank	3	4	1	2
	Completion Time (msec)	0.16			
Download	Ranking Score	0.5894	0.4009	0.6096	0.5309
	Rank	2	4	1	3
	Completion Time (msec)	0.139			

network's individual attribute's value are varied one at a time in relation to network versus attribute a_{ij} (see Table 5.7). Each of the attributes of a network is varied from minimum (0) to maximum: 100, 100, 1, 1, 10 and 1 with respect to bandwidth, signal-to-noise ratio, dwell time, seamlessness, price and battery consumption respectively. As shown in Figures 5.6 and 5.7 individual lines illustrate the network selection sensitivity of SI-MAAR for variation of an individual network's individual attribute's value. Each of the subgraphs shown in Figures 5.6 and 5.7 is obtained by varying individual network's (N_1, N_2, N_3 and N_4) individual attributes value (j) one at a time and grouped in one subgraph for the analysis.

As shown in Figure 5.6 following are the observations in SI-MAAR to voice application's e_j (see Table 5.5) for the variations of an individual network's individual attributes value in relation to a_{ij} (see Table 5.7).

- Bandwidth: For bandwidth variations of four networks one at a time, network N_3 is selected for handover. However, during network N_3 bandwidth is in the range of 0-20, network N_4 is selected for handover.

- Signal-to-Noise Ratio: To signal-to-noise ratio variations of four networks, one at a time, handover decision is toggling between network N_3 and network N_4. As shown in Figure 5.6, SI-MAAR method is sensitive only for the network N_3 and network N_4 signal-to-noise ratio variations in range of 0-20 and 60-100 respectively.

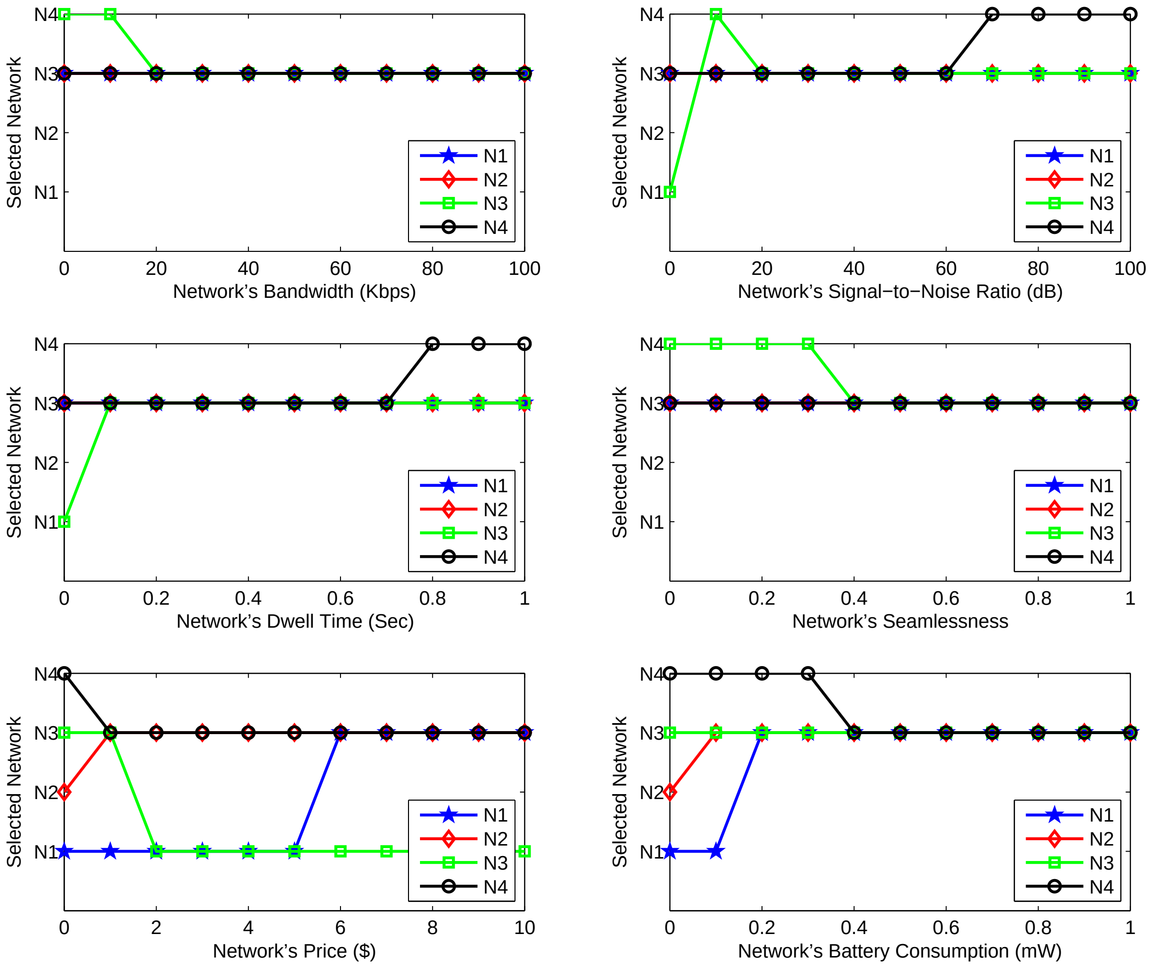


Figure 5.6: Network selection sensitivity of SI-MAAR to voice application's e_j in relation to variations of a_{ij}

- Dwell Time: To dwell time variations of four networks, SI-MAAR is sensitive towards networks' N_3 and N_4 dwell time variations in the range of 0-0.1 and 0.7-1.0 respectively. The selected network for handover during handover decision for networks' N_1, N_2 and N_3 dwell time variations is network N_3 and for network N_4 dwell time variations, handover decision toggle between network N_3 and network N_4.

- Seamlessness: SI-MAAR is sensitive towards network N_3 seamlessness variations in the range of 0-0.4 among seamlessness variations of the four networks. The selected network for handover during handover decision for variations of the seamlessness of network N_1, N_2 and N_4 is network N_3 and during seamlessness variations of network N_3, handover decision toggles between network N_3 and network N_4.

- Price: SI-MAAR is more sensitive to variations in price attribute of all four networks. During, network N_1 price attribute variations in the range of 0-6, network N_1 itself is selected for handover and network N_3 for other ranges of price attribute of network N_1. Further, for price attribute of network N_2 in the range of 0-1, network N_1 is selected for handover and for other value network N_3. Similarly, for price attribute in the range of 0-2 of network N_3, network N_3 itself is selected for handover and network N_1 for other value. Finally, for price attribute in the range of 0-1 of network N_4, network N_4 itself is selected for handover and network N_3 for other ranges.

- Battery Consumption: SI-MAAR is more sensitive towards variations in battery consumption in the range 0-0.2, 0-0.1 and 0-0.4 of network N_1, N_2 and N_3 respectively, the selected network for handover during the handover decision is either network N_1, N_2, N_3 or N_4. Further, for battery consumption of all four networks higher than 0.4, network N_3 is selected for handover.

Additionally, in relation to Figure 5.7 following are the observations in SI-MAAR to download application's expected objective attributes e_j (see Table 5.5) for the variations of an individual network's individual attributes value in relation to a_{ij} (see Table 5.7).

- Bandwidth: SI-MAAR is sensitive only towards network N_1 and network N_3 bandwidth variations and the selected network for handover is either network N_1 or network N_3.

- Signal-to-Noise Ratio: To signal-to-noise ratio variations, SI-MAAR is sensitive only to network N_4 and the selected network for the majority of handover decision is network N_3.

- Dwell Time: To dwell time variations, SI-MAAR is sensitive to network N_3 and network N_4 and the selected network for handover during handover decision is either network N_1 or network N_3.

- Seamlessness: For seamlessness variations, SI-MAAR is sensitive only towards network N_3. The selected network for handover during seamlessness variations

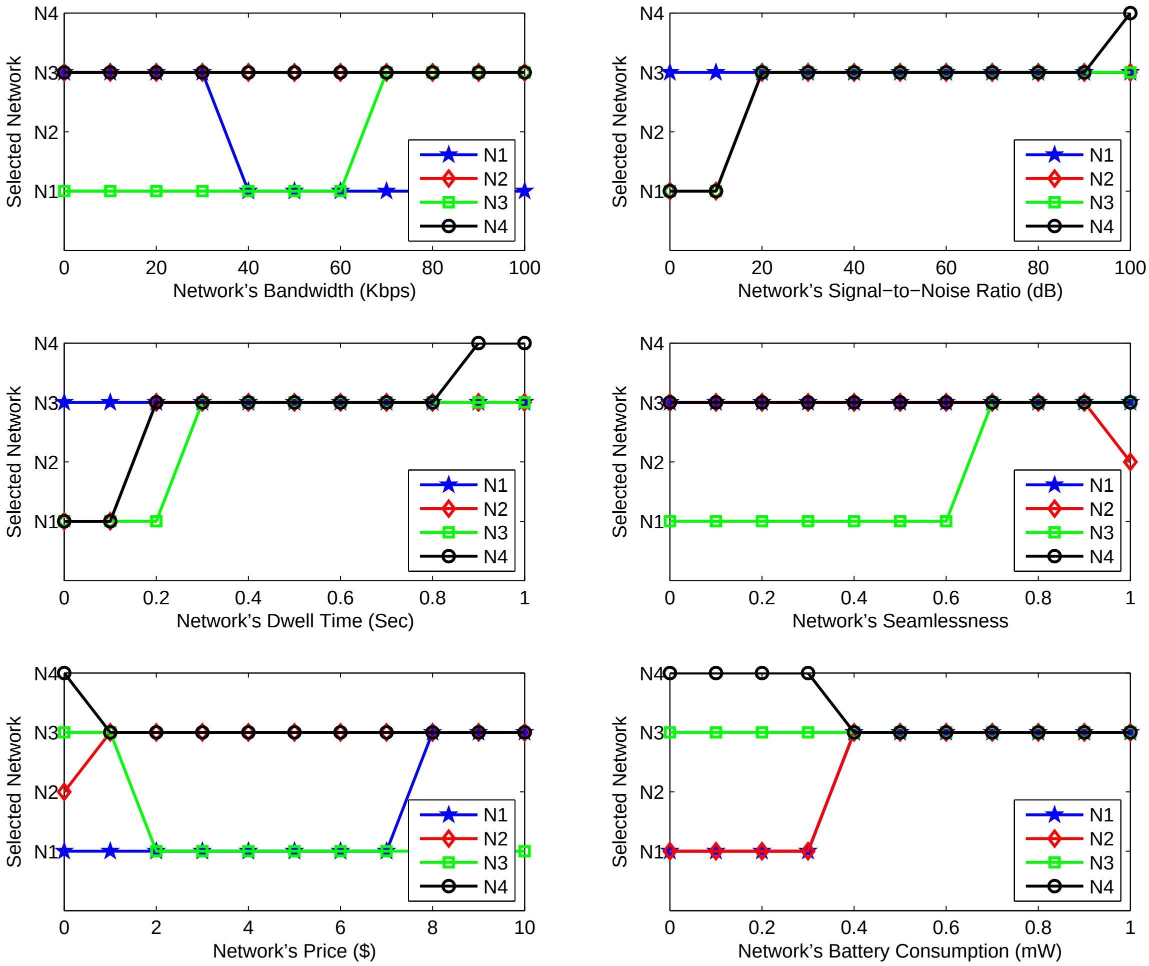


Figure 5.7: Network selection sensitivity of SI-MAAR to download application's e_j in relation to variations of a_{ij}

of network N_3 is network N_1, and for other three networks N_1, N_2 and N_4, the selected for handover is network N_3.

- Price: SI-MAAR is more sensitive to all the four networks price variations and the selected network for handover during the handover decision is either network N_1, N_2, N_3 or N_4, but for the majority of time network N_1 and network N_3 are selected.

- Battery Consumption: For battery consumption variations, SI-MAAR is sensitive to networks N_1, N_2 and N_4. The handover decision is either with network N_1, N_3 or N_4 and for battery consumption variations of all four networks higher than 0.4, network N_3 is selected for handover.

Inference: Referring to Figures 5.6 and 5.7, it can be concluded that, SI-MAAR's network selection during the handover decision is sensitive to variations of an individual network's individual attributes value for both voice and download applications.

Further, to study the network selection sensitivity of SI-MAAR, individual expected objective attributes e_j of voice and download application's are varied from minimum (0) to maximum: bandwidth and signal-to-noise ratio to 100, dwell time, seamlessness and battery consumption to 1, and price to 10 in relation to Table 5.5 for the constant network versus attribute a_{ij} (see Table 5.7).

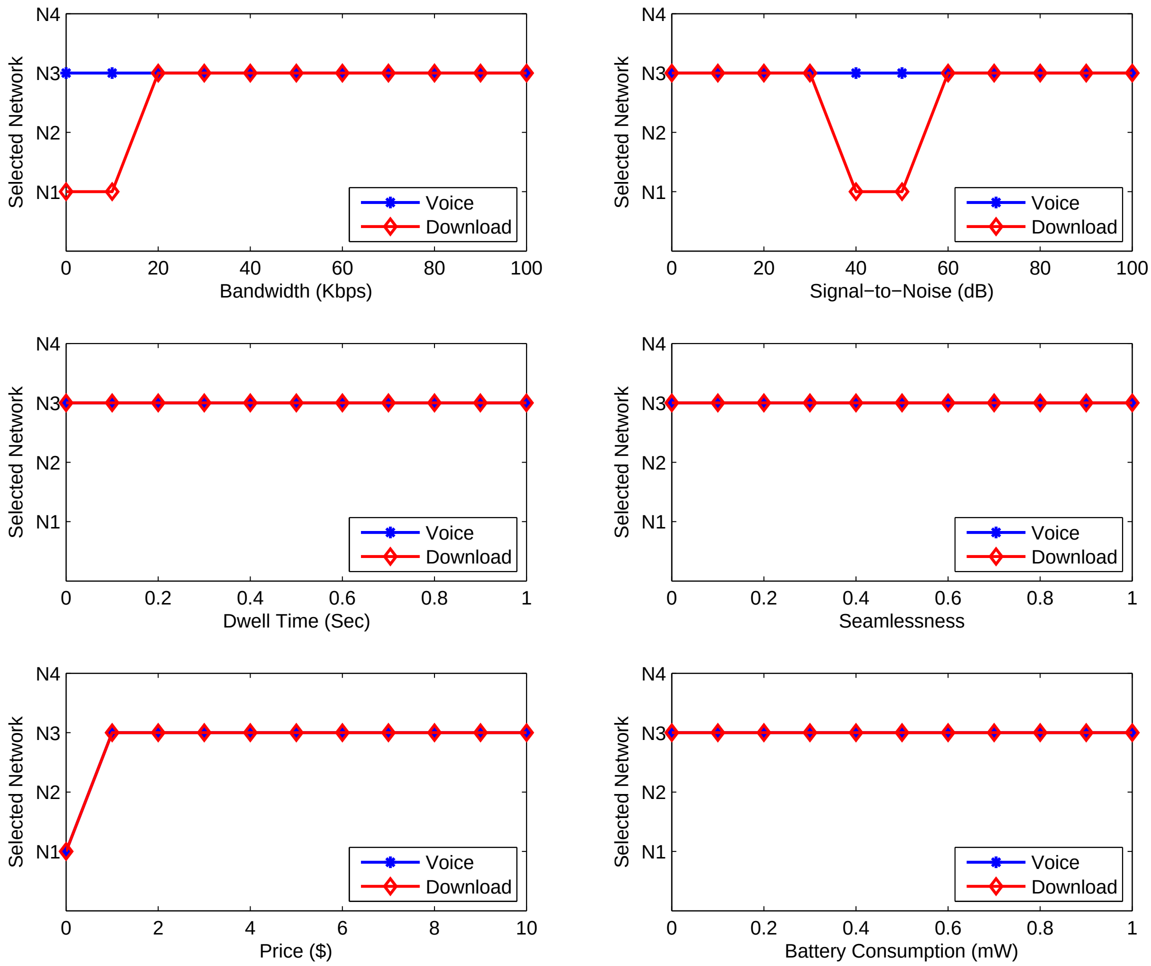


Figure 5.8: Network selection sensitivity of SI-MAAR for variations of individual objective attributes of voice and download applications

In Figure 5.8, individual lines represent the network selection sensitivity of SI-MAAR towards the variation of individual expected objective attributes of voice and download applications. Each of the subgraphs shown in Figure 5.8 are obtained by varying voice and download applications with respect to individual expected objective attributes one at a time shown in Table 5.5 and these are grouped in one subgraph for the analysis.

As shown in Figure 5.8 following are the observations in SI-MAAR to the variations of individual expected objective attributes e_j of voice and download application's in relation to Table 5.5 for the constant network versus attribute a_{ij} (see Table 5.7).

- To the variations of voice application's expected objective attributes such as, bandwidth, signal-to-noise ratio, dwell time, seamlessness and battery consumption network N_3 is selected for handover and to price attribute variation initially network N_1 and later network N_3 is selected for handover.
- To the variations of download application's expected objective attributes such as, seamlessness, dwell time and battery consumption network N_3 is selected for handover and to bandwidth, signal-to-noise ratio and price attributes variation selected network for handover toggles between network N_1 and network N_3.

Inference: In relation to network versus attribute a_{ij} (see Table 5.7), SI-MAAR is also sensitive to the variations of individual expected objective attributes of voice and download applications.

5.3.2 Analysis for Expected Subjective Attributes

This subsection compares SI-MAAR with the classical MADM methods: TOPSIS, SAW and GRA for the performance metric; network ranking, ranking completion time and number of handover in 400 and 700 different combinations of expected subjective attributes l_j. Moreover, SI-MAAR and the classical MADM methods: TOPSIS, SAW and GRA are compared for network selection sensitivity to the variations of voice and download applications attributes weight and individual network's individual attribute's value in relation to a_{ij} (see Table 5.7).

