Graduate School of Engineering Fukuoka Institute of Technology

PhD Thesis

Implementation of Intelligent and Hybrid Systems for Wireless Mesh Networks: A Comparison Study

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Implementation of Intelligent and Hybrid Systems for Wireless Mesh Networks: A Comparison Study

Graduate Course of Intelligent Information System Engineering

Shinji Sakamoto

Abstract

Wireless Mesh Networks (WMNs) are gaining a lot of attention because their low cost nature makes them attractive for providing wireless Internet connectivity. A WMN is dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves. In WMNs, the mesh node placement is a very important problem. However, this problem is known to be NP-hard. To deal with this problem, new methods, algorithms and systems are needed.

In this thesis, we design and implement intelligent and hybrid systems in order to solve the node placement problem in WMNs. We consider a bi-objective optimization in which we first maximize the network connectivity through the maximization of Size of Giant Component (SGC) and then the maximization of the Number of Covered Mesh Clients (NCMC). We evaluate the implemented systems through many simulations. From the evaluation results, we found that the hybrid systems have very good performance for optimizing the node placement in WMNs.

This thesis contributes to the research field as follows: 1) Implementation of intelligent systems for solving node placement problem in WMNs. 2) Evaluation of various intelligent algorithms based systems for different scenarios. 3) Comparison of implemented intelligent and hybrid systems. 4) Implementation of a WMN simulation system using Network Simulator 3 (ns-3). 5) Application of an implemented system for WMN node placement problem in a realistic scenario. 6) Give insights about future developments and integration of WMNs as an important technology in wireless communications.

This thesis is composed of eight chapters. Chapter 1 presents the background, the motivation and thesis structure. Chapter 2 introduces general aspects of wireless networks. Also, Wireless Sensor and Actor Networks (WSANs) and Mobile Ad-hoc Networks (MANETs) are explained as a related work to this thesis. In Chapter 3, we explain about the node classification in WMNs and routing protocols for WMNs. In addition, we define the node placement problem in WMNs. In Chapter 4, intelligent algorithms such as Hill Climbing (HC), Simulated Annealing (SA), Tabu Search (TS), Genetic Algorithm (GA), Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) are discussed. We present in detail the PSO algorithm in Chapter 5. The implemented intelligent and hybrid systems are presented in Chapter 6. Chapter 7 shows the evaluation and comparison of implemented systems by conducting simulations and applications for a realistic scenario. In Chapter 8, we give some concluding remarks and future work.

Keywords: Wireless Mesh Networks, Intelligent Algorithms, Node Placement Problem.

1 March 2018

無線メッシュネットワークのための知的および
ハイブリッドシステムの実装：比較研究

知能情報システム工学専攻

坂本 真仁

概要

無線メッシュネットワーク（WMN）は，低コストで無線インターネット接続を提供する魅力的な性質を有するため，多くの注目を集めている．WMN は動的に自己組織化・自己構成され，ネットワーク内のメッシュノードは自動的に接続を確立し，その状態を維持する．メッシュルータの配置は，WMN にとって非常に重要な問題である．しかし，この問題は NP 困難であることが知られており，対処するためには，新しい方法，アルゴリズムおよびシステムが必要である．

本論文では，WMN におけるメッシュルータ配置問題を解決するため，知的およびハイブリッドシステムの設計と実装を行う．実装システムでは，Size of Giant Component（SGC）を最大化し，次に Number of Covered Mesh Clients（NCMC）を最大化する二目的最適化を考慮する．実装したシステムを多くのシミュレーションで評価する．評価結果から，ハイブリッドシステムが，WMN におけるメッシュルータ配置最適化に対して，非常に良好な性能を有することがわかった．

本研究は，次のような特色と独創的な点を有しており，科学技術への貢献が期待できる．1）様々な知的アルゴリズムを用いたメッシュルータ配置最適化システムの実装，2）様々なシミュレーションシナリオによる知的アルゴリズムを用いたメッシュルータ配置最適化システムの評価，3）ハイブリッド型知的アルゴリズムを含む様々な知的アルゴリズムに基づいたシステムの比較，4）Network Simulator 3 を用いた WMN のシミュレーションシステムの実装，5）実環境を考慮したシナリオのための WMN のメッシュルータ配置最適化システムの応用，6）本研究の結果から，今後の無線通信の技術の発展のための WMN の統合についての見識を与える．

以下に論文の構成を示す．第 1 章では，研究背景と目的，論文構成を述べている．第 2 章では，無線ネットワークの一般的な技術を紹介し，WMN の関連研究として，無線センサアクタネットワーク（WSAN）とモバイルアドホックネットワーク（MANET）について述べる．第 3 章では，WMN におけるノードの分類や，ルーティングプロトコルについて説明する．加えて，WMN におけるメッシュルータ配置問題を定義する．第 4 章では，山登り法（HC），焼き鈍し法（SA），禁錮探索法（TS），遺伝的アルゴリズム（GA），アントコロニー最適化（ACO），粒子群最適化（PSO）といった知的アルゴリズムについて紹介する．第 5 章では，PSO の詳細について述べる．第 6 章では，シミュレーションシステムの設計と実装について述べる．第 7 章では，シミュレーション結果を議論する．第 8 章では，結論とこの分野における今後の課題の見識を与え，論文をまとめる．

キーワード：無線メッシュネットワーク，知的アルゴリズム，メッシュルータ配置最適化.