First, to compute expected objective attributes e_j to rank network using SI-MAAR for different combinations of expected subjective attribute l_j, linguistic terms: very low, low, medium, high and very high of the expected subjective attributes is converted into fuzzy numbers: 1, 3, 5, 7 and 9 respectively using a conversion scale (Tzeng and Huang 2011). Further, the resulting fuzzy number with respect to linguistic terms: very low, low, medium, high and very high of expected subjective attributes are converted into crisp number (c_j); 0.091, 0.283, 0.5, 0.717 and 0.909 respectively.

Equation (5.13), represent the computation of the expected objective attributes e_j using crisp number c_j in relation to expected subjective attributes l_j and network versus attribute a_{ij} (see Table 5.7).

$$e_j = \begin{cases} \max_i(a_{ij}) * c_j, & \text{for benefit attribute } c_j \geq 0.5 \text{ (medium)} \\ \min_i(a_{ij}) * c_j, & \text{for benefit attribute } c_j < 0.5 \text{ (medium)} \\ \min_i(a_{ij}) * c_j, & \text{for cost attribute } c_j \geq 0.5 \text{ (medium)} \\ \max_i(a_{ij}) * c_j, & \text{for cost attribute } c_j < 0.5 \text{ (medium)} \end{cases} \tag{5.13}$$

Further, Equation (5.14) represents the computation of attributes weight using the crisp value c_j in relation to expected subjective attributes l_j.

$$w_j = c_j / \sum_{j=1}^{m} c_j \tag{5.14}$$

Table 5.9: Voice and download applications' attributes crisp value and weight in relation to subjective attributes Table 5.6

Service/Parameter		**Attributes**					
Service	**Parameter**	**Bandwidth**	**Signal-to-Noise**	**Dwell Time**	**Seamlessness**	**Price**	**Battery Consumption**
Voice	c_j	0.5	0.283	0.717	0.717	0.5	0.283
Download	c_j	0.717	0.283	0.283	0.5	0.717	0.5
Voice	w_j	0.167	0.094	0.239	0.239	0.167	0.094
Download	w_j	0.239	0.094	0.094	0.167	0.239	0.167

Table 5.9 shows crisp value c_j and weight w_j of attributes in relation to expected subjective attributes of voice and download applications (see Table 5.6) computed using Equation (5.14).

Note: As shown in Figure 5.1, SI-MAAR depends on expected objective attributes and classical MADM methods on attributes weight during ranking the networks. Equations (5.13) and (5.14) presents one way of mapping subjective attributes to related objective attributes e_j and attributes weight w_j for comparisons of SI-MAAR with classical MADM methods.

A Performance analysis of SI-MAAR and classical MADM methods to different combinations of subjective attributes

To compare the performance of SI-MAAR with the classical MADM methods: TOPSIS, SAW and GRA, each of the attributes subjective value one at a time is varied from 'low' to 'very high' resulting into expected objective attribute e_j using Equation (5.13) for SI-MAAR and relative attributes weight w_j using Equation (5.14) for classical MADM methods. The different combinations of subjective attributes are independent of voice and download applications, but the different combinations used here are represents all different application's subjective attribute expectations of today's internet.

Table 5.10: Comparison of SI-MAAR with the classical MADM methods for 400 and 700 different combinations of subjective attributes

Simulation	Metrics	Algorithm			
		SI-MAAR	**TOPSIS**	**SAW**	**GRA**
400 combinations of Linguistic Value	Selected Network Average Ranking Score	0.62514	0.61981	0.33169	0.59435
	Avg. N/W Selection Completion Time (msec)	0.0361	0.0616	0.0328	0.116
	Number Of Handovers	80	117	2	32
700 combinations of Linguistic Value	Selected Network Average Ranking Score	0.6241	0.6169	0.3260	0.5860
	Avg. N/W Selection Completion Time (msec)	0.0492	0.0809	0.0383	0.162
	Number Of Handovers	117	229	6	88

Table 5.10 shows the comparison of SI-MAAR with the classical MADM methods: TOPSIS, SAW and GRA for the performance metric; selected network's average ranking score, average completion time of network selection and number of handover in 400 and 700 different combinations of subjective attributes and fixed network versus attribute a_{ij} (see Table 5.7).

As shown in Table 5.10, SI-MAAR out performed compared to classical MADM methods in terms of selected network's average ranking score (the higher the score, the better is the approach) and the average completion time of network selection (minimum the time, better is the approach). Since, TOPSIS, SAW and GRA select the network for handover based on attributes weight, the number of handover in TOPSIS, SAW and GRA show that TOPSIS is more sensitive to the variations in subjective attributes than SAW and GRA. (This may also lead to the ping-pong effect in TOPSIS, resulting in maximum packet drops and packet delay.) Whereas, for the SI-MAAR rank of the network is based on expected objective attributes e_j, which are normally in ranges, such as data rate of conversational voice is 4-25 kbps (Cacheda et al. 2007). It is not desirable that change in the expected value of any attributes within the range leads to handover.

B Network selection sensitivity of SI-MAAR and classical MADM methods for variations in attributes weight

This subsection presents network selection sensitivity of SI-MAAR and classical MADM methods: TOPSIS, SAW and GRA to the variations of individual attributes weight $w_{k\in j}$ (see Table 5.9) of voice and download applications for the fixed network versus attribute a_{ij} (see Table 5.7). The variations in individual attributes weight results in variations of expected objective attributes e_j and change in other attributes weight $w_{x\in j,x\neq k}$.

Following is the procedure used in computing attributes e_j and w_j for the variations in individual attributes weight of voice and download applications in relation to the Table 5.9 :

- Vary the weight $w_{k\in j}$ of an attribute k in relation to Table 5.9 for voice and download applications.
- Compute new crisp value $c_{k\in j}$ of k using Equation (5.15)

$$c_{k\in j} = \frac{(\sum_{j=1,j\neq k}^{6} c_j) * w_{k\in j}}{1 - w_{k\in j}} \tag{5.15}$$

- Compute the expected objective attribute $e_{k\in j}$ of k using Equation (5.13).
- Recompute weight of other attributes $w_{x\in j,x\neq k}$ using Equation (5.14) with the condition $\sum_{j=1}^{6} w_j = 1$ (Alinezhad and Amini 2011).

Example: In relation to expected subjective attributes l_j of voice and download applications shown in Table 5.6, Table 5.9 illustrate related crisp value c_j and attributes weight w_j of voice and download applications. Attributes weight w_j of voice and download applications in relation to c_j are computed using Equation (5.14). Similarly, in relation to crisp value c_j, as shown in Table 5.9, the expected objective attributes of voice and download applications are computed using Equation (5.13). To numerically demonstrate the computation of expected objective attributes and attributes weight, consider, if the weight of the bandwidth attribute $w_{x=1\in j}$ is varied from 0.167 to 0.1 for voice application, the modified crisp value $c_{x=1\in j}$ and the new weight of other attributes (j = 2, 3, 4, 5 and 6) are computed as follows;

$$\begin{aligned} c_{x=1\in j} &= \frac{(\sum_{j=1,j\neq x}^{6} c_j) * 0.1}{0.9} \\ &= 0.2778 \end{aligned}$$

The new crisp value of the bandwidth attribute with other attributes crisp value as shown in Table 5.9 results into $\sum_{j=1}^{6} c_j = 2.778$ in Equation (5.15) and the modified weight of the attributes are $w_j = \{$ 0.1, 0.102, 0.258, 0.258, 0.179, 0.102$\}$.

Note: In Figures 5.9 and 5.10, voice and download applications' attributes weight are varied only from 0 to maximum 0.26, since the linguistic value of any attribute changes up to 'very high' (0.909) resulting in maximum weight of an attribute being 0.26 by retaining the linguistic value of other attributes as shown in Table 5.6.

Figures 5.9 and 5.10 illustrate variations in attributes weight of voice and download applications. As shown in Table 5.9 computed using Equations (5.13) and (5.14) to voice application, weight of attributes seamlessness and dwell time are high, bandwidth and price are medium, and signal-to-noise ratio and battery consumption are minimum. Moreover, to download application, weight of attributes bandwidth and price are maximum, seamlessness and battery consumption medium, and signal-to-noise ratio and dwell time are minimum. The similar relation between the attributes weight to voice and download applications, illustrated in Table 5.9 can be observed in Figures 5.9 and 5.10 for the variations of weight of any one attribute. As shown in Figure 5.9, weight of the attributes dwell time and seamlessness is high, bandwidth and price medium and signal-to-noise ratio and battery consumption is low for voice application. Similarly, Figure 5.10 shows, the weight of the attributes bandwidth and price high, seamlessness and battery consumption medium and signal-to-noise ratio and dwell time is low for download application.

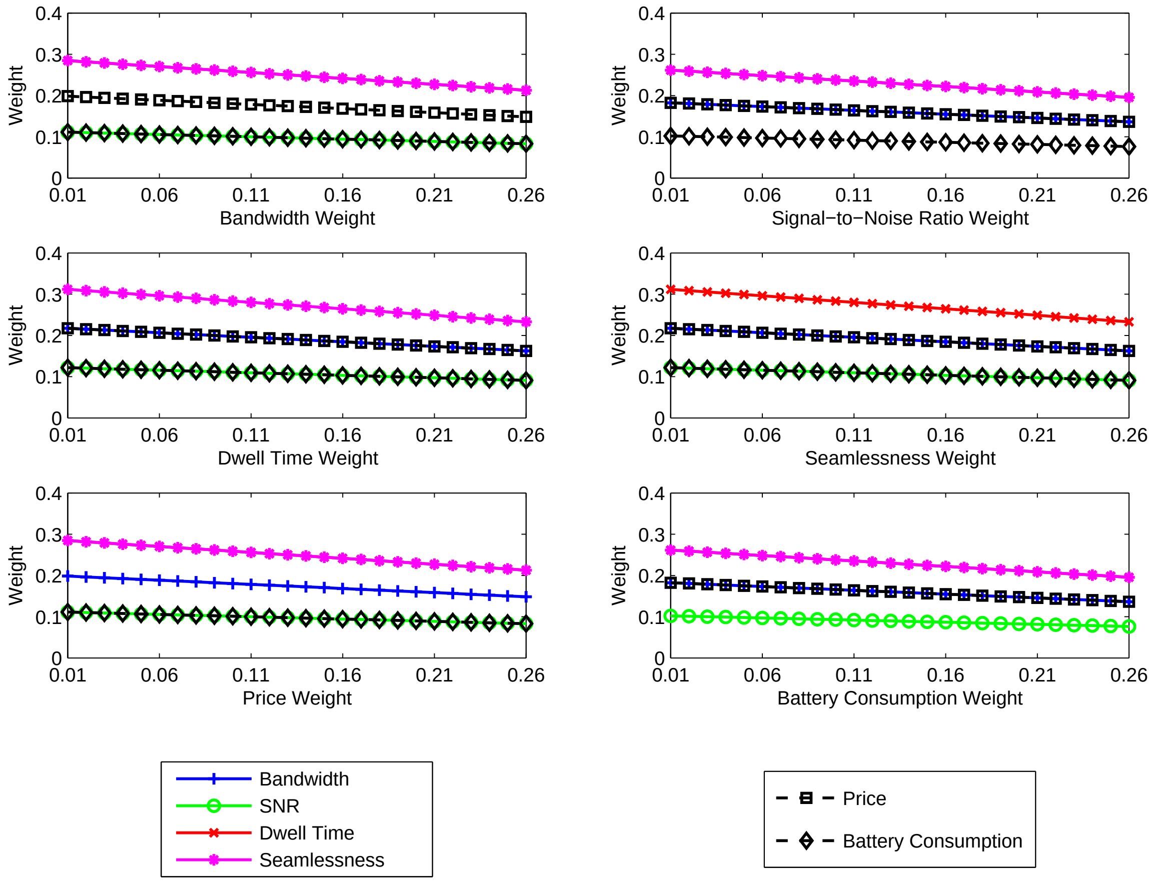


Figure 5.9: Variations in attributes weight of voice application

Figures 5.11 and 5.12 illustrate network selection sensitivity of SI-MAAR and classical MADM methods: TOPSIS, SAW and GRA for variations of attributes weight of voice and download applications as shown in Figure 5.9 and 5.10 and network versus attribute a_{ij} (see Table 5.7). Each of the lines in subgraphs shown in Figures 5.11 and 5.12 illustrates network selection sensitivity of SI-MAAR, TOPSIS, SAW and GRA for the variation of weight of attributes bandwidth, signal-to-noise ratio, dwell time, seamlessness, price and battery consumption.

Analysis of Figure 5.11 for voice application:

- Bandwidth: As shown in Table 5.7 bandwidth of network N_3 (80) is higher than other three networks. In SI-MAAR, for subjective attribute of bandwidth l_1 lower than 'medium', network N_1 is selected for handover (since, network N_1 is better in terms of other five attributes of networks N_1, N_2 and N_4) and thereafter, network N_3 is selected. Similar results can be noticed in TOPSIS for bandwidth-weight less than and more than 0.1. Whereas, SAW and GRA are

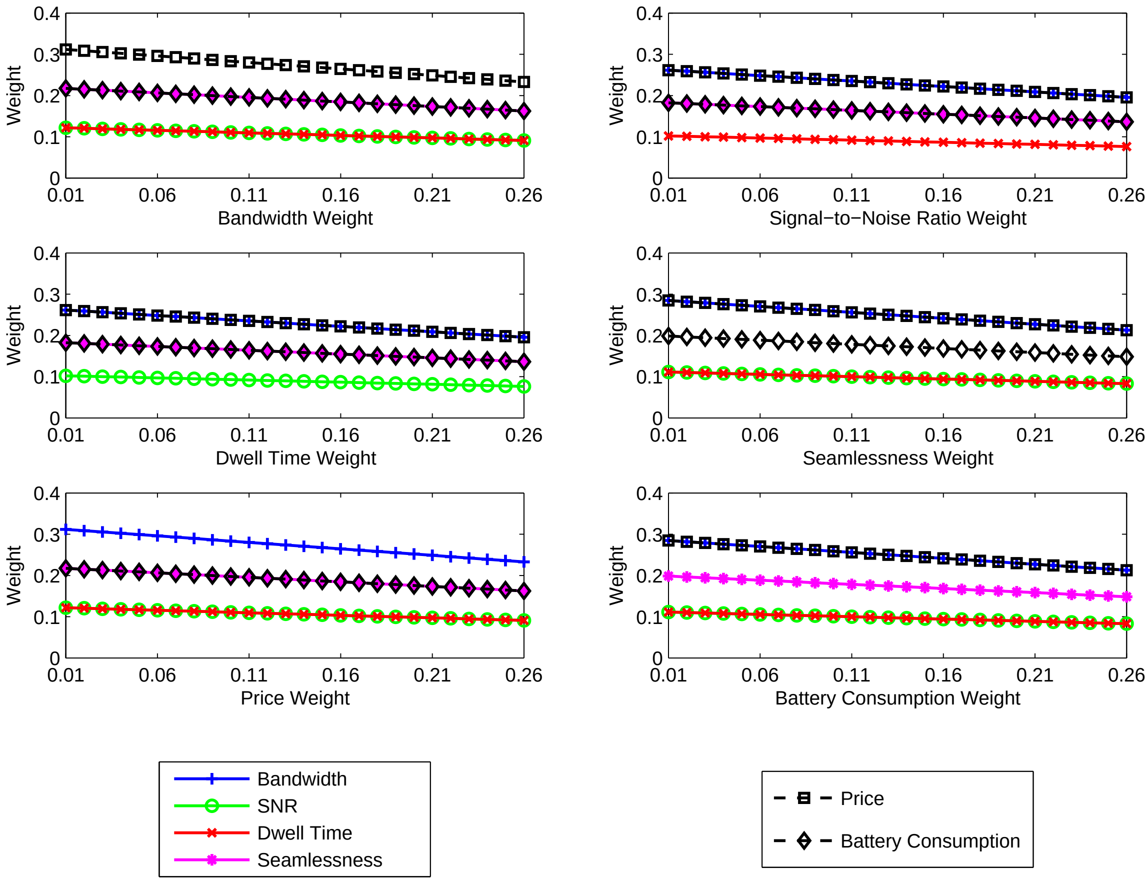


Figure 5.10: Variations in attributes weight of download application

not sensitive to the variations of weight of the bandwidth attribute and so, the selected network for handover is network N_1.

- Signal-to-Noise Ratio: In SI-MAAR, for signal-to-noise ratio crisp value c_2 less than 0.3701 (between low and medium), network N_3 is selected for handover even though networks' N_1 and N_2 signal-to-noise ratio is 80 (more than N_3 (20)) and thereafter, network N_1 is selected for handover. Similarly, in TOPSIS handover, decision change from network N_3 to network N_1 happens at the signal-to-noise ratio weight 0.16. Whereas, SAW and GRA are not sensitive to the variations of weight of signal-to-noise ratio attribute and the selected network for handover is network N_1.

- Dwell Time: To dwell time weight variations, SI-MAAR and TOPSIS selects network N_3, SAW and GRA select network N_1. SI-MAAR and classical MADM methods are not sensitive towards variations of dwell time attributes weight.