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Chapter 1

Introduction

In this chapter, the background information, the goal and the structure of this thesis are shown.

1.1 Background

With the development of Information Communication Technology (ICT), our life has changed rapidly. The history of telecommunications started with Alexander Graham Bell[1)]. He got a patent for the telephone on 7^{th} March 1876[2)]. Until he invented the phone, we were not able to talk to people when they were not nearby. On 5^{th} December 1969, the Internet was born. At that time, only four nodes were connected to each other: the University of California, the Stanford Research Institute, Santa Barbara, and the University of Utah[3,4)]. Moreover, it was only 50kbps. However, the Internet has made explosive growth since the appearance of its killer application, called the World Wide Web (WWW)[5–7)].

The Internet consists of a very large number of nodes[8)]. The International Telecommunication Union shows that the number of Internet users is constantly increasing as shown in Figure 1.1. The number of Internet users exceeded 3.5 billion in 2016. The growth of the Internet makes our life better. We can use e-mail and even talk using the Internet. The importance of the Internet is increasing day by day.

Marker Weiser of Xerox proposed a concept called "ubiquitous computing" as the computer environment of the 21^{st} century in 1991[9)]. Ubiquitous is derived from the word meaning "exists everywhere" in Latin. In "ubiquitous computing", a large number of ubiquitous terminals function effectively without anyone's notice, and at that time the optimum information and services are provided according to the situation[10)].

The development of ICT started from semiconductor technology making up the hardware[11)]. Advances in semiconductor technology have reduced the size of terminals, and they have become portable mobile terminals[12)]. The development of wireless communication technology is becoming more popular and we have many technological innovations.

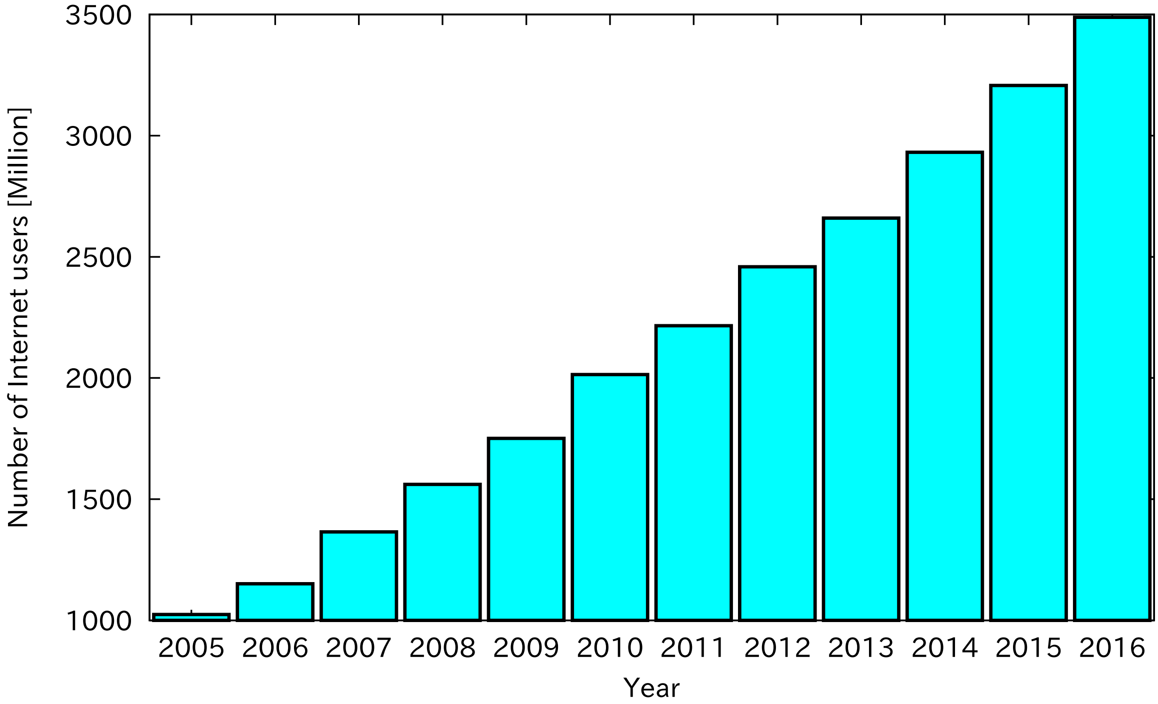


Figure 1.1: A result of a survey on the number of Internet users by the International Telecommunication Union. (`http://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx`)

In recent years, new types of devices, such as smartphones, tablet PCs and wearable devices have been developed. According to a survey by the Ministry of Internal Affairs and Communications, the rates of smartphone and tablet PC adoption have kept increasing since 2010, as shown in Figure 1.2. Since 2014, wearable types of equipment have appeared and their penetration rate in Japan has kept increasing. Not only new devices, but also a lot of new ideas are coming out such as Internet of Things (IoT)[13–16], Ambient Intelligence (AmI)[17–19] and Wireless Sensor and Actor Networks (WSANs)[20–22].