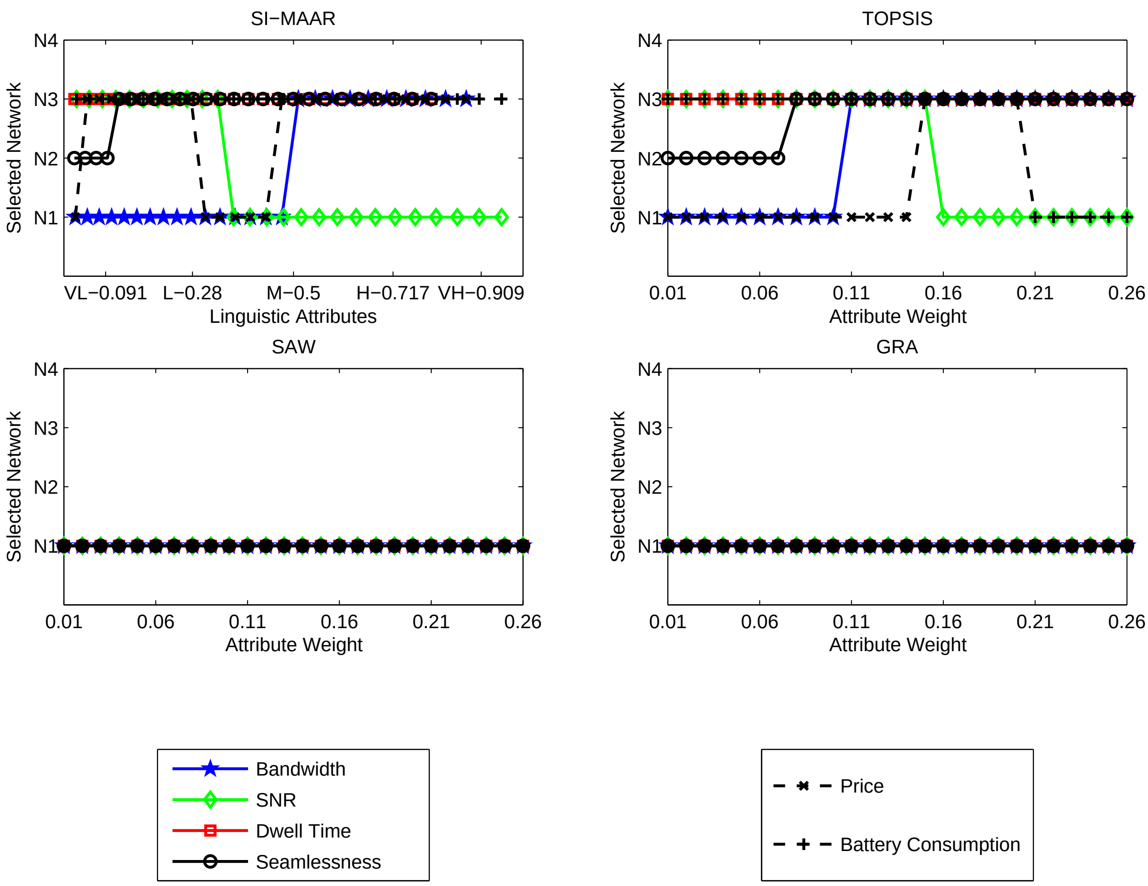


Figure 5.11: Network selection sensitivity of SI-MAAR and classical MADM methods to variations of attributes weight of voice application

- Seamlessness: To seamlessness attribute weight variations, SI-MAAR selects network N_2 for crisp value c_4 less than 0.1198 and thereafter, network N_3 is selected for handover. Similarly, TOPSIS selects network N_2 based on seamlessness attribute weight less than 0.08 and thereafter, network N_3 is selected for handover. Whereas, SAW and GRA are not sensitive to the variations of seamless attribute weight and the selected network for handover is network N_1.

- Price: For price attribute crisp value c_5 or weight w_5 variations, SI-MAAR and TOPSIS select initially network N_1 and then network N_3 for handover. Whereas, SAW and GRA are not sensitive towards the variations of weight of price attribute and the selected network for handover is network N_1.

- Battery Consumption: SI-MAAR is not sensitive to battery consumption crisp value c_6 variations, and it selects only network N_3 for handover. In TOPSIS, handover decision changes from network N_3 to N_1. Whereas, SAW and GRA are not sensitive to the variations of weight of battery consumption attribute and the selected network for handover is network N_1.

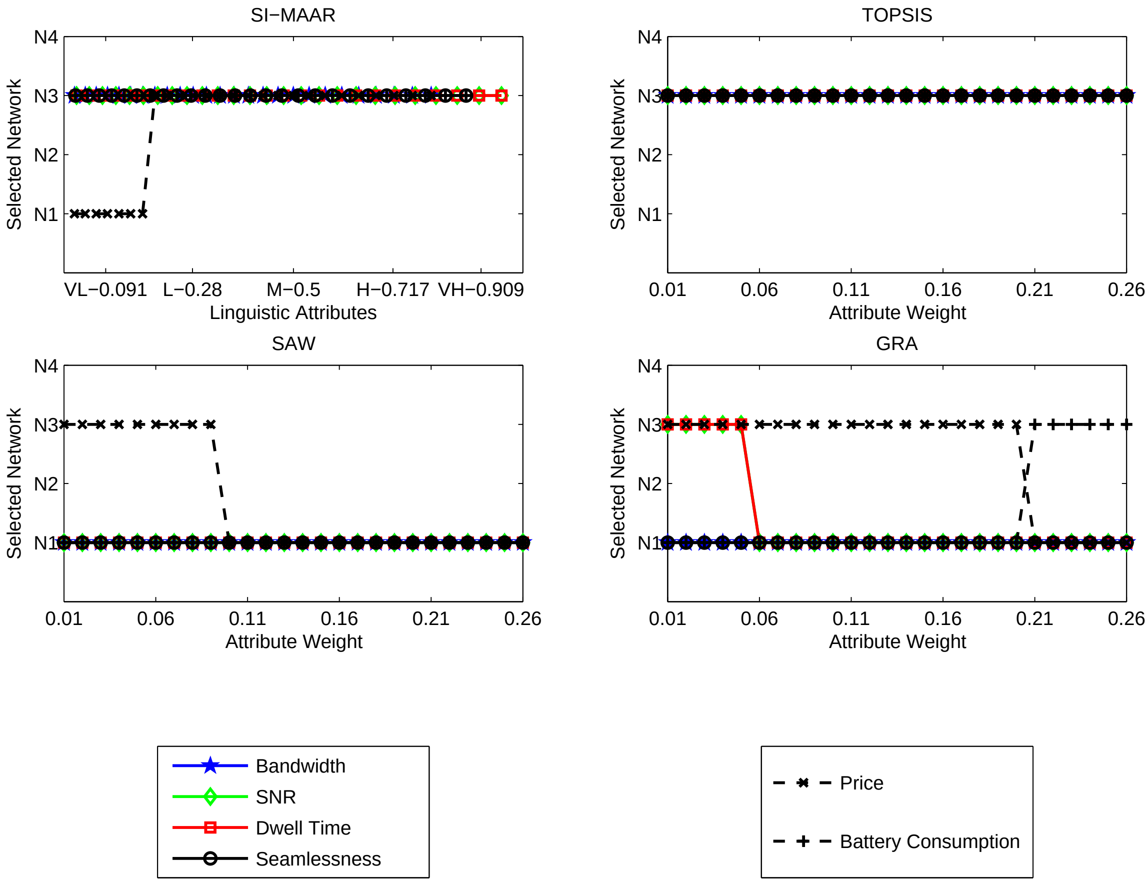


Figure 5.12: Network selection sensitivity of SI-MAAR and classical MADM methods to variations of attributes weight of download application

Analysis of Figure 5.12 for download application:

- Bandwidth: For variations of the bandwidth attribute crisp value c_1 and attribute weight w_1, network N_3 is selected for handover in SI-MAAR and TOPSIS. The main reason behind selecting network N_3 in SI-MAAR and TOPSIS is due to the higher weight a_{35} of cost attribute, which is less than that for networks N_1, N_2, and N_4. Whereas, SAW and GRA are not sensitive to the variations of weight of the bandwidth attribute and the selected network for handover is network N_1. Finally, SI-MAAR and classical MADM methods are not sensitive to variations of the bandwidth attribute crisp value and attribute weight of download application.

- Signal-to-Noise: For variations of signal-to-noise ratio attribute crisp value c_2 and attribute weight w_2, similar results of variations to bandwidth attribute crisp value and attribute weight in SI-MAAR, TOPSIS, SAW and GRA can be observed. Finally, SI-MAAR and classical MADM methods are not sensitive to variations of signal-to-noise ratio attribute crisp value or the attributes weight of download application.

- Dwell time: For variations of dwell time attribute crisp value c_3 and attribute weight w_3, only GRA is sensitive and SI-MAAR, TOPSIS and SAW are insensitive. In GRA, initially network N_3 and subsequently network N_1 is selected for handover.

- Seamlessness: All four methods SI-MAAR, TOPSIS, SAW and GRA, are insensitive to variations of seamlessness attribute crisp value c_4 and attribute weight w_4. Although, selected network for handover in SI-MAAR and TOPSIS is different from SAW and GRA.

- Price: Besides TOPSIS, other three methods: SI-MAAR, SAW and GRA are highly sensitive to variations of price attribute c_5 and attribute weight w_5.

- Battery consumption: Only SAW and GRA is sensitive to variations of battery consumption attribute crisp value c_6 and attribute weight w_6.

C Network Selection Sensitivity of SI-MAAR and classical MADM methods for Variations in Network Attributes

This subsection compares network selection sensitivity of SI-MAAR with the classical MADM methods to the variations of an individual network's individual attribute value one at a time through minimum - 0 to maximum - 100, 100, 1, 1, 10, 1 for bandwidth, signal-to-noise ratio, dwell time, seamlessness, price and battery consumption respectively in relation to network versus attribute a_{ij} (see Table 5.7). One network's one attribute value is varied from minimum to maximum with other attributes value as shown in Table 5.7. Similarly, expected objective attributes e_j and attributes weight

w_j of voice and download applications used in this study are shown in Table 5.5 and Table 5.9 respectively.

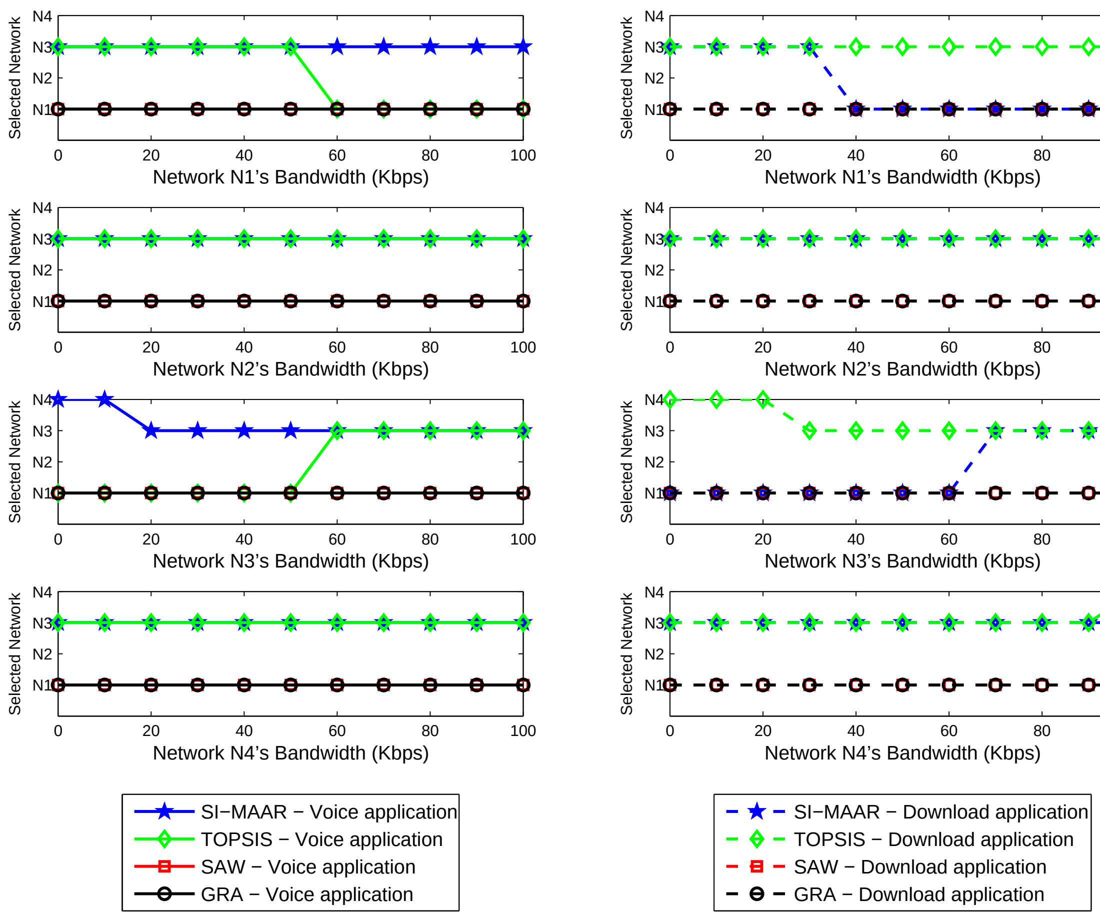


Figure 5.13: Network selection sensitivity of SI-MAAR and classical MADM methods to voice and download applications for variations of a_{i1}

As shown in Figures 5.13 - 5.18, lines in each subgraph illustrate the network selection sensitivity of SI-MAAR, TOPSIS, SAW and GRA for the variations of individual network's individual attribute value in relation to Table 5.7 to voice and download applications expected objective attributes and attributes weight as shown in Table 5.5 and Table 5.9 respectively.

Figure 5.13 shows the network selection sensitivity of SI-MAAR and classical MADM methods to voice and download applications for variations of the bandwidth attribute (a_{i1}) of the four networks. As shown in the Figure 5.13, for voice application SI-MAAR is sensitive to network N_3 and TOPSIS for networks' N_1 and N_3 bandwidth variations. Similarly, for download application, SI-MAAR is sensitive to networks' N_1

and N_3, and TOPSIS for networks' N_3 and N_4 bandwidth variations. Whereas, SAW and GRA are insensitive to bandwidth variations of any network.

To summarize, following are the observations about selected network for handover in SI-MAAR to voice and download applications:
Voice application:

- Network N_3 is selected for network N_1 bandwidth attribute variations in the range of 0-50 and subsequently network N_1. Network N_3 is selected for networks' N_2 and N_4 bandwidth variations in the range 0-100. Whereas, network N_4 is selected for network N_2 bandwidth variations in the range of 0-10 and subsequently network N_3.

Download application:

- Network N_3 is selected for network N_1 bandwidth variations in the range of 0-30 and subsequently network N_1. Similarly, for networks' N_2 and N_4 bandwidth variation in the range of 0-100, network N_3 is selected for handover. Whereas, network N_1 is selected for network N_3 bandwidth variations in the range of 0-60 and subsequently network N_3.

Figure 5.14 shows the network selection sensitivity of SI-MAAR and classical MADM methods: TOPSIS, SAW and GRA to voice and download applications for variations of signal-to-noise ratio attribute (a_{i2}) of networks N_1, N_2, N_3 and N_4. As shown in the Figure 5.14, for voice application, SI-MAAR is sensitive to networks' N_3 and N_4 signal-to-noise ratio variations, whereas TOPSIS, SAW and GRA are insensitive. Similarly, for download application, SI-MAAR is sensitive for all four networks' N_1, N_2, N_3 and N_4, and GRA for networks' N_1 and N_3 signal-to-noise ratio variations. Whereas, TOPSIS and SAW are not sensitive to signal-to-noise variations of any network.

To summarize, following are the observations about selected network for handover in SI-MAAR to voice and download applications:
Voice application:

- Network N_3 is selected for networks' N_1 and N_2 signal-to-noise ratio variations in the range of 0-100. Similarly, for network N_3 signal-to-noise ratio variations in

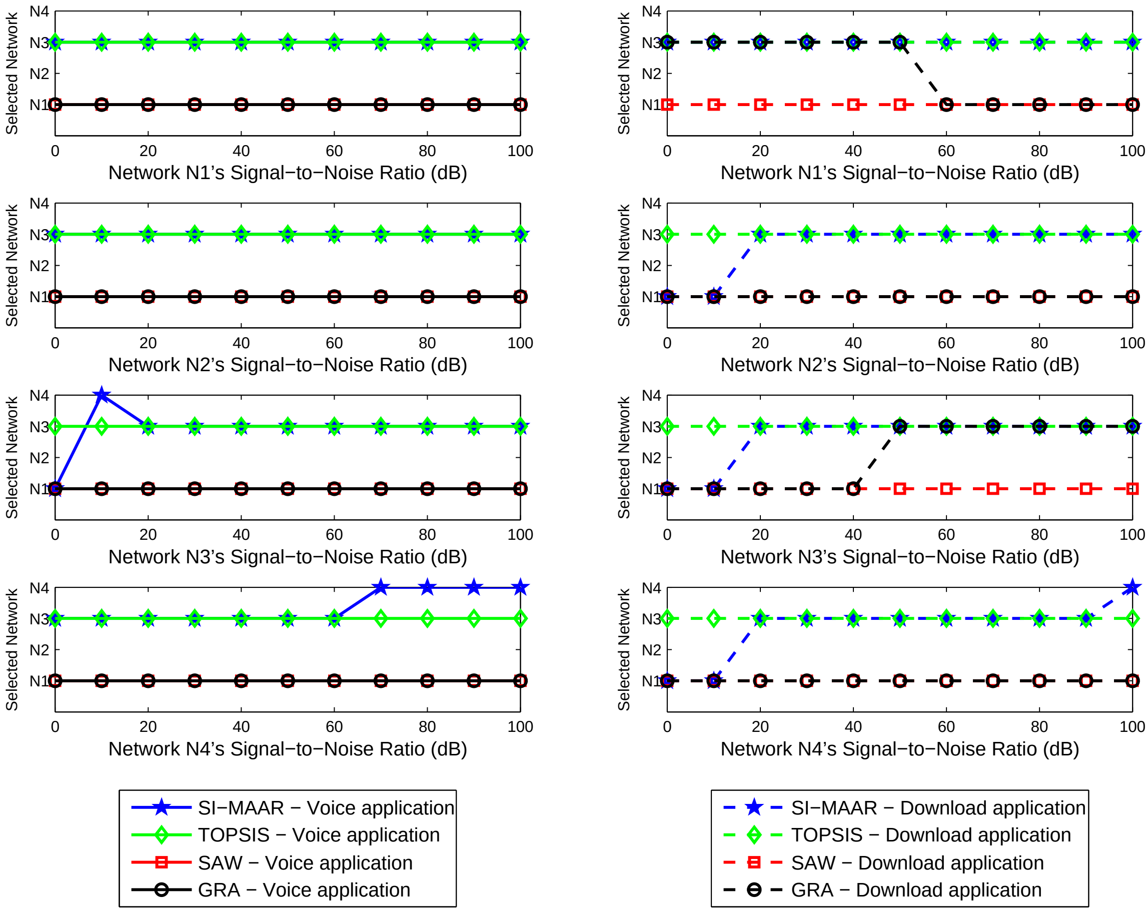


Figure 5.14: EPS-Network selection sensitivity of SI-MAAR and classical MADM methods to voice and download applications for variations of a_{i2}

the range of 0-10, initially network N_1, thereafter network N_4 and subsequently network N_3 is selected for handover. Whereas, for network N_4 signal-to-noise ratio variations in the range of 0-60, network N_3 and subsequently network N_4 is selected for handover.