In Japan, for the 2020 Tokyo Olympic Games[23] Tokyo will realize becoming a Smart City[24]. Smart City is a challenge for reducing the costs of resources or energy. We consume electrical power to communicate, especially for wireless communications. Thus, researchers want to cut down costs by realizing Smart City. In Smart City, the first focus is on changing from incandescent light bulbs to Light Emitting Diodes (LED). Now, we focus on wireless communications[25,26].

According to the Friis transmission formula, which is described by

$$P_R = \left(\frac{\lambda}{4\pi D}\right)^2 G_T G_R P_T,$$

where P_R is received power [W], P_T is transmission power [W], G_R is received gain [1], G_T is transmission gain [1], λ is wave length [m], D is distance [m], derived from the Maxwell

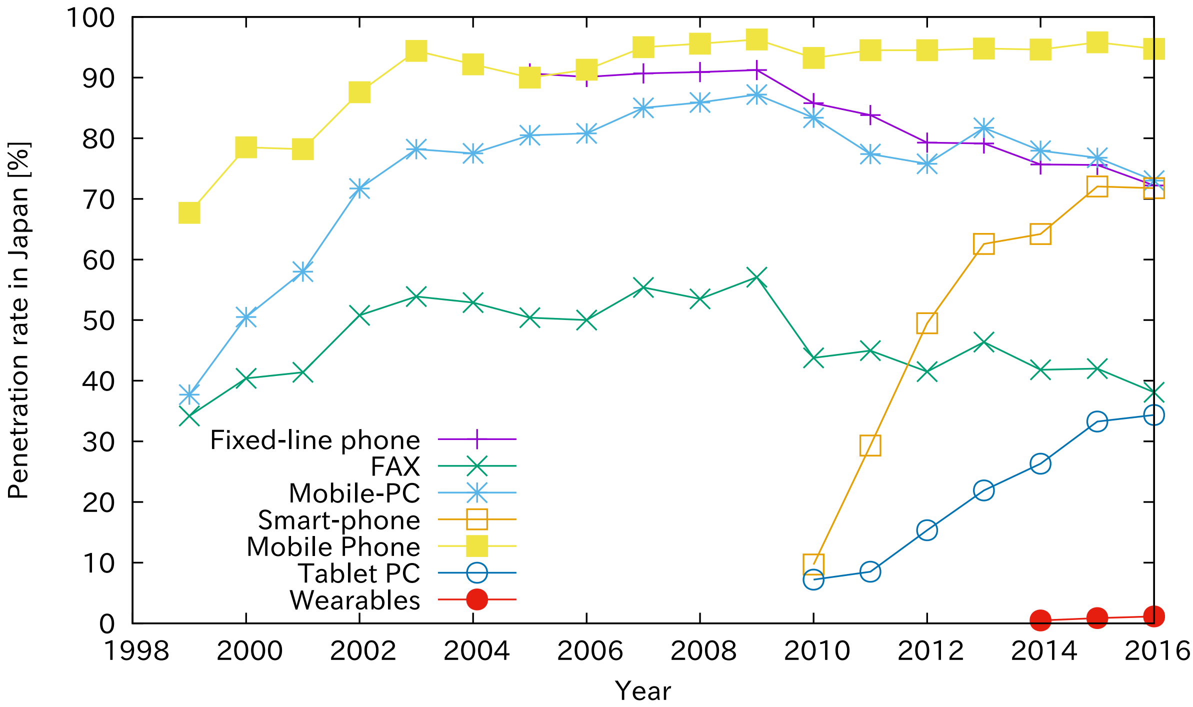


Figure 1.2: A result of a survey on a trend of communication equipment in Japan. (`http://www.soumu.go.jp/johotsusintokei/statistics/statistics05.html`)

equation, the power required for communication is proportional to the square of the distance, theoretically[27)]. However, actually, the power required for communication is proportional to the third to fifth power of the distance, because there are obstacles in the real environment. The Cellular Networks (CNs) use much power because the communication distance is long. On the other hand, the Wireless Mesh Networks (WMNs) can shorten the communication distance of each router by hopping information. Also, WMNs have many advantages such as low cost and increased high-speed wireless Internet connectivity. Therefore, WMNs are becoming an important networking infrastructure. However, WMNs have some problem which should be solved. For example, because WMNs have multi-paths, WMNs have to decide the communication path dynamically. In other words, WMNs must be self-organized and self-configured.

In WMNs, the hidden terminal problem and exposed terminal problem should be considered, because WMNs use mainly wireless communication. Smart City aims to make effective use of resources such as frequency and electric power. In order to solve these problems, mesh routers should be placed optimally.