Download application:

- Network N_3 is selected for network N_1 signal-to-noise ratio variations in the range of 0-100. Similarly, for networks' N_2 and N_3 signal-to-noise ratio variations in the range of 0-10, network N_1 and subsequently network N_3 is selected for handover. Whereas, for network N_4 signal-to-noise ratio variations in the range of 0-10, 20-90 and 90 onwards networks N_1, N_3 and N_4 respectively are selected for handover.

Figure 5.15 shows the network selection sensitivity of SI-MAAR and classical MADM methods: TOPSIS, SAW and GRA to voice and download applications for

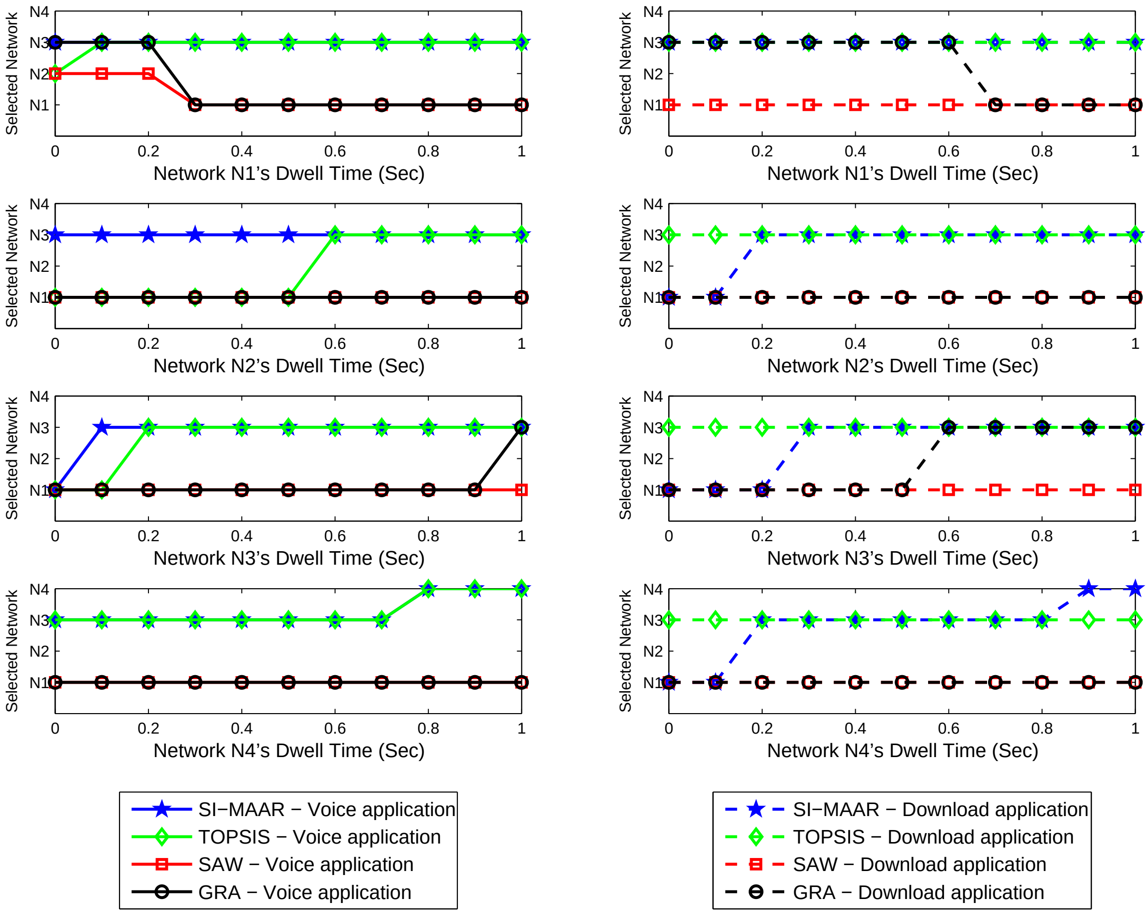


Figure 5.15: Network selection sensitivity of SI-MAAR and classical MADM methods to voice and download applications for variations of a_{i3}

variations of dwell time attribute (a_{i3}) of networks N_1, N_2, N_3 and N_4. As shown in the Figure 5.15, for voice application, SI-MAAR is sensitive to networks' N_3 and N_4, TOPSIS for all four networks' N_1, N_2, N_3 and N_4, SAW for network N_1 and GRA for networks' N_1 and N_3 dwell time variations. Similarly, for download application, SI-MAAR is sensitive to networks' N_2, N_3 and N_4 and GRA to networks' N_1 and N_3 dwell time variations. Whereas, TOPSIS and SAW are not sensitive to dwell time variations of any network. To summarize, following are the observations about selected network for handover in SI-MAAR to voice and download applications:

Voice application:

- Network N_3 is selected for networks' N_1 and N_2 dwell time variations in the range of 0-1. Similarly, for N_3 dwell time in the range of 0-0.1, network N_1 and subsequently network N_3 is selected for handover. Whereas, for N_4 dwell time in the range of 0-0.7, N_3 and subsequently network N_4 is selected for handover.

Download application:

- Network N_3 is selected for network N_1 dwell time variations in the range of 0-1. Similarly, for networks' N_2 and N_4 dwell time variations in the range of 0-0.1, network N_1 and subsequently network N_3 is selected for handover. Additionally, for network N_4 dwell time variations above 0.8, network N_4 is selected for handover. Whereas, for network N_3 dwell time variations in the range of 0-0.2, network N_1 and subsequently network N_3 is selected for handover.

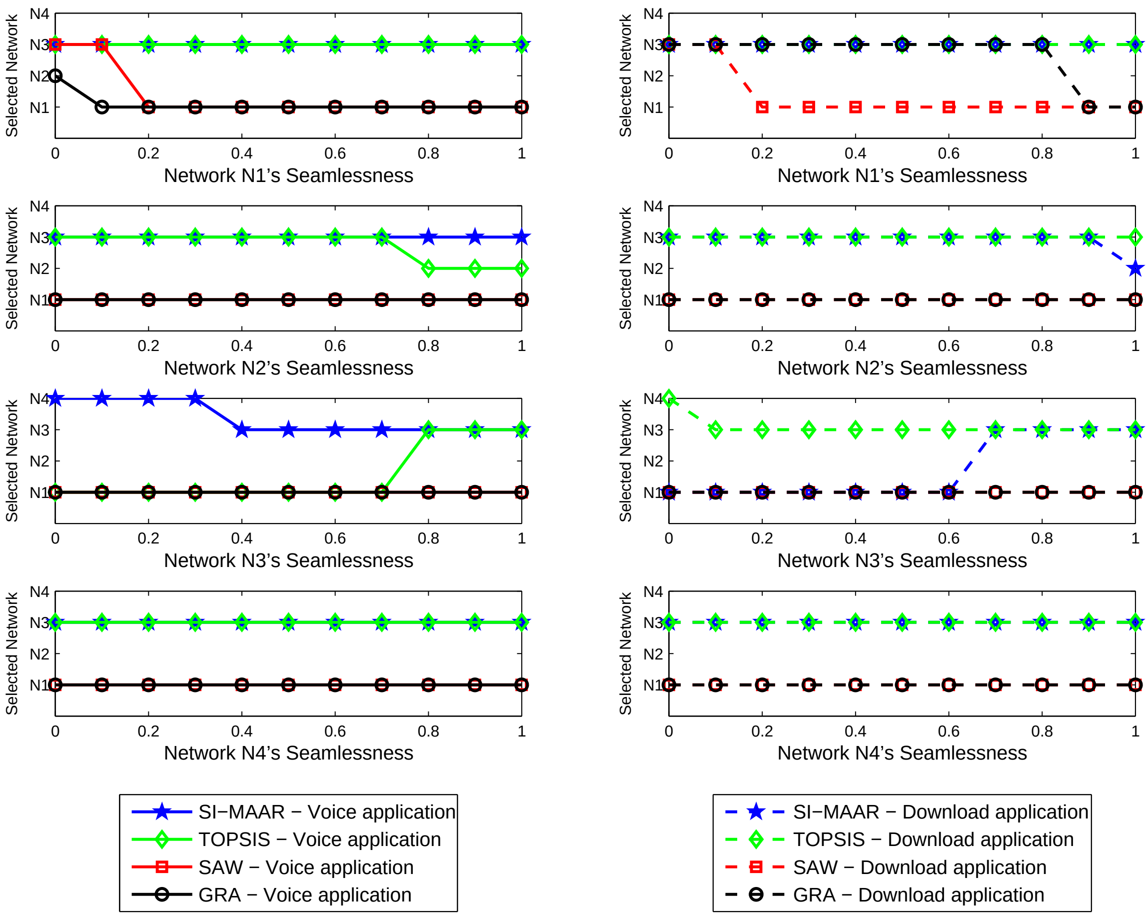


Figure 5.16: Network selection sensitivity of SI-MAAR and classical MADM methods to voice and download applications for variations of a_{i4}

Figure 5.16 shows the network selection sensitivity of SI-MAAR and classical MADM methods: TOPSIS, SAW and GRA to voice and download applications for variations of seamlessness attribute (a_{i4}) of networks N_1, N_2, N_3 and N_4. As shown in the Figure 5.16, for voice application, SI-MAAR is sensitive to network N_3, TOPSIS for network N_2 and N_3, SAW and GRA for network N_1 seamlessness variations.

Similarly, for download application, SI-MAAR is sensitive to networks' N_2 and N_3, TOPSIS for network N_3, SAW and GRA for network N_1 seamlessness variations. To summarize, following are the observations about selected network for handover in SI-MAAR to voice and download applications:

Voice application:

- Network N_3 is selected for networks' N_1, N_2 and N_4 seamlessness variations in the range of 0-1. Whereas, network N_4 is selected for network N_3 seamlessness variations in the range of 0-0.3 and subsequently network N_3 is selected for handover.

Download application:

- Network N_3 is selected for networks' N_1, N_2 and N_4 seamlessness variations in the range of 0-1. Whereas, network N_1 is selected for network N_3 seamlessness variations in the range of 0-0.6 and subsequently network N_3 is selected for handover.

Figure 5.17 shows the network selection sensitivity of SI-MAAR and classical MADM methods: TOPSIS, SAW and GRA to voice and download applications for variations of price attribute (a_{i5}) of networks N_1, N_2, N_3 and N_4. As shown in the Figure 5.17, for voice application, SI-MAAR is sensitive to all the four networks, TOPSIS for networks' N_1, N_3 and N_4, and SAW for network N_1 price variations. Whereas, GRA is not sensitive to price variations of any network. Similarly, for download application, SI-MAAR is sensitive to all the four networks, TOPSIS for network N_3, SAW for networks' N_1 and N_3, and GRA for networks' N_1, N_3 and N_4 price variations. To summarize, the following are the observations about the selected network for handover in SI-MAAR to voice and download applications:

Voice application:

- To network N_1 price variations in the range of 0-5 and 6-10, networks N_1 and N_3 are selected for handover respectively. Similarly, to networks' N_2 and N_4 price variations above 1\$, network N_3 is selected for handover and below 1\$ networks N_2 and N_4 are selected for networks' N_2 and N_4 price variations. Whereas, network 3 bandwidth variations in the range of 0-2, network N_3 and subsequently network N_1 is selected for handover.

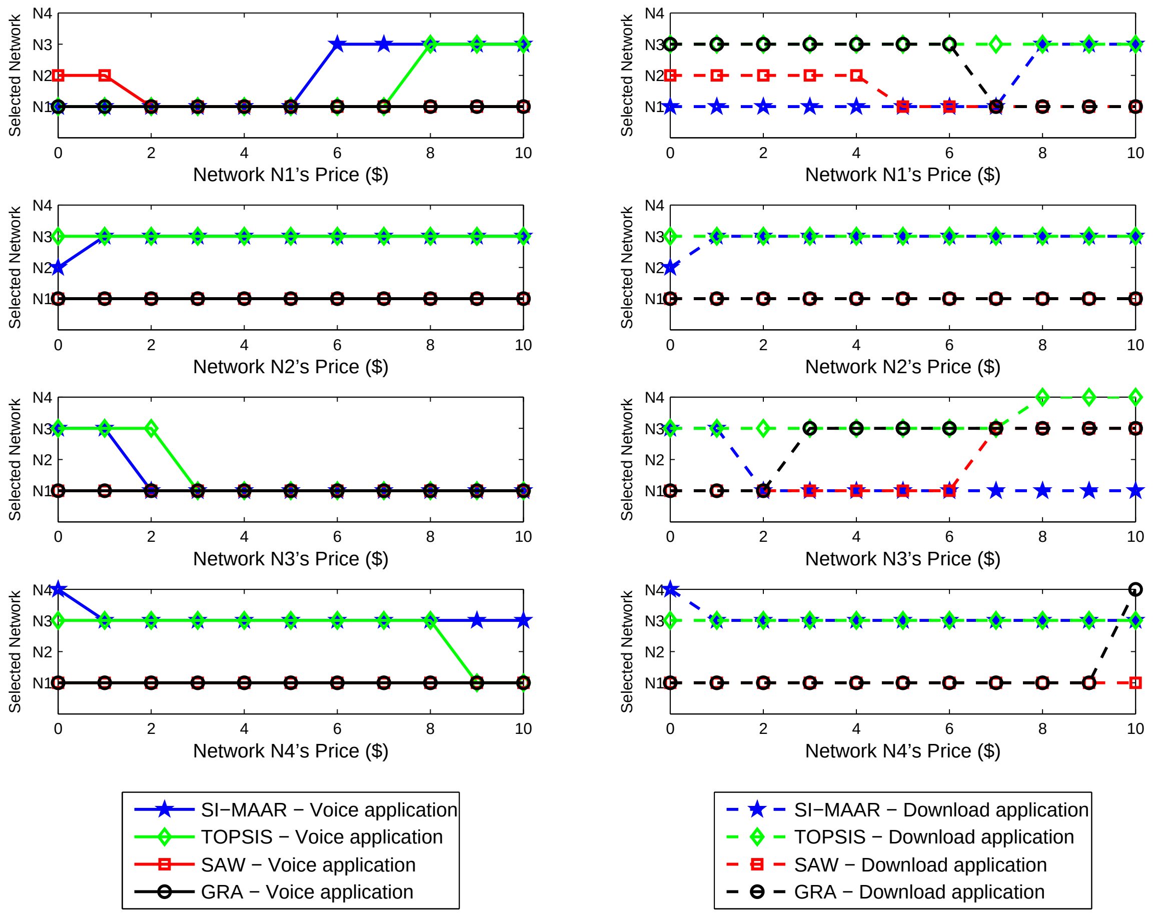


Figure 5.17: Network selection sensitivity of SI-MAAR and classical MADM methods to voice and download applications for variations of a_{i5}

Download application:

- Handover decision of SI-MAAR is very sensitive to all four networks price variations. To network N_1 price variations in the range of 0-7, network N_1 and subsequently network N_3 is selected for handover. Similarly, to networks' N_2 and N_4 price variations above 1$, network N_3 is selected for handover and below 1$ networks N_2 and N_4 are selected for networks' N_2 and N_4 price variations. Whereas, network 3 bandwidth variations in the range of 0-2, network N_3 and subsequently network N_1 is selected for handover.