However, the mesh router placement is a node placement problem. It is known as computationally hard. Thus, the author uses intelligent algorithms such as Particle Swarm Optimization, Hill Climbing Algorithm, Simulated Annealing Algorithm, Tabu Search Algorithm and Genetic Algorithm. These intelligent algorithms are effective for NP-hard problems, such as node placement problem. Also, there are some challenges to realize WMNs such as:

- establishing a method for mesh router placement;
- establishing a routing protocol;
- establishing a method for allocating channels;
- solving problems related to hidden/exposed terminal problem;
- resolving security-related issues.

1.2 PhD Thesis Goal

The goal of this PhD thesis is to implement intelligent and hybrid systems for solving mesh router placement problem in WMNs by using various intelligent algorithms and to evaluate the performance of the proposed and implemented systems by considering realistic scenarios.

There are many problems to be solved for standardization in IEEE 802.11s. By solving the problem related to mesh router placement, we can deal with various problems such as client coverage ratio, self-healing capability against sudden failure, communication quality, and effective utilization of resources. In addition, mesh router placement optimization problem is an NP-hard problem. Therefore, new approaches are needed.

There are intelligent algorithms which are known to be effective against NP-hard problems. The intelligent algorithm aims at establishing metrics up to exact solutions, such as tolerance scores in a solution, and deriving a good solution within real time, according to the metric.

In this work, we implement and evaluate intelligent and hybrid systems for the deployment of mesh routers using Particle Swarm Optimization (PSO), Simulated Annealing (SA), Tabu Search (TS), Hill Climbing (HC) and Genetic Algorithm (GA). Mesh routers are deployed and optimized by using the implemented systems. Also, parameters are tuned for the systems for optimizing WMNs. Finally, systems are compared in order to evaluate their performance.

1.3 Thesis Structure

This thesis consists of eight chapters. Chapter 1 presents the background and the motivation for this thesis. Chapter 2 introduces general aspects of wireless networks. Also, WSANs and MANET are explained as a related work to this thesis. We present WMNs in Chapter 3. We explain about the node classification in WMNs and routing protocols for WMNs. In addition, we define the Node Placement Problem in WMNs. In Chapter 4, Intelligent Algorithms are discussed such as Hill Climbing (HC), Simulated Annealing (SA), Tabu Search (TS), Genetic Algorithm (GA), Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO). We give details about the PSO and its processes and stability in Chapter 5. The implemented intelligent and hybrid systems are presented in Chapter 6. Chapter 7 shows the evaluation and comparison of implemented systems by conducting simulations and application for a realistic scenario. In Chapter 8, we give some concluding remarks and future work.

1.4 Thesis Contribution

This thesis contributes to the following research fields:

- Implementation of intelligent systems for solving node placement problem in WMNs.
- Evaluation of various intelligent algorithm based systems for different scenarios.
- Comparison of implemented intelligent and hybrid systems.
- Implementation of a WMN simulation system using ns-3.
- Application of an implemented system for WMN node placement problem in a realistic scenario.
- Give insights about future developments and integration of WMNs as an important technology in wireless communications.