Figure 5.18 shows the network selection sensitivity of SI-MAAR and classical MADM methods: TOPSIS, SAW and GRA to voice and download applications for variations of battery consumption attribute (a_{i6}) of networks N_1, N_2, N_3 and N_4. As shown in the Figure 5.18, for voice application, SI-MAAR is sensitive to networks' N_1, N_2 and N_4 battery consumption variations. Whereas, TOPSIS, SAW and GRA is not

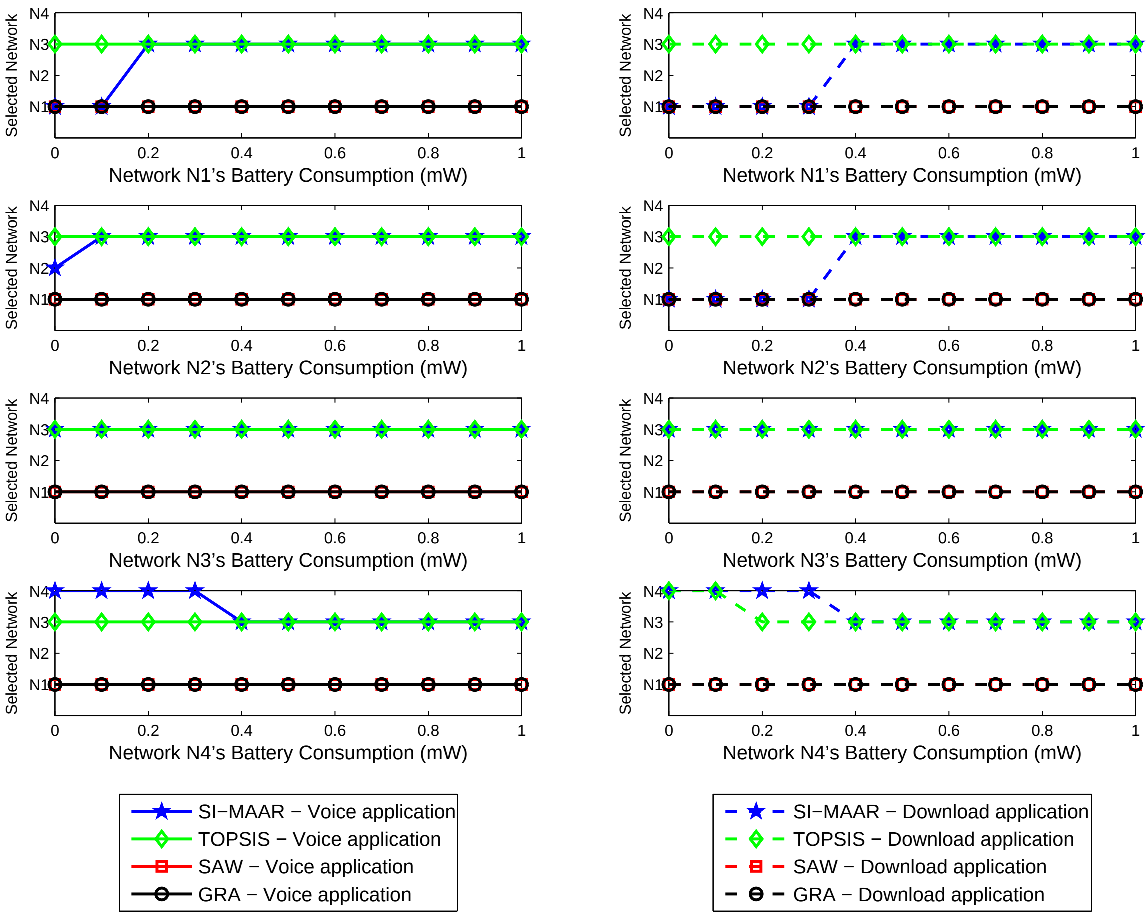


Figure 5.18: Network selection sensitivity of SI-MAAR and classical MADM methods to voice and download applications for variations of a_{i6}

sensitive to battery consumption variations of any network. Similarly, for download application, SI-MAAR is sensitive to networks' N_1, N_2 and N_4, and TOPSIS for network N_4 battery consumption variations. Whereas, SAW and GRA is not sensitive to battery consumption variations of any network. To summarize, following are the observations about selected network for handover in SI-MAAR to voice and download applications:

Voice application:

- For networks' N_2 and N_3 battery consumption variations in the range of 0-1, network N_3 is selected for handover. Similarly, to network N_1 battery consumption variations in the range of 0-1, network N_1 and subsequently network N_3 is selected for handover. Whereas, to network N_4 battery consumption variations in the range of 0-3, network N_4 and subsequently network N_3 is selected for handover.

Download application:

- To networks' N_1 and N_2 battery consumption variations in the range of 0-0.3, network N_1 and thereafter network N_3 is selected for handover. Similarly, to network N_3 battery consumption variations in the range of 0-1, network N_3 itself is selected for handover. Whereas, to network N_4 battery consumption variations in the range of 0-0.3, network N_4 and thereafter, network N_3 is selected for handover.

5.4 Summary

To summarize, in this chapter of the thesis, Section 5.1 presented the Simplified and Improved Multiple Attributes Alternate Ranking (SI-MAAR) method of eliminating attributes normalization and weight computation dependency. Section 5.2 demonstrated 100% reliable network selection and 0% rank reversal problem of SI-MAAR in comparison with the classical MADM methods. Finally, Section 5.3 demonstrated the network selection sensitivity of SI-MAAR in comparison with the classical MADM methods to voice and download applications.

Overall, Chapter 5 demonstrated that, the SI-MAAR method is one of the best replacements for the existing classical MADM methods, not only applicable to the field of heterogeneous wireless networks, but also for the other fields where classical MADM methods are widely used in real life.

The following chapter presents the deployment of simple and cost-effective Mobile IPv6 testbed for the study of handover execution.

Chapter 6

Development of Simple and Cost-Effective Mobile IPv6 Testbed

The main contributions of the thesis are SI-AHP and SI-MAAR presented in Chapter 4 and Chapter 5 respectively. Further, verification of SI-MAAR and SI-AHP in NS2 is started using ES-UDP tool presented in Chapter 3. Additionally, SI-MAAR and SI-AHP verification with the testbed is also began using Linux-based MIPv6 testbed. This chapter of the thesis presents the details about the deployment of simple and cost-effective Mobile IPv6 (MIPv6) testbed for the study of handover execution in homogeneous and heterogeneous wireless networks (HWNs).

The core issue in HWNs testbed deployment is handover (handoff) execution, preceded by handover decision and handover information gathering (Kassar et al. 2008). Handover execution is the process of switching the ongoing session of a Mobile Node (MN) from the present accessing network to the new accessible network for seamless communication. The Handover process may be a result of weak received signal strength of the present accessing network or better Quality of Service (QoS) attributes of the newly accessible networks to the MN. MIPv6 [1] is one of the network layer protocols used by MNs for handover execution in homogeneous and HWNs.

The major problem with the MIPv6 testbed available in the literature is the lack of detailed testbed deployment information, testing checkpoints and debugging procedures. The main challenges in any testbed deployment are its complexity, cost and time. This motivated us to propose a detailed simple and cost-effective Linux-based MIPv6 testbed deployment procedure, enabling the research community to use the same for realistic results.

[1] RFC 6275-Mobility Support in IPv6. Available: `http://www.ietf.org/rfc/rfc6275.txt`

The main contributions in this chapter are:

- Detailed explanation of deploying a simple and cost-effective Linux-based Mobile IPv6 testbed with testing checkpoints and debugging procedures
- An analysis of TCP and UDP-based applications in Mobile IPv6 testbed
- A comparison of Mobile IPv6 testbed results with network simulator NS2 simulation results.

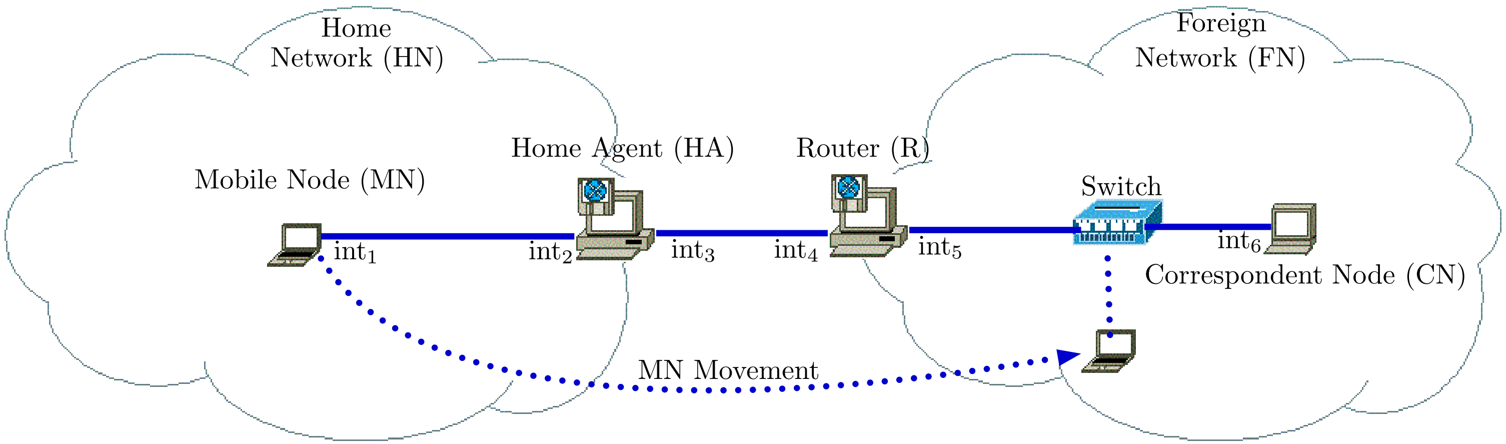
The rest of the chapter is organized as follows: Section 6.1 presents an overview of MIPv6; Section 6.2 presents the deployment of a simple and cost-effective Linux-based MIPv6 testbed with testing checkpoints and debugging procedures; Section 6.3 illustrates the performance analysis of deployed MIPV6 testbed and NS2 simulation for TCP and UDP-based applications. Finally, the summary is given in Section 6.4.

6.1 Mobile IPv6 Overview

Mobile IPv6 is a network layer protocol that supports seamless handover of MNs between accessible networks. A MN which supports MIPv6 maintains the continuity of ongoing communication with the other communicating node (it may be a source or destination) referred to as a Correspondent Node (CN) even after the MN changes its Point of Attachment (PoA). To support seamless communication, a MN is identified in the entire network by the permanent Home Address (HoA) and a Foreign Network (FN) dependent Care of Address (CoA); CoA varies when MN changes its PoA. When the handover of MN occurs to a new accessible network, it updates its CoA using the Binding Update (BU) message to the Home Agent (HA) of the Home Network (HN) to which MN belongs. Further, HA responds to the MN's BU message using Binding Acknowledgement (BA) message. If a MN handover to a newly accessible network during communication with the CN, the MN also updates its CoA with the CN using BU message followed by a BA message sent by the CN to MN, thereby avoiding triangular routing [2] of the packets. The entire handover message exchange between the HA, MN and CN can also be protected by the IP Security (IPsec) [3].

[2]RFC 3775-Mobility Support in IPv6. Available: `http:https://www.ietf.org/rfc/rfc3775.txt`

[3]RFC 4877-Mobile IPv6 Operation with IKEv2 and the Revised IPsec Architecture. Available: `http://www.ietf.org/rfc/rfc4877.txt`



int_1 (eth0): 2001:db8:aaaa:3:72f3:95ff:fe14:58c1
2001:db8:aaaa:3::2 (HoA)
2001:db8:aaaa:1:72f3:95ff:fe14:58c1 (CoA)
int_2 (eth0): 2001:db8:aaaa:3::1
int_3 (eth1): 2001:db8:aaaa:2::2

int_4 (eth0) 2001:db8:aaaa:2::1
int_5 (eth1): 2001:db8:aaaa:1::1
int_6 (eth0): 2001:db8:aaaa:1:72f3:95ff:fe0c:e4d4

Figure 6.1: MIPv6 testbed set-up

6.2 MIPv6 Testbed Set-up

Figure 6.1 shows the entities of MIPv6 testbed set-up such as, MN, HA, Router (R) and CN deployed using low-end desktops. Table 6.1 shows the hardware and software specifications of the testbed entities with the approximate cost of the entire set-up excluding the low-end desktops being 42$.

Table 6.1: MIPv6 testbed specifications

Entity	**Hardware**	**Software**
Mobile Node (MN) and Correspondent Node (CN)	Intel Core i7 CPU 870@2.93 GHz, Intel 82578DM Gigabit Ethernet (eth0).	Ubuntu 12.04, Kernel 3.8.2, 32-bit OS, Jperf 2.0.2, Wireshark 1.6.7
Home Agent (HA) and Router (R)	Intel Core i7 CPU 870@2.93 GHz, Intel 82578DM Gigabit Ethernet (eth0), Realtek RTL-8139/8139C/8139c+ (eth1).	
Switch	Netgear 10/100 Mbps Fast Ethernet (FS608)	

As shown in Figure 6.1, interfaces of the testbed entities HA (int_2 and int_3) and R (int_4 and int_5) are configured with the static global IPv6 address, and interfaces of the entities MN (int_1) and CN (int_6) are dynamically configured with the IPv6 addresses through Stateless Address Autoconfiguration using the advertised prefix of HA and R [4]. The mobility of the MN is introduced manually by disconnecting the MN's interface (int_1) from HN and connecting it to the switch in the FN. The deployment of HA, R, MN and CN are explained as follows.

6.2.1 MIPv6 Testbed Configuration

Figure 6.2 illustrates the detailed flow of the MIPv6 testbed entities deployment. As shown in Figure 6.2, the first step in the MIPv6 testbed deployment is to enable MIPv6 in Linux kernel, followed by configuring UMIP in each entity [5]. UMIP (**U**sagi Patched **M**obile **IP**v6 Stack) is the MIPv6 implementation for the Linux kernel. After the successful execution of the first step, entities in the testbed are ready (presence of the MIPv6 daemon: *mip6d*) for the next step of deployment, i.e., configuring the interface in MN, HA, R and CN, and routing table in HA and R. After this step, the

[4] RFC 862-IPv6 Stateless Address Autoconfiguration. Available: `https://tools.ietf.org/html/rfc4862`

[5] UMIP - Mobile IPv6 and NEMO for Linux. Available: `http://umip.org/`

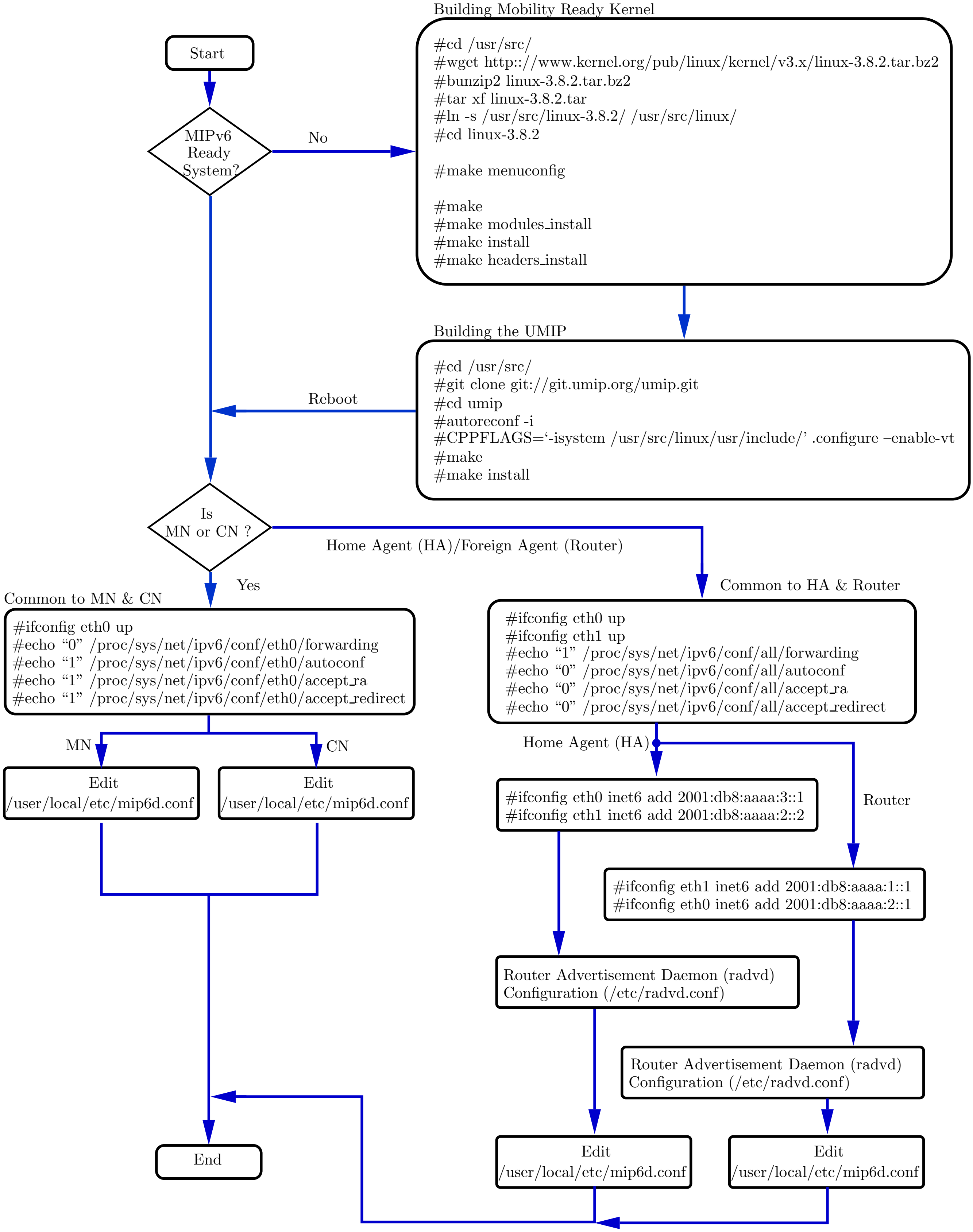


Figure 6.2: Steps of MIPv6 Testbed Configuration in Linux

entities in the set-up should be able to *ping* each other with their IPv6 addresses. This is a very important checkpoint of the testbed to proceed further with the remaining steps of the deployment. The following subsections explain the remaining steps of the testbed deployment, which are unique with respect to each of the entities.

6.2.2 Router Advertisement Daemon (*radvd*)

This subsection explains the router advertisement daemon (*radvd*) configuration in HA and R [6]. The purpose of the router advertisement daemon is to broadcast the router prefix at regular intervals which will be used by the MN and CN to self-configure IPv6 address using their respective 48-bit MAC address. The IPv6 address generated by the MN or CN being in the foreign network is referred to as Care of Address (CoA). As shown in Figure 6.1, FN for MN is the HN for CN. Similarly, the CoA of the MN represents the present location of the MN in the entire network. Successful execution of the *radvd* in HA and R can be verified by executing the command *radvdump* [7] in HA and R.

Table 6.2 shows one of the router advertisement daemon (*radvd*) configuration file (*radvd.conf*) of HA and R for the testbed shown in Figure 6.1.

The option 'AdvSendAdvert' indicates whether or not the router should send periodic router advertisements and responds to router solicitations. 'AdvIntervalOpt' indicates the router advertisement interval's minimum (MinRtrAdvInterval) and maximum (MaxRtrAdvInterval) value in sec. 'AdvHomeAgentFlag' indicates that the router advertisement sending router is able to serve as a MIPv6 Home Agent with the HA information option 'AdvHomeAgentInfo'. 'HomeAgentPreference' indicates the preference (integer) of the HA by sending this router advertisement with the lifetime 'HomeAgentLifetime' (sec).