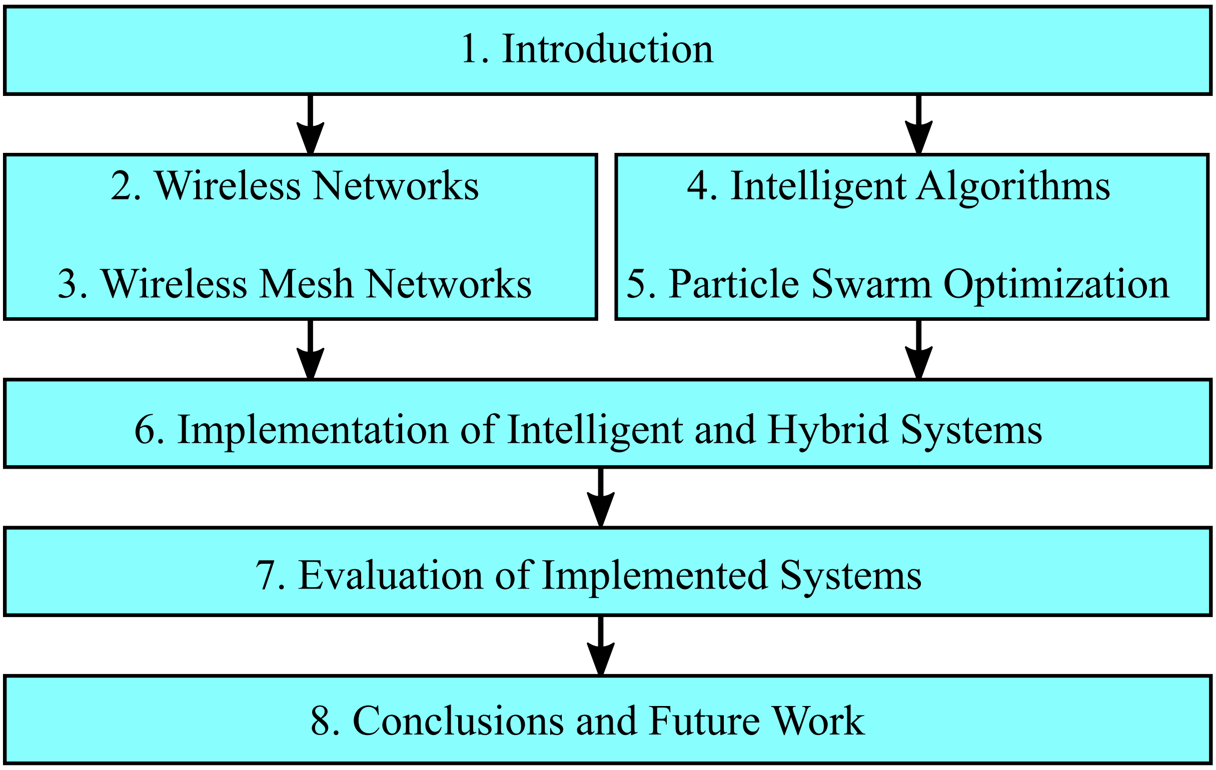


Figure 1.3: The structure chart of this thesis.

Chapter 2

Wireless Networks

This chapter describes the wireless network, and is deeply related to this thesis.

Wireless networks are currently classified by communication distance[28)]. An example of the classification is shown in Figure 2.1.

- **Wireless WAN:** Wireless Wide Area Networks (WAN) are wide area networks such as a mobile phone network.
- **Wireless RAN:** IEEE802.22 standardize Wireless Regional Area Networks (RAN). The wireless RAN covers smaller than wireless WAN but wider than wireless MAN.
- **Wireless MAN:** Wireless Metropolitan Area Networks (MAN) are networks which covers several kilometers. IEEE 802.16 (BWA) and IEEE 802.20 (MBWA, high-speed mobile) standardize Wireless Metropolitan Area Networks.
- **Wireless LAN:** IEEE802.11 standardize Wireless Local Area Networks (LAN). Wireless LAN covers a range of about 100 meters.
- **Wireless PAN:** IEEE802.15 standardize Wireless Personal Area Networks (PAN). Wireless PAN covers a range of about 10 to 20 meters.
- **Shorter than above:** For example, wireless Body Area Networks (BAN).

As a relevant study, there are many themes that have much in common with WMNs, such as the Wireless Sensor and Actor Network (WSANs) described in Section 2.1 and the Mobile Adhoc Network (MANET) described in Section 2.2. These kinds of networks have many common problems to be solved regarding mobility and power problems. In addition, optimized routing protocols for each are not currently established.

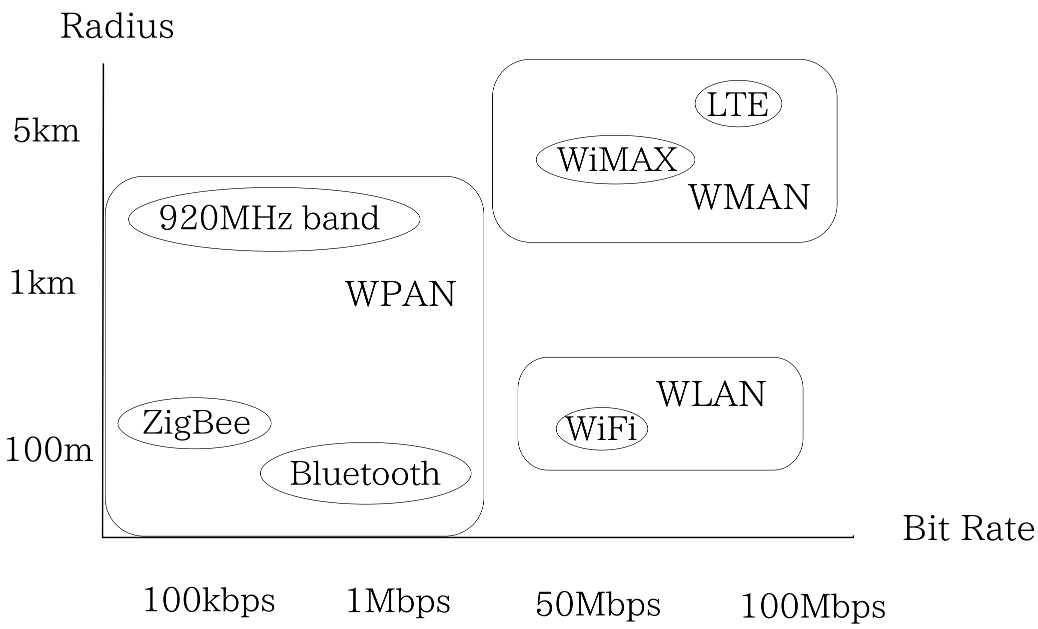


Figure 2.1: Classification of various wireless networks.

2.1 Wireless Sensor and Actor Networks: WSANs

WSANs are a typical application of Wireless Sensor Networks (WSNs). In this Section, WSNs are described in Section 2.1.1, then WSANs are introduced in Section 2.1.2.

2.1.1 Wireless Sensor Networks

Conventional sensors were built into factory machines and incorporated in sensors, equipment or products for control and quality control, and were sensors to enable automation, ease of use, and safety improvements. The development of WSNs is proceeding to widely survey areas where it is difficult for human beings to monitor and dangerous areas with monitoring sensor terminals. M. Mirhosseini, et. al.[29] introduced a system that applies WSNs to agriculture and gathers the data of sensed farms etc. on a server in real time. According to classification by communication distance (see Figure 2.1), it is classified as a Personal Area Network (PAN), and communication by ZigBee[30–33] and Bluetooth[32–37] is spreading, in particular.

ZigBee

ZigBee is one of the wireless communication standards developed for WSN promoted by ZigBee Alliance. ZigBee has a feature that although the transfer speed is low, it is power saving, since communication and driving methods are designed as simple as possible, and a battery-driven environment is suitable for communication between sensor terminals frequently assumed.

The greatest merit of power saving is that it can be driven with dry batteries, solar batteries, etc. Depending on how the application is used, it is possible to have a battery life of several months to several years. In addition, both the communication cable and the power cable can be made wireless, so it has excellent workability.

ZigBee was also applied to communication between communication devices attached to motorcycle helmets, and commercialization was also realized because of its power savings[38)]. Ultra-compact wireless microcomputer modules are also on sale[39)].

In addition, ZigBee has an advantage that it is suitable for accommodating a large number of terminals as compared with the conventional wireless LAN. Specifically, ZigBee has a 16-bit address space, and theoretically, up to 65,534 terminals can be accommodated in one network[38)].

Bluetooth

In 1998, Telefonaktiebolaget LM Ericsson, Intel Corporation, International Business Machines Corporation (IBM), Nokia Corporation, Motorola, Inc. and Toshiba Corporation organized Bluetooth SIG[40)] (Special Interest Group). In 2002, Bluetooth was officially standardized as IEEE802.15.1[32)]. In 2013, more than 10,000 companies joined Bluetooth SIG. Bluetooth SIG authorizes a device, and then the device gets the Bluetooth logo[41)]. Bluetooth has three topologies:

Point to Point
: In this topology, a device connects to a device. This type of topology provides communication between two devices. Bluetooth SIG introduced in this topology one-to-one[1:1] connections[42)]. Also, Bluetooth SIG introduced that this type can be used for sports, fitness, health, wellness, PC peripherals, and accessories.

Broadcast
: In this topology, a device communicates to many devices. This type can be applied to point-of-interest beacons, item-finding beacons, and way finding beacons. Bluetooth SIG introduced in this topology one-to-many [1:m] connection[43)].

Mesh
: In 2017, this type of topology is still not widely known; however, mesh topology will be used soon. This type can be applied to building automation, and WSNs. Bluetooth SIG introduced in this topology many-to-many [m:m] connection[44)].

2.1.2 Introduction of WSANs

WSANs composed of actors and sensors have emerged as a variation of WSNs. Comparing WSNs, WSANs have actors which provide various services. Also, sensors are deployed in a service area in WSANs. Sensors collect and send various data to actors to let them know the situation. Then, actors do tasks depending on the situation at that time. In other words, actors collect sensed data from sensors in order to do tasks. Of course, actors also can monitor physical phenomenon, process sensed data, make decisions based on the sensed data and complete appropriate tasks when needed[20]. For example, sensors can find abnormalities in the temperature and humidity in a room. Actors may check the room due to their decision. Then, the actor may find a fire and try to extinguish it before it spreads though the whole building, or, in a more complex scenario, to save people who may be trapped by a fire.

Unlike WSNs, where the sensor nodes tend to communicate all the sensed data to the sink * by sensor-sensor communication, in WSANs, two new communication types may take place:

Sensor-Actor

Sensed data is sent to the actors in the network through sensor-actor communication. After the actors analyze the data, they communicate with each other in order to assign and complete tasks.

Actor-Actor

Also, an actor can communicate with other actors to share information of the tasks concerning the situation.

To effectively operate a WSAN, it is very important that sensors and actors coordinate in what is called sensor-actor and actor-actor coordination. Coordination is not only important during task conduction, but also during a network's self-improvement operations, i.e. connectivity restoration[45,46], reliable service[47], Quality of Service (QoS)[48,49] and so on. Sensor-Actor (SA) coordination defines the way sensors communicate with actors, which actor is accessed by each sensor and which route data packets should follow to reach it. Among other challenges, when designing SA coordination, care must be taken in considering energy minimization because sensors, which have limited energy supplies, are the most active nodes in this process. On the other hand, Actor-Actor (AA) coordination helps actors to choose which actor will lead performing the task (actor selection), how many actors should perform it and how they will perform. Actor selection is not a trivial task because it needs to be solved in real time, considering different factors. It becomes more complicated when the actors are moving, due to the dynamic topology of the network.

*There may be applications with single-sink or multiple-sinks.

Table 2.1: Ad-hoc routing protocols.

Types	Protocols
Proactive Routing	OLSR, TBRPF, LANMAR, DSDV, FSR, IARP
Reactive Routing	DSR, AODV, DYMO, TORA, ABR, ETR, IERP
Hybrid Routing	ZRP, B.A.T.M.A.N.