With the 'AdvRouterAddr', the address of the interface is sent instead of the network prefix with the lifetime 'AdvValidLifetime' (sec). Further, this is used for on-link determination 'AdvOnLink' with autonomous address configuration 'AdvAutonomous'. 'AdvPreferredLifetime' indicates the lifetime of the generated IPv6 address by the MN and CN through Stateless Address Autoconfiguration in sec.

[6] Ubuntu manuals. Available: `http://manpages.ubuntu.com/manpages/utopic/man5/radvd.conf.5.html`

[7] radvdump. Available: `http://www.linuxcommand.org/man_pages/radvdump8.html`

Table 6.2: *radvd.conf* in HA (int_2) and R (int_5)

Home Agent (HA)	**Router (R)**
# cat /etc/radvd.conf interface eth0 { *AdvSendAdvert on;* AdvIntervalOpt off; AdvHomeAgentFlag on; MaxRtrAdvInterval 3; MinRtrAdvInterval 1; HomeAgentLifetime 10000; HomeAgentPreference 20; AdvHomeAgentInfo on; prefix 2001:db8:aaaa:3::1/64 { *AdvRouterAddr on;* *AdvOnLink on;* *AdvAutonomous on;* AdvPreferredLifetime 10000; AdvValidLifetime 12000; }; };	# cat /etc/radvd.conf interface eth1 { *AdvSendAdvert on;* AdvIntervalOpt on; MinRtrAdvInterval 1; MaxRtrAdvInterval 3; AdvHomeAgentFlag off; prefix 2001:db8:aaaa:1::1/64 { *AdvOnLink on;* *AdvAutonomous on;* *AdvRouterAddr on;* }; };

'2001:db8:aaaa:3::1' and '2001:db8:aaaa:1::1' represents the IPv6 address of the HA interface (int_2) and R interface (int_5) during broadcasting the router advertisement by HA and R respectively.

The *radvd* configuration of the R is similar to HA, except that the options 'HomeAgentLifetime', 'HomeAgentPreference' and 'AdvHomeAgentInfo' are not defined in R. In the case of R as a HA in the FN, *radvd* configuration of R will be same as HA (Table 6.2).

6.2.3 MIPv6 Daemon (*mip6d*) Configuration without IPsec

The next very important step of the MIPv6 testbed deployment is configuring the MIPv6 daemon, i.e., *mip6d* [8]. This daemon is present in all MIPv6 enabled entities MN, CN, HA and R. In the testbed shown in Figure 6.1, *mip6d* is enabled in MN, CN and HA but not in R; since the MN belonging to HA is executing the handover in the deployed testbed and CN is stationary. The MIPv6 daemon *mip6d* focuses on

[8]mip6d.conf-Linux man page. Available: `http://linux.die.net/man/5/mip6d.conf`

handover execution and is essential in the entities which are involved in the handover execution procedure. The binding messages BU and BA are exchanged during handover execution and can be protected with IPsec using keys shared by the MN and HA. This subsection illustrates the *mip6d* configuration without IPsec represented by the option 'UseMnHaIPsec' in MN, HA and CN being *disabled* as shown in Table 6.3.

Table 6.3: *mip6d.conf* in MN, HA and CN without IPsec

Home Agent (HA)	**Correspondent Node (CN)**
# cat /usr/local/etc/mip6d.conf NodeConfig HA; DebugLevel 10; DoRouteOptimizationCN enabled; Interface "eth0"; UseMnHaIPsec disabled;	# cat /usr/local/etc/mip6d.conf NodeConfig CN; DebugLevel 10; DoRouteOptimizationCN enabled;
Mobile Node (MN)	
# cat /usr/local/etc/mip6d.conf NodeConfig MN; DebugLevel 10; DoRouteOptimizationCN enabled; Interface "eth0"; UseMnHaIPsec disabled; DoRouteOptimizationMN enabled; UseCnBuAck enabled; MnHomeLink "eth0" { HomeAgentAddress 2001:db8:aaaa:3::1; HomeAddress 2001:db8:aaaa:3::2/64; }	

Table 6.3 shows one of the MIPv6 daemon (*mip6d*) configuration file (*mip6d.conf*) of MN, HA and CN for the testbed shown in Figure 6.1.

'NodeConfig' indicates the role of the host as MN, HA or CN along with the interface of MN, CN and HA enabled for the route optimization using 'DoRouteOptimizationCN' by eliminating triangular routing of the packets without IP security indicated by 'UseMnHaIPsec' being *disabled* in MN and HA. This is followed by support for debug messages 'DebugLevel'. As shown in Table 6.3, in MN *mip6d.conf* file '2001:db8:aaaa:3::2' indicates the HoA (permanent) of the MN used by the other communicating devices in the network to communicate with the MN, in-spite of MN location is in HN or FN.

Table 6.4: *mip6d.conf* in HA and MN with IPsec

Home Agent (HA)	**Mobile Node (MN)**
# cat /usr/local/etc/mip6d.conf NodeConfig HA; DebugLevel 10; DoRouteOptimizationCN enabled; Interface "eth0"; *UseMnHaIPsec enabled;* *IPsecPolicySet {* *HomeAgentAddress 2001:db8:aaaa:3::1;* *HomeAddress 2001:db8:aaaa:3::2/64;* *IPsecPolicy HomeRegBinding UseESP;* *IPsecPolicy TunnelMh UseESP;* *}*	# cat /usr/local/etc/mip6d.conf NodeConfig MN; DebugLevel 10; DoRouteOptimizationCN enabled; Interface "eth0"; *UseMnHaIPsec enabled;* DoRouteOptimizationMN enabled; UseCnBuAck enabled; MnHomeLink "eth0" { HomeAgentAddress 2001:db8:aaaa:3::1; HomeAddress 2001:db8:aaaa:3::2/64; } *IPsecPolicySet {* *HomeAgentAddress 2001:db8:aaaa:3::1;* *HomeAddress 2001:db8:aaaa:3::2/64;* *IPsecPolicy HomeRegBinding UseESP;* *IPsecPolicy TunnelMh UseESP;* *}*

6.2.4 MIPv6 Daemon (*mip6d*) Configuration with IPsec

This subsection of the chapter presents configuration of IPsec for the secure communication of handover messages between MN, CN and HA. As shown in Table 6.4, '2001:db8:aaaa:3::2' represents the IPv6 HoA of the MN and '2001:db8:aaaa:3::1' represents the IPv6 HA address of the MN. During the handover of MN to FN, the binding update of the MN is saved in the HA with respect to the MN's HoA. The option 'IPsecPolicySet' defines the security association between HA and MN.

Table 6.5: Security association key between MN and HA

cat /usr/local/etc/sa.conf # IPsec MN ⟶ HA Transport mode (BU) add 2001:db8:aaaa:3::2 2001:db8:aaaa:3::1 esp 0001 -m transport -EA null; # IPsec HA ⟶ MN Transport mode (BA) add 2001:db8:aaaa:3::1 2001:db8:aaaa:3::2 esp 0002 -m transport -EA null; # IPsec MN ⟶ HA Tunnel mode (HoTI) add 2001:db8:aaaa:3::2 2001:db8:aaaa:3::1 esp 0016 -m tunnel -EA null; # IPsec HA ⟶ MN Tunnel mode (HoT) add 2001:db8:aaaa:3::1 2001:db8:aaaa:3::2 esp 0017 -m tunnel -EA null;

A Security Association Key

Table 6.5 shows security association file *sa.conf* of MN and HA indicating the keys used for the handover message (BU, BA, Home Test (HoT) and Home Test Initialization (HoTI)) exchanged between the MN and HA [9]. HoT and HoTI are the Home Test messages used by the MN to update its CoA with the CN. In Table 6.5, '-m' indicates security protocol mode, '-E' encryption and '-A' authentication algorithm.

6.2.5 Pre-testing of MIPv6 Testbed

Figure 6.3 shows the step-by-step procedure to start the MIPv6 testbed entities MN, HA, R and CN deployed as shown in Figure 6.1. As shown in Figure 6.3, after the successful configuration of all the entities and checking the communication between all the entities (using *ping*) with static IPv6 address, the first step is to start router advertisement daemon (*radvd*) in HA and R. After the successful execution of *radvd*, MN and CN interfaces are configured with dynamic IPv6 address. The next step is executing security association file and MIPv6 daemon (*mip6d*) in HA and MN. Successful execution of *mip6d* in MN and HA indicates the successful creation of a tunnel between HA and MN and can be observed in MN by using *ifconfig*.

Additionally, during the deployment of testbed, problems with the operating system, misconfiguration of related files and hardware (network card and LAN cable) failures result in many errors. As shown in Figure 6.3, 'C1' and 'C2' represent the possible places of checking error (checkpoints) occurs due misconfiguration of *radvd.conf*, *mip6d.conf* and *sa.conf* files, daemons are not under execution, and order of running the entities during testbed deployment and testing.

Causes for C1 errors:

- Misconfiguration of *radvd.conf*
- *radvd* being not under execution (or stopped)
- Routing table misconfiguration in HA and R
- Order in which interfaces in HA and R are active.

[9] Setkey-Linux man page. Available: `http://linux.die.net/man/8/setkey`

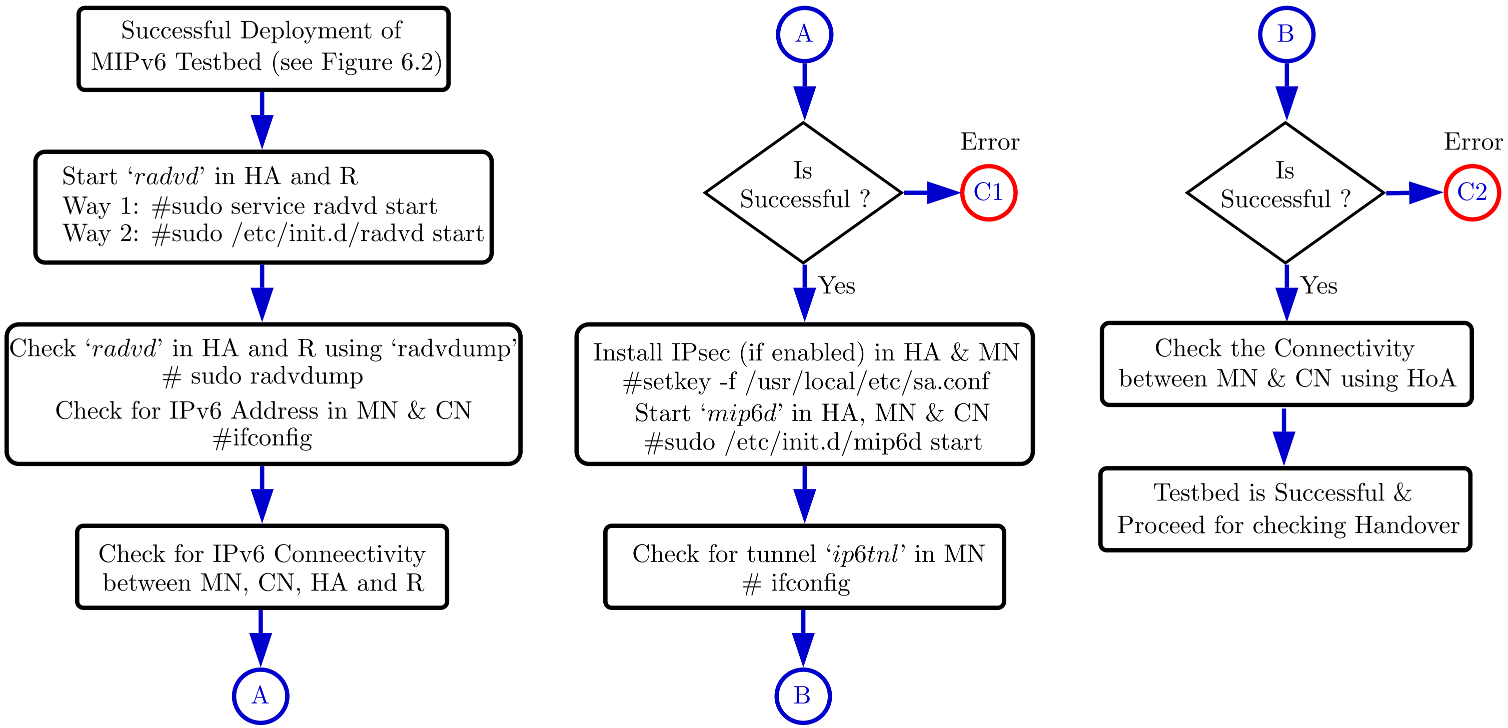


Figure 6.3: Pre-Testing of MIPv6 testbed

Causes for C2 errors:

- *mip6d* being stopped
- Misconfiguration of *mip6d.conf*,
- Order in which *mip6d* was started in MN, CN and HA.

Table 6.6: MN's interface configuration before handover

```
eth0      Link encap:Ethernet HWaddr 70:f3:95:14:58:c1
          inet6 addr: 2001:db8:aaaa:3:72f3:95ff:fe14:58c1/64 Scope:Global
          inet6 addr: 2001:db8:aaaa:3::2/64 Scope:Global
          inet6 addr: fe80::72f3:95ff:fe14:58c1/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST MTU:1500 Metric:1
          RX packets:248414 errors:1 dropped:0 overruns:0 frame:1
          TX packets:454393 errors:0 dropped:0 overruns:0 carrier:0
          collisions:7509 txqueuelen:1000
          RX bytes:59890219 (59.8 MB) TX bytes:410172850 (410.1 MB)
          Interrupt:20 Memory:fb300000-fb320000

ip6tnl1   Link encap:UNSPEC HWaddr 20-01-0D-B8-AA-AA-00-03-00-..
          inet6 addr: fe80::72f3:95ff:fe14:58c1/64 Scope:Link
          UP POINTOPOINT RUNNING NOARP MTU:1460 Metric:1
          RX packets:11 errors:0 dropped:0 overruns:0 frame:0
          TX packets:17 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:860 (860.0 B) TX bytes:13066 (13.0 KB)
```

Table 6.6 shows interface configuration details of the MN generated using *ifconfig* when the MN is in HN (before handover) with *mip6d* in MN is under execution. As shown in Table 6.6, 'ip6tnl1' represents the tunnel indicating the successful execution of *mip6d* in MN and HA. A very important point to be noted in Table 6.6 is that the HoA of MN '2001:db8:aaaa:3::2' is assigned to the interface 'eth0' when the MN is in the HN. The HoA is the permanent static IPv6 address of the MN used to communicate with MN when it is in HN or FN. Similarly, no global IPv6 address is assigned to the tunnel existing between MN and HA. Whereas, 'eth0' interface of MN is configured with two global IPv6 address i.e, HoA and stateless IPv6 address. The stateless IPv6 address changes as MN changes its PoA.

Note: Checking the existence of a tunnel and HoA with the 'eth0' are two key points indicating the successful execution of entity MN before the handover in MIPv6 testbed shown in Figure 6.1.

Table 6.7 shows interface configuration details of the MN generated using *ifconfig* when the MN is in FN (after handover) with *mip6d* in MN is under execution. As shown in Table 6.7, after MN handover to FN, HoA of the MN is used to identify the other end of the tunnel created between HA and MN. The tunnel between HN and MN is used to redirect the packets intended to MN when it is FN and also, this is the way packets are sent to MN after handover without route optimization (triangular routing). Similarly, the router prefix in the stateless global IPv6 address of 'eth0' is changed from HN router advertised prefix to FN.

Note: Checking the HoA of MN with IPv6 tunnel (ip6tnl1) and MN's interface 'eth0' with the new stateless global IPv6 address (CoA) are the two main key points indicating the successful execution of entity MN after handover in MIPv6 testbed shown in Figure 6.1

Table 6.7: MN's interface configuration after handover

```
eth0    Link encap:Ethernet HWaddr 70:f3:95:14:58:c1
        inet6 addr: 2001:db8:aaaa:1:72f3:95ff:fe14:58c1/64 Scope:Global
        inet6 addr: fe80::72f3:95ff:fe14:58c1/64 Scope:Link
        UP BROADCAST RUNNING MULTICAST MTU:1500 Metric:1
        RX packets:248444 errors:1 dropped:0 overruns:0 frame:1
        TX packets:454416 errors:0 dropped:0 overruns:0 carrier:0
        collisions:7509 txqueuelen:1000
        RX bytes:59893991 (59.8 MB) TX bytes:410178062 (410.1 MB)
        Interrupt:20 Memory:fb300000-fb320000

ip6tnl1  Link encap:UNSPEC HWaddr 20-01-0D-B8-AA-AA-00-01-00-..
        inet6 addr: 2001:db8:aaaa:3::2/128 Scope:Global
        inet6 addr: fe80::72f3:95ff:fe14:58c1/64 Scope:Link
        UP POINTOPOINT RUNNING NOARP MTU:1460 Metric:1
        RX packets:11 errors:0 dropped:0 overruns:0 frame:0
        TX packets:17 errors:0 dropped:0 overruns:0 carrier:0
        collisions:0 txqueuelen:0
        RX bytes:860 (860.0 B) TX bytes:13066 (13.0 KB)
```

Table 6.8: CN's binding cache after MN handover to FN

```
brc@CN: $ telnet localhost 7777
Trying 127.0.0.1...
Connected to localhost.
Escape character is '^]'.
mip6d> bc
mip6d> bc
hoa 2001:db8:aaaa:3:0:0:0:2 status cached
coa 2001:db8:aaaa:1:72f3:95ff:fe14:58c1 flags A- - -
local 2001:db8:aaaa:1:72f3:95ff:fe14:56c6
lifetime 414 / 420 seq 8774 unreach 0
mip6d>
```

Similarly, Table 6.8 shows the binding cache (*bc*) entries in CN (if MIPv6 enabled) after MN handover to FN. Using *telnet* with port '7777' *bc* entries in CN can be checked for BU received by CN after MN handover to FN as shown in Table 6.8. Similar results can also be observed in HA with *bc*.