2.2 Mobile Ad-hoc Networks: MANET

2.2.1 Introduction of MANET

MANET is now standardized by IETF MANET WG and AUTOCONF WG, and assumes that mobile terminals perform communication between ad-hoc mobile terminals[50)]. The most defining characteristic of MANET is that each communicates to a target node by using the resources of neighboring nodes. Also, there is no client-server relationship in MANET. Therefore, it can be said that MANET is a kind of P2P communication in a broad sense.

MANET is a network composed of mobile terminals that can be carried. Therefore, power saving among mobile terminals is attracting great interest[51)].

MANET is an autonomous decentralized system, and the more nodes there are, the stronger the infrastructure. Therefore, some researchers are exploring the development of killer applications[52,53)].

In addition, the idea of Delay/Disruption Tolerant Networking (DTN) is applied to MANET, and research into it as a more useful network is also being carried out in the event of a disaster[54–57)].

2.2.2 Routing Protocols in MANET

Currently, many routing protocols have been proposed and evaluated such as DSR, AODV, DYMO, B.A.T.M.A.N., and OLSR. In addition, it is also possible to use a number of protocols such as: Topology Dissemination Based on Reverse-Path Forwarding (TBRPF), Landmark Routing (LANMAR), Fisheye State Routing (FSR), Temporally Ordered Routing Algorithm (TORA), Associativity Based Routing (ABR), Estimated-TCP-Throughput maximization based routing (ETR), Destination Sequenced Distance Vector (DSDV), IntrAzone Routing Protocol (IARP), IntErzone Routing Protocol (IERP), and Zone Routing Protocol (ZRP) that selectively uses IARP and IERP have also been proposed and evaluated.

As shown in Table 2.1, the ad hoc routing protocols developed so far can be classified into three types: Proactive, Reactive and Hybrid. These can be used properly depending on the environment in which the characteristics can be utilized[28)].

Dynamic Source Routing

Dynamic Source Routing (DSR) is a Reactive protocol that performs a route search after a communication request is generated. Its feature is that the source terminal designates a route to the destination terminal and performs communication.

Each terminal from the DSR route search to the data communication start has a cache and keeps the state where the route information which has been transmitted and received so far is stored. When a communication request is issued to the terminal, it checks whether or not the route information to the destination terminal exists in the cache held by the transmission source terminal. If it exists, data communication is started using the route information. If it does not exist, it floods RREQ (Route Request) including its own terminal ID in the route information. After receiving the flooded RREQ, the adjacent node adds the route information to the cache and then checks the destination of the RREQ. If the destination is itself, it creates a route reversing the cached route information and transmits RREP to the source terminal. If the destination is not itself, it checks whether there is route information to the destination terminal in its own cache. If there is route information, it transmits RREP (Route Reply) to the source terminal. If it does not exist, it floods again the RREQ that added its own terminal ID to the route information. Here, if its packet's route information contains its own ID, it discards it without flooding. It repeats the transfer of RREQ until it reaches the terminal holding the route information of the destination terminal or the destination terminal[58)].

The terminal that has received the RREQ transmits the RREP having the route information reverse the cached route information after adding the route information to the cache. Upon receiving the RREP, the transmission source terminal starts transmitting the data packet.

When the link used for data communication is disconnected, the route information including the link is deleted from the cache. RERR (Route Error) is transmitted to all source terminals that transmitted the packet using the link. Upon receiving the RERR, the terminal deletes the route information, including the link, from the cache. In DSR, RERR is not sent immediately when the used route is disconnected. First, it checks whether there is an alternative route in its own cache and rewrites the route information of the packet if it exists. By doing this, the DSR also has a Packet Salvage function to resume data communication.

Therefore, when the network topology does not change much, it has the advantage of exhibiting high performance. On the other hand, as the path length becomes longer, the packet size becomes larger, and overhead also increases as the communication becomes long distance.

Ad-hoc On Demand Distance Vector

Ad-hoc On Demand Distance Vector (AODV)[59–63)] is a Reactive type protocol. The reason it is called Reactive type is because it updates the routing table after a communication request is