Table 6.9: MN's BU list before and after handover

```
brc@MN: $ telnet localhost 7777
Trying 127.0.0.1...
Connected to localhost.
Escape character is '^]'.
mip6d> bul
mip6d> bul
== BUL_ENTRY ==
Home address    2001:db8:aaaa:3:0:0:0:2
Care-of address  2001:db8:aaaa:1:72f3:95ff:fe14:58c1
CN address      2001:db8:aaaa:3:0:0:0:1
lifetime = 11996, delay = 11396000
flags: IP6_MH_BU_HOME IP6_MH_BU_ACK
ack ready
lifetime 11990 / 11996 seq 58919 resend 0 delay 11396(after 11390s)
mps -1437558206 / 10796
== BUL_ENTRY ==
Home address    2001:db8:aaaa:3:0:0:0:2
Care-of address  2001:db8:aaaa:1:72f3:95ff:fe14:58c1
CN address      2001:db8:aaaa:1:72f3:95ff:fe14:56c6
lifetime = 420, delay = 420000
flags: IP6_MH_BU_ACK
ack ready RR state ready
lifetime 415 / 420 seq 36772 resend 0 delay 420(after 416s)
mip6d> bul
```

Further, Table 6.9 shows the binding update list (*bul*) entries in MN before and after the handover to FN. In MIPv6 enabled entities *mip6d* daemon (after its successful execution) runs at port '7777'. Using *telnet* with port '7777' *bul* entries in MN can be checked for BU sent to the HA and CN before and after the handover to FN as shown in Table 6.9. Execution of *bul* in MN with no results indicate the presence of MN in HN. In the case of MN communicating with CN during handover, *bul* results in to a details indicating the BU message sent to the HA and CN (if MIPv6 is enabled). Moreover, MN sends BU only to HA in the case of no communication with CN during handover.

Figure 6.4 shows the flow of binding message (BU and BA) exchange between MN, HA and CN captured using Wireshark after MN handover to FN. As shown in Figure 6.4, the first two messages (BU and BA) represent the MN is updating HA with the new CoA after MN handover to FN. The next four messages (HoT, HoTI, CoT and CoTI) exchanged between MN and CN indicate the procedure to check the authenticity of MN, before MN updates it's new CoA with the CN. After the successful exchange of HoT, HoTI, CoT and CoTI, MN updates its CoA with the CN to eliminate triangular routing of packets and this is also referred to as route optimization (RO).

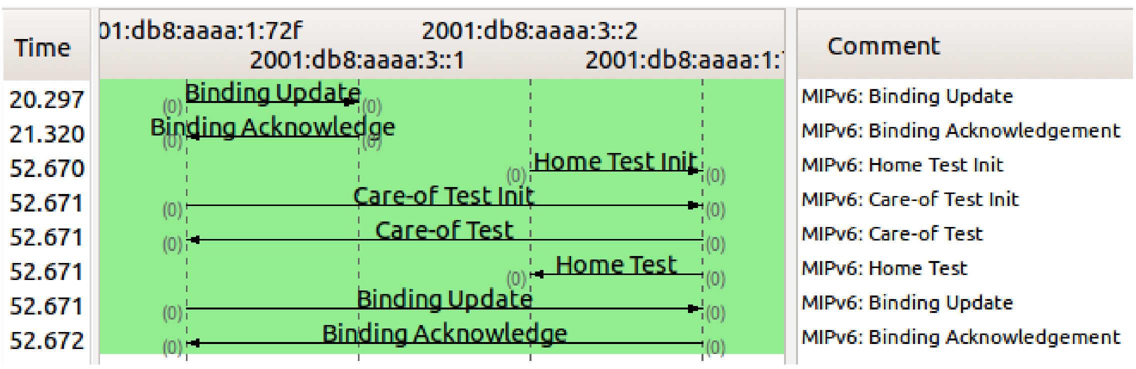


Figure 6.4: MIPv6 handover messages captured by Wireshark

Hence, the successful deployment of the MIPv6 testbed is completed. In the next section the deployed MIPv6 testbed is used to study performance metrics such as bandwidth, delay and jitter with respect to the TCP and UDP-based applications.

6.3 Results and Analysis

To study the performance of MIPv6 testbed with respect to TCP and UDP-based applications, tools such as *ping*, *jperf*, and Wireshark are used. Table 6.10 shows the performance of TCP and UDP-based applications in the MIPv6 testbed. As shown in Table 6.10 bandwidth, packet delay and jitter of TCP and UDP-based applications are obtained for before handover, after handover with RO and after handover without RO. After MN handover to FN, MN and CN being in the same network (FN), bandwidth is high after MN handover to FN with RO compared to before handover and handover without RO.

Table 6.10: Performance of TCP and UDP-based applications in MIPv6 testbed

Metrics	**MN's Location**	**Jperf TCP**	**Jperf UDP**
Bandwidth (Kbps)	Home Network	3353	499
	Foreign Network	5258	512
	Without RO	1082	282
Delay (ms)	Home Network	0.05	0.05
	Foreign Network	0.075	0.025
	Without RO	0.5	0.4
Jitter (ms)	Home Network	0.06	0.049
	Foreign Network	0.2	0.136
	Without RO	0.32	0.2

Table 6.11: Binding update delay comparisons of MIPv6 testbed and NS2 simulation

Environment	**Home Network To Foreign Network**		**Foreign Network To Home Network**	
	To HA	To CN	To HA	To CN
Testbed	1.017262 ms	1.108 ms	0.0208 s	2.485 ms
Simulation (UDP)	9 ms	9.78 ms	9.6 ms	9.11 ms
Simulation (TCP)	41.4 ms	27.3 ms	36 ms	45 ms

Further, the MIPv6 testbed topology is repeated in network simulator NS2 to compare testbed results with simulation results with respect to binding delay, i.e., the time taken to send BU and receive BA message. The NS2 simulation is carried out with the topology shown in Figure 6.1 for 1 KB packet size, 100 Kbps packet generation rate and the 0.01 sec packet interval. Further, the link bandwidth is 100 Mbps with propagation delay of 1.8 msec. Table 6.11 shows the comparison between MIPv6 testbed and NS2 simulation results with respect to the BU delay. Numerical results show that there are differences between the testbed and simulation experiments.

6.4 Summary

This chapter of the thesis presented the deployment of a simple and cost-effective Linux-based MIPv6 testbed with the testing checkpoints and debugging procedures. Additionally, the chapter also presented comparisons between TCP and UDP-based applications performances in the MIPv6 testbed. Further, the BU delay of MIPv6 testbed is compared with NS2 simulation results of MIPv6. Numerical results showed the differences between testbed and simulation experiments.

The following chapter presents the conclusions and future directions of the contributed Chapters 3 - 6.

Chapter 7

Conclusions and Future Directions

4^{th} Generation heterogeneous wireless networks is the future of communication technology to provide users' with Always Best Connected (ABC) services anywhere at anytime. The handover process of mobility management in heterogeneous wireless networks is one of the major issues for seamless communication of MNs with maximized users' satisfaction. MADM based VHD making is one of the method for selecting the suitable network among the available networks because of its simplicity and design for multiple attributes. This chapter of the thesis summarizes the research contributions with the future directions.

The first set of contributions of the thesis targeted at demonstrating the issues of heterogeneous wireless networks. This contribution started with the presentation of the attributes normalization and weight computation dependency of classical MADM methods resulting in unreliable network selection (ranking) and the rank reversal problem. With the MATLAB simulation of different pairs of attributes normalization and weight computation methods carried out for 1,000 different combinations of network versus attribute, demonstrated network selection unreliability and the rank reversal problem of classical MADM methods.

Further, this research contribution also presented a comparison and analysis of the three sigmoidal utility functions based network selection in heterogeneous wireless networks. The outcome of the MATLAB simulation for 81 different combinations of network versus attribute and different pairs for attributes weight with sigmoidal function constant ζ, demonstrated the influence of the attributes weight and sigmoidal utility function constant in network selection. Furthermore, this contribution of the thesis addressed the issues in implementation and verifications of all available solutions for heterogeneous wireless networks using network simulator NS2. Hence, Evaluation Suite for the User Datagram Protocol referred to as ES-UDP for WiFi and WiMAX interfaced MNs simulation in heterogeneous wireless networks is developed and experimentally verified. In future work, the first set of contributions can be further enriched to address the following issues:

- MATLAB simulations of sigmoidal utility functions for additional network versus attribute and attributes weight with the constant ζ pair. Identifying an appropriate ζ value for different applications.

- ES-UDP's support for many additional parameters of an MN and their applications. Developing an evaluation suite for TCP applications in heterogeneous wireless networks.

The second set of contributions of the thesis presented the drawbacks of state-of-the-art AHP and proposed an improvement over AHP referred to as SI-AHP for computing reliable attributes weight. Initially, with the MATLAB simulation for 5,31,441 different combinations of reciprocal matrix, inconsistent eigenvector in AHP is demonstrated for 99.5% combinations of reciprocal matrix. Further, the proposed SI-AHP method was simulated for linguistic value of voice and download applications for 100% consistent eigenvector. Additionally, SI-AHP was simulated for 78,125 combinations of linguistic value and demonstrated 100% reliable attributes weight. In future work, SI-AHP can be verified by implementing in network simulators and Linux kernel for reliable attributes weight computation.

The third set of contributions of the thesis presented SI-MAAR method for eliminating attributes normalization and weight computation dependency of classical MADM. Initially, with the MATLAB simulations, 100% reliable network selection and the 0% rank reversal problem in SI-MAAR is demonstrated for 1,000 combinations of network versus attribute. Additionally, with the MATLAB simulation, network selection sensitivity of SI-MAAR method is demonstrated for objective and subjective attributes of voice and download applications. Also, network selection sensitivity of SI-MAAR method in comparisons with the classical MADM methods was also demonstrated for varying one attribute value of individual network one at a time, varying one attribute value one at a time of applications and varying one attribute weight one at a time. In future work, SI-MAAR can be verified by implementing in Linux kernel for reliable ranking of networks and the elimination of the rank reversal problem.

The fourth set of contributions of the thesis presented the issues of testbed approach and demonstrated the deployment of a simple and cost-effective Linux-based MIPv6 testbed with the testing checkpoints and debugging procedures. This contribution also presented the comparisons between TCP and UDP-based applications performances in the MIPv6 testbed. The BU delay of MIPv6 testbed is compared with NS2 simulation results of MIPv6. Numerical results showed the differences between testbed and simulation experiments. In future with the MIPv6 testbed, work can be initiated to implement SI-AHP and SI-MAAR in heterogeneous wireless networks.

To summarize, this thesis addressed the problem of unreliable attributes weight computation in AHP and provided an efficient solution for computing 100% reliable attributes weight using optimized "SI-AHP". Further, unreliable network ranking and the rank reversal problem in classical MADM methods are addressed by providing an efficient solution for 100% reliable network ranking with the 0% rank reversal problem using optimized "SI-MAAR". Additionally, simulation related issues such as configuration and result analysis of heterogeneous wireless networks is addressed by developed tool referred to as "ES-UDP" in NS2. Finally, handover related testbed issues such as deployment complexity, cost and time are addressed by providing a simplified and cost-effective framework for MIPv6 testbed in Linux.

References

Abid, M., Yahiya, T. A., and Pujolle, G. (2012). "A utility-based handover decision scheme for heterogeneous wireless networks". In *IEEE Consumer Communications and Networking Conference (CCNC)*, pages 650–654. IEEE.

Ahmed, A., Boulahia, L. M., and Gaiti, D. (2014). "Enabling vertical handover decisions in heterogeneous wireless networks: A state-of-the-art and a classification". *IEEE Communications Surveys and Tutorials*, 16(2):776–811.

Ahuja, K., Singh, B., and Khanna, R. (2014). "Network selection algorithm based on link quality parameters for heterogeneous wireless networks". *Optik-International Journal for Light and Electron Optics*, 125(14):3657–3662.

Alinezhad, A. and Amini, A. (2011). "Sensitivity analysis of TOPSIS technique: the results of change in the weight of one attribute on the final ranking of alternatives". *Journal of Optimization in Industrial Engineering*, 7:23–28.

Antonopoulos, A., Alonso-Zárate, J., Kartsakli, E., Alonso, L., and Verikoukis, C. (2013). "Cross layer access point selection mechanisms for a distributed queuing MAC protocol". *Telecommunication Systems*, 53(3):329–342.

Aragonés-Beltrán, P., Chaparro-González, F., Pastor-Ferrando, J.-P., and Pla-Rubio, A. (2014). "An AHP (Analytic Hierarchy Process)/ANP (Analytic Network Process)-based multi-criteria decision approach for the selection of solar-thermal power plant investment projects". *Elsevier Energy*, 66:222–238.

Aretz, K., Haardt, M., Konhäuser, W., and Mohr, W. (2001). "The future of wireless communications beyond the third generation". *Elsevier Computer Networks*, 37(1):83–92.

Azadeh, A., Saberi, M., Atashbar, N. Z., Chang, E., and Pazhoheshfar, P. (2013). "Z-AHP: a Z-number extension of fuzzy analytical hierarchy process". In *7th IEEE International Conference on Digital Ecosystems and Technologies (DEST)*, pages 141–147. IEEE.

Azzuhri, S., Suhaimi, S., Wong, K. D., and Ali, N. M. (2008). "Mobile IPV6: Simultaneous and Consecutive Mobility Experiments on MIPL Testbed". In *4th International Conference on Wireless Communications, Networking and Mobile Computing*, pages 1–6. IEEE.

Behzadian, M., Otaghsara, S. K., Yazdani, M., and Ignatius, J. (2012). "A state-of the-art survey of TOPSIS applications". *Expert Systems with Applications*, 39(17):13051–13069.

Bernasconi, M., Choirat, C., and Seri, R. (2010). "The analytic hierarchy process and the theory of measurement". *Management Science*, 56(4):699–711.

Bilalb, S. M., Othmana, M., et al. (2013). "A Performance Comparison of Network Simulators for Wireless Networks". *arXiv preprint arXiv:1307.4129.*

Bouras, C., Charalambides, S., Drakoulelis, M., Kioumourtzis, G., and Stamos, K. (2013). "A tool for automating network simulation and processing tracing data files". *Simulation Modelling Practice and Theory*, 30:90–110.

C. Perkins, D. J. and Arkko, J. (2011). "RFC 6275 Mobility Support in IPv6".

Cacheda, R. A., García, D. C., Cuevas, A., Castano, F. J. G., Sánchez, J. H., Koltsidas, G., Mancuso, V., Novella, J. I. M., Oh, S., and Pantò, A. (2007). "QoS requirements for multimedia services". In *Resource Management in Satellite Networks*, pages 67–94. Springer.

Cavalcanti, D., Agrawal, D., Cordeiro, C., Xie, B., and Kumar, A. (2005). "Issues in integrating cellular networks WLANs, AND MANETs: a futuristic heterogeneous wireless network". *IEEE Wireless Communications*, 12(3):30–41.

Çelen, A. (2014). "Comparative analysis of normalization procedures in TOPSIS method: with an application to Turkish deposit banking market". *Informatica*, 25(2):185–208.

Chamodrakas, I. and Martakos, D. (2012). "A utility-based fuzzy TOPSIS method for energy efficient network selection in heterogeneous wireless networks". *Applied Soft Computing*, 12(7):1929–1938.

Charilas, D. E. and Panagopoulous, A. D. (2010). "Multiaccess radio network enviroments". *IEEE Vehicular Technology Magazine*, 5(4):40–49.

Chen, T., Zhang, H., Chen, X., and Tirkkonen, O. (2014). "SoftMobile: control evolution for future heterogeneous mobile networks". *IEEE Wireless Communications*, 21(6):70–78.

Chen, Y., Farley, T., and Ye, N. (2004). "QoS requirements of network applications on the Internet". *IOS Press - Information Knowledge Systems Management*, 4(1):55–76.

Chen, Y.-C., Hsia, J.-H., and Liao, Y.-J. (2009). "Advanced seamless vertical handoff architecture for WiMAX and WiFi heterogeneous networks with QoS guarantees". *Computer Communications*, 32(2):281–293.

Cheung, M. H., Mohsenian-Rad, A.-H., Wong, V. W., and Schober, R. (2010). "Random access for elastic and inelastic traffic in WLANs". *IEEE Transactions on Wireless Communications*, 9(6):1861–1866.

Chua, K. C., Li, Y., and Foo, C. (1999). "On a Linux implementation of mobile IP and its effects on TCP performance". *Computer Communications*, 22(6):568–588.

D'Agostino, M. and Dardanoni, V. (2009). "What's so special about Euclidean distance?". *Social Choice and Welfare*, 33(2):211–233.

De La Oliva, A., Banchs, A., Soto, I., Melia, T., and Vidal, A. (2008). "An overview of IEEE 802.21: media-independent handover services". *IEEE Wireless Communications*, 15(4):96–103.

Drissi, M. and Oumsis, M. (2015). "Performance Evaluation of multi-criteria vertical handover for heterogeneous wireless networks". In *Intelligent Systems and Computer Vision (ISCV)*, pages 1–5. IEEE.

Eastwood, L., Migaldi, S., Xie, Q., and Gupta, V. (2008). "Mobility using IEEE 802.21 in a heterogeneous IEEE 802.16/802.11-based, IMT-advanced (4G) network". *IEEE Wireless Communications*, 15(2):26–34.

Fernandes, S. and Karmouch, A. (2012). "Vertical mobility management architectures in wireless networks: A comprehensive survey and future directions". *IEEE Communications Surveys and Tutorials*, 14(1):45–63.

Fernandez, M., Wahle, S., and Magedanz, T. (2012). "A new approach to ngn evaluation integrating simulation and testbed methodology". In *Proceedings of the The Eleventh International Conference on Networks (ICN12)*, pages 22–27.

Fratu, O., Popovici, E. C., Vulpe, A., and Halunga, S. V. (2011). "Heterogeneous wireless access networks analysis from simulation to implementation". In *10th International Conference on Telecommunication in Modern Satellite Cable and Broadcasting Services (TELSIKS)*, volume 2, pages 481–488. IEEE.

Haseeb, S. and Kurup, G. (2007). "Performance analysis of MIPL based Mobile IPv6 testbed". In *IEEE International Conference on Telecommunications and Malaysia International Conference on Communications (ICT-MICC 2007)*, pages 582–587. IEEE.

He, D., Chi, C., Chan, S., Chen, C., Bu, J., and Yin, M. (2011). "A simple and robust vertical handoff algorithm for heterogeneous wireless mobile networks". *Wireless Personal Communications*, 59(2):361–373.

Heidemann, J., Mills, K., and Kumar, S. (2001). "Expanding confidence in network simulations". *IEEE Network*, 15(5):58–63.

Hui, S. Y. and Yeung, K. H. (2003). "Challenges in the migration to 4G mobile systems". *IEEE Communications magazine*, 41(12):54–59.

Ibrahim, I. S., King, P. J., and Loidl, H.-W. (2015). "NsGTFA: A GUI Tool to Easily Measure Network Performance through the Ns2 Trace File". *Journal of Intelligent Systems*, 24(4):467–477.

Imran, M., Said, A. M., and Hasbullah, H. (2010). "A survey of simulators, emulators and testbeds for wireless sensor networks". In *International Symposium on Information Technology*, volume 2, pages 897–902. IEEE.

Ishizaka, A., Pearman, C., and Nemery, P. (2012). "AHPSort: an AHP-based method for sorting problems". *International Journal of Production Research*, 50(17):4767–4784.

Issariyakul, T. and Hossainp, E. (2011). *"Introduction to Network Simulator NS2"*, volume 1. Springer US.

Jain, R. K. (2015). *"Art of Computer Systems Performance Analysis: Techniques for Experimental Design Measurements... Simulation and Modeling"*. John Wiley.

Javanbarg, M. B., Scawthorn, C., Kiyono, J., and Shahbodaghkhan, B. (2012). "Fuzzy AHP-based multicriteria decision making systems using particle swarm optimization". *Expert Systems with Applications*, 39(1):960–966.

Kassar, M., Kervella, B., and Pujolle, G. (2008). "An overview of vertical handover decision strategies in heterogeneous wireless networks". *Computer Communications*, 31(10):2607–2620.

Khloussy, E., Gelabert, X., and Jiang, Y. (2015). "Investigation on MDP-based radio access technology selection in heterogeneous wireless networks". *Computer Networks*, 91:57–67.

Kuo, Y., Yang, T., and Huang, G.-W. (2008). "The use of grey relational analysis in solving multiple attribute decision-making problems". *Computers and Industrial Engineering*, 55(1):80–93.

Lampropoulos, G., Salkintzis, A. K., and Passas, N. (2008). "Media-independent handover for seamless service provision in heterogeneous networks". *IEEE Communications Magazine*, 46(1):64–71.

Lessmann, J., Janacik, P., Lachev, L., and Orfanus, D. (2008). "Comparative study of wireless network simulators". In *Seventh International Conference on Networking (ICN 2008)*, pages 517–523. IEEE.

Lin, J. (1991). "Divergence measures based on the Shannon entropy". *IEEE Transactions on Information theory*, 37(1):145–151.

Makaya, C. and Pierre, S. (2008). "An architecture for seamless mobility support in IP-based next-generation wireless networks". *IEEE Transactions on vehicular technology*, 57(2):1209–1225.

Marques, H., Ribeiro, J., Marques, P., and Rodriguez, J. (2010). "Simulation of 802.21 handovers using ns-2". *Journal of Computer Systems, Networks, and Communications*, 2010:1–11.

Márquez-Barja, J., Calafate, C. T., Cano, J.-C., and Manzoni, P. (2011). "An overview of vertical handover techniques: Algorithms, protocols and tools". *Computer Communications*, 34(8):985–997.

McNair, J. and Zhu, F. (2004). "Vertical handoffs in fourth-generation multinetwork environments". *IEEE Wireless Communications*, 11(3):8–15.

Millet, I. and Saaty, T. L. (2000). "On the relativity of relative measures–accommodating both rank preservation and rank reversals in the AHP". *European Journal of Operational Research*, 121(1):205–212.

Monika, A. K. and Shekhar, M. (2014). "Network Simulators for Next Generation

Networks: An Overview". *International Journal of Mobile Network Communications and Telematics (IJMNCT) Vol*, 4:39–51.

Montavont, J., Ivov, E., and Noel, T. (2007). "Analysis of mobile ipv6 handover optimizations and their impact on real-time communication". In *IEEE Conference on Wireless Communications and Networking*, pages 3244–3249. IEEE.

Mosadeghi, R., Warnken, J., Tomlinson, R., and Mirfenderesk, H. (2015). "Comparison of Fuzzy-AHP and AHP in a spatial multi-criteria decision making model for urban land-use planning". *Computers, Environment and Urban Systems*, 49:54–65.

Nasser, N., Hasswa, A., and Hassanein, H. (2006). "Handoffs in fourth generation heterogeneous networks". *IEEE Communications Magazine*, 44(10):96–103.

Nguyen-Vuong, Q.-T., Agoulmine, N., Cherkaoui, E. H., and Toni, L. (2013). "Multicriteria optimization of access selection to improve the quality of experience in heterogeneous wireless access networks". *IEEE Transactions on Vehicular Technology*, 62(4):1785–1800.

Nguyen-Vuong, Q.-T., Agoulmine, N., and Ghamri-Doudane, Y. (2007). "Terminal-controlled mobility management in heterogeneous wireless networks". *IEEE Communications Magazine*, 45(4):122–129.

Nikou, S. and Mezei, J. (2013). "Evaluation of mobile services and substantial adoption factors with Analytic Hierarchy Process (AHP)". *Telecommunications Policy*, 37(10):915–929.

Ning, F. and Zhang, P. (2012). "A multiple attribute decision making-based access selection for heterogeneous WCDMA and WLAN networks". In *Proceedings of International Conference on Affective Computing and Intelligent Interaction (ICACII-2012)*, volume 10, pages 15–21. Citeseer.

Orfanus, D., Lessmann, J., Janacik, P., and Lachev, L. (2008). "Performance of wireless network simulators: a case study". In *Proceedings of the 3nd ACM workshop on Performance monitoring and measurement of heterogeneous wireless and wired networks*, pages 59–66. ACM.

Ozdemir, M. S. (2005). "Validity and inconsistency in the analytic hierarchy process". *Applied Mathematics and Computation*, 161(3):707–720.

Ozdemir, M. S. and Saaty, T. L. (2006). "The unknown in decision making: What to do about it". *European Journal of Operational Research*, 174(1):349–359.

Perrone, L. F., Cicconetti, C., Stea, G., and Ward, B. C. (2009). "On the automation of computer network simulators". In *Proceedings of the 2nd International Conference on Simulation Tools and Techniques*, pages 1–10. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

Piamrat, K., Ksentini, A., Bonnin, J.-M., and Viho, C. (2011). "Radio resource management in emerging heterogeneous wireless networks". *Computer Communications*, 34(9):1066–1076.

Pontes, A. B., dos Passos Silva, D., Jailton, J., Rodrigues, O., and Dias, K. L. (2008). "Handover management in integrated WLAN and mobile WiMAX networks". *IEEE Wireless Communications*, 15(5):86–95.

Rahman, M. A., Pakštas, A., and Wang, F. Z. (2009). "Network modelling and simulation tools". *Simulation Modelling Practice and Theory*, 17(6):1011–1031.

Robbins, A. (2015). *"Effective Awk Programming: Universal Text Processing and Pattern Matching"*. O'Reilly Media, Inc.

Ruchala, R. and Zielinski, K. (2006). "Measurements of data streaming QoS during handover process in Mobile IPv6 testbed". In *2nd International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities(TRIDENTCOM 2006).*

Rumekasten, M. (1994). "Simulation of heterogeneous networks". In *Winter Conference Proceedings on Simulation*, pages 1264–1271. IEEE.

Saaty, T. L. (1990). "How to make a decision: the analytic hierarchy process". *European journal of operational research*, 48(1):9–26.

Saaty, T. L. (2003). "Decision-making with the AHP: Why is the principal eigenvector necessary". *European journal of operational research*, 145(1):85–91.

Saaty, T. L. (2006). "Rank from comparisons and from ratings in the analytic hierarchy/network processes". *European Journal of Operational Research*, 168(2):557–570.

Saaty, T. L. and Begicevic, N. (2010). "The scope of human values and human activities in decision making". *Applied Soft Computing*, 10(4):963–974.

Saaty, T. L. and Vargas, L. G. (2012). *"Models, methods, concepts and applications of the analytic hierarchy process"*, volume 175. Springer Science and Business Media.

Sekitani, K. and Yamaki, N. (1999). "A logical interpretation for the eigenvalue method in AHP". *Journal of the Operations Research Society of Japan*, 42(2):219–232.

Shi, F., Li, K., and Shen, Y. (2010). "Seamless handoff scheme in Wi-Fi and WiMAX heterogeneous n/w". *Future Generation Computer Systems*, 26(8):1403–1408.

Siddiqui, F. and Zeadally, S. (2006). "Mobility management across hybrid wireless networks: Trends and challenges". *Computer Communications*, 29(9):1363–1385.

Sirisena, H., Perera, S., Pawlikowski, K., Liu, W., and Begg, L. (2006). "Survey of simulators of next generation networks for studying service availability and resilience". Technical report, Department of Computer Science and Software Engineering, University of Canterbury.

Song, Y., Kong, P.-Y., and Han, Y. (2014). "Power-optimized vertical handover scheme for heterogeneous wireless networks". *IEEE Communications Letters*, 18(2):277–280.

Stevens-Navarro, E., Lin, Y., and Wong, V. W. (2008). "An MDP-based vertical handoff decision algorithm for heterogeneous wireless networks". *IEEE Transactions on Vehicular Technology*, 57(2):1243–1254.

Stevens-Navarro, E., Martinez-Morales, J., and Pineda-Rico, U. (2012). "Evaluation of vertical handoff decision algorightms based on madm methods for heterogeneous wireless networks". *Journal of applied research and technology*, 10(4):534–548.

Stevens-Navarro, E. and Wong, V. W. (2006). "Comparison between vertical handoff decision algorithms for heterogeneous wireless networks". In *IEEE 63rd Vehicular Technology Conference*, volume 2, pages 947–951. IEEE.

Sun, C., Stevens-Navarro, E., and Wong, V. W. (2008). "A constrained MDP-based vertical handoff decision algorithm for 4G wireless networks". In *IEEE International Conference on Communications*, pages 2169–2174. IEEE.

Tan, R., Aviso, K., Huelgas, A., and Promentilla, M. (2014). "Fuzzy AHP approach to selection problems in process engineering involving quantitative and qualitative aspects". *Process Safety and Environmental Protection*, 92(5):467–475.

Trestian, R., Ormond, O., and Muntean, G.-M. (2012). "Game theory-based network selection: Solutions and challenges". *IEEE Communications surveys and tutorials*, 14(4):1212–1231.

Tzeng, G.-H. and Huang, J.-J. (2011). *"Multiple attribute decision making: methods and applications"*. CRC press.

Wang, H. J., Katz, R. H., and Giese, J. (1999). "Policy-enabled handoffs across heterogeneous wireless networks". In *Second IEEE Workshop on Mobile Computing Systems and Applications (WMCSA'99)*, pages 51–60. IEEE.

Wang, L. and Binet, D. (2009). "TRUST: A Trigger-Based Automatic Subjective Weighting Method for Network Selection". In *Proceedings of the Fifth Advanced International Conference on Telecommunications (AICT-2009)*, pages 362–368.

Wang, L. and Kuo, G.-S. G. (2013). "Mathematical modeling for network selection in heterogeneous wireless networksâĂŤA tutorial". *IEEE Communications Surveys and Tutorials*, 15(1):271–292.

Wang, Y.-M. and Luo, Y. (2009). "On rank reversal in decision analysis". *Mathematical and Computer Modelling*, 49(5):1221–1229.

Weingartner, E., Vom Lehn, H., and Wehrle, K. (2009). "A performance comparison of recent network simulators". In *IEEE International Conference on Communications*, pages 1–5. IEEE.

Wen, Y.-F. and Hung, K.-Y. (2015). "Energy efficiency heterogeneous wireless access selection for multiple types of applications". *Journal of Systems and Software*, 101:97–109.

Williams, T., Kelley, C., Broker, H., Merritt, E., Campbell, J., Cunningham, R., Denholm, D., Elber, G., Fearick, R., Grammes, C., et al. (2010). "Gnuplot 4.4: an interactive plotting program". *Official gnuplot documentation, http://sourceforge.net/projects/gnuplot.*

Xenakis, D., Passas, N., Merakos, L., and Verikoukis, C. (2014). "Mobility management for femtocells in LTE-advanced: key aspects and survey of handover decision algorithms". *IEEE Communications Surveys and Tutorials*, 16(1):64–91.

Yan, X., Şekercioğlu, Y. A., and Narayanan, S. (2010). "A survey of vertical handover decision algorithms in Fourth Generation heterogeneous wireless networks".

Computer networks, 54(11):1848–1863.

Yang, S.-J. and Tseng, W.-C. (2013). "Design novel weighted rating of multiple attributes scheme to enhance handoff efficiency in heterogeneous wireless networks". *Computer Communications*, 36(14):1498–1514.

Zardari, N. H., Ahmed, K., Shirazi, S. M., and Yusop, Z. B. (2014). *"Weighting Methods and their Effects on Multi-Criteria Decision Making Model outcomes in water resource management"*. Springer Briefs in Water Science and Technology.

Zekri, M., Jouaber, B., and Zeghlache, D. (2012). "A review on mobility management and vertical handover solutions over heterogeneous wireless networks". *Computer Communications*, 35(17):2055–2068.

Zhang, W. (2004). "Handover decision using fuzzy MADM in heterogeneous networks". In *IEEE Wireless communications and networking conference (WCNC 2004)*, volume 2, pages 653–658. IEEE.

List of Publications

Journal Publications

1. B. R. Chandavarkar, G. Ram Mohana Reddy, *Simplified and Improved Analytical Hierarchy Process Aid for Selecting the Candidate Networks in an Overlay Heterogeneous Networks*, Springer Wireless Personal Communication, Volume: 83, pp 2593-2606, August 2015.

2. B. R. Chandavarkar, G. Ram Mohana Reddy, *Simplified and Improved Multiple Attribute Alternate Ranking Method for Vertical Handover Decision in Heterogeneous Wireless Networks*, Elsevier Computer Communications, Volume: 83, pp 81-97, June 2016.

3. B. R. Chandavarkar, G. Ram Mohana Reddy, *User Datagram Protocol Evaluation Suite for Heterogeneous Wireless Networks*, Elsevier Simulation Modelling: Practice and Theory (Accepted).

Conference Publications

1. B. R. Chandavarkar and G. Ram Mohana Reddy, *Modifications in the Working Model and Handoff Mechanism of MIPv6*, Proceedings of the 4th National Conference; INDIACom-2010, Bharti Vidyapeeth's Institute of Computer Application and Management, New Delhi, Feb 25-26, 2010.

2. B. R. Chandavarkar and G. Ram Mohana Reddy, *Improvement in Packet Drop during Handover between WiFi and WiMAX*, International Conference on Network and Electronics Engineering (ICNEE 2011), September 2011, Singapore. (Springer) [Citation: 10]

3. B. R. Chandavarkar and G. Ram Mohana Reddy, *Survey Paper: Mobility Management in Heterogeneous Wireless Networks*, International Conference on Communication Technology and System Design December 2011 (ICCTSD 2011), Amrita School of Engineering, Coimbatore. (Elesvier Procedia, Volume: 30, pp 113-123) [Citation: 12]

4. B. R. Chandavarkar, G. Ram Mohana Reddy, *Comparisons with Analysis of Sigmoidal Utility Function based Candidate Network Selection in Heterogeneous Wireless Network*, 5th International Symposium on Frontiers in Ambient and Mobile Systems (FAMS-2015), University of Greenwich, London, UK, 2-5 June 2015.

5. B. R. Chandavarkar, G. Ram Mohana Reddy, *Comparisons of Entropy Based Multi Attribute Decision Making Point of Attachment Selection in Heterogeneous Wireless Networks*, 5th International Conference on Digital Information Processing and Communications (ICDIPC2015) at the University of Applied Sciences and Arts Western Switzerland, 7-9 October 2015.

6. B. R. Chandavarkar, G. Ram Mohana Reddy, *Comparisons with Analysis of Sigmoidal Utility Function based Handover Decision in Heterogeneous Wireless Network*, 5th International Conference on Digital Information Processing and Communications (ICDIPC2015) at the University of Applied Sciences and Arts Western Switzerland, 7-9 October 2015.

7. B. R. Chandavarkar, G. Ram Mohana Reddy, *Analysis of Sigmoidal Utility Function based Handover in Heterogeneous Wireless Network*, International Conference on Microwave, Optical and Communication Engineering (ICMOCE-2015), School of Electrical Sciences, IIT Bhubaneswar, Odisha, 18-20 December 2015.

Brief Bio-Data

B. R. Chandavarkar

Asst. Prof.,

Department of Computer Science and Engineering

National Institute of Technology Karnataka, Surathkal

P.O. Srinivasnagar

Mangalore, 575025

Phone: 08242473408

Email: brcnitk@gmail.com

Permanent Address

B. R. Chandavarkar

Shree Nilaya, H. No. 22-65/2A1

Near Ramnagar Layout Busstop

Munchoor, Srinivasnagar

Mangalore, 575025

Qualification

M. Tech. Computer Network Engineering, Visvesvaraya Technological University, Belgaum, Karnataka, 2004.

B. E. Electronics and Communications Engineering, S. D. M. College of Engineering and Technology, Dharwad, Karnataka, 1997.