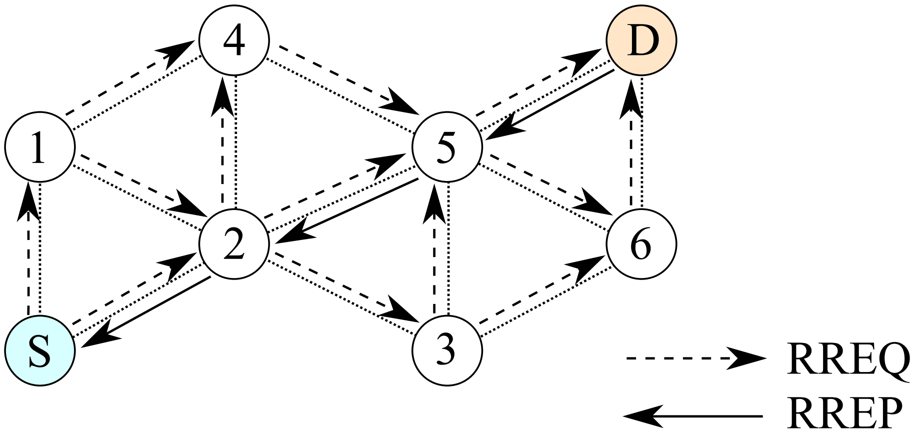


Figure 2.2: An example of routing path construction of DYMO

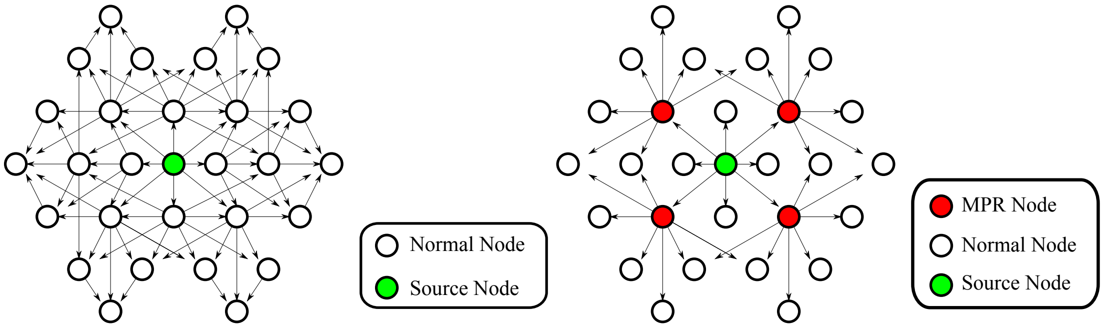
received and communicates it to the destination node.

In AODV, broadcasting is performed to surrounding terminals, and a temporary routing table is created after the transmission request is generated. AODV is fundamentally different from the DSR protocol, and packet transfer uses a routing table. In other words, in the DSR protocol, the source node has the route information, designates the direct route, and tries to transmit through it. On the other hand, in the case of AODV, each node has information on which terminal to transmit to next, so that routing is performed to the destination.

When a message arrives at a terminal that knows the route to the target terminal, it traces the route in reverse and sends a message to the transmitting terminal. Then, the transmitting terminal selects the route with the shortest number of relays from the route in the returned message.

When the link is disconnected, an error message arrives at the sending terminal, and the above process repeats. Furthermore, if the route request fails, the route request can not be transmitted until more than twice the time of first request has elapsed.

In AODV, each terminal does not grasp the entire network but routes only with the information of the destination terminal and the adjacent node. The terminal manages the unique sequence number and conducts efficient routing. By introducing the sequence number, loops in routing are prevented. In addition, AODV uses Hello message used in Reactive type routing protocol, exchanges the information of surrounding terminals and performs efficient routing. Also, at the beginning of the broadcast called Expanding Ring Search, TTL (Time To Live) is intentionally set small, and the reach range is limited to a small extent. This is a technique for suppressing the occurrence of unnecessary packets and suppressing the power consumption of the surrounding terminals in consideration of the case where the target receiving terminal exists within a short distance of the transmitting terminal.



(a) General flooding (b) MPR flooding

Figure 2.3: Examples of general flooding and MPR flooding.

Dynamic MANET On-demand

Dynamic MANET On-demand (DYMO)[64,65] is a routing protocol developed as a successor to AODV, and it is also influenced by DSR. Compared with AODV, the basic operation of routing is simplified, and although it is based on AODV, it has been changed greatly.

Routing in DYMO consists mainly of route construction and route management. Path construction begins with flooding of RREQ. An example of the routing path construction of DYMO is shown in Figure 2.2. As shown in Figure 2.2, when node S transmits data to node D, S broadcasts RREQ and it forwards the received RREQ, except for the destination node. When the destination D receives the RREQ, it unicasts the RREP towards the transmission source S. The relay node transfers the received RREP to the destination, and the route is established by reaching S. In Figure 2.2, the communication route is $S \longrightarrow 2 \longrightarrow 5 \longrightarrow D$.

Also, all the nodes in the MANET have a routing table and have one routing entry for one destination. Each entry has information, such as the IP address of the destination node, the adjacent node, the number of relays to the destination, the sequence number of the destination node, the timeout, etc., and furthermore connections outside of the MANET such as whether the destination is inside or outside the MANET It also has information to consider. Based on the received routing message, the routing entry destined to the source of the routing message is updated. This enables a sequence number that establishes a route based on the latest information of a route, with the route being loop-free. Also, by comparing the number of relays it is possible to construct a route with the minimum number of relays.

When a relay node discovers a link failure in a route in communication or when the forwarding destination of a received data packet cannot be found, the node broadcasts RERR towards the routing message and the source of the data. Upon receiving the RERR, the transmission source (node S) again transmits the RREQ and constructs a newly communicable path.

Optimized Link State Routing

Optimized Link State Routing (OLSR) is a Proactive protocol. The reason why it is called a Proactive type is because it keeps the communication route information up-to-date at all times, so that when a communication request occurs, it responds to the communication request immediately using the latest routing table held in advance. Even if a communication request is not received, if the network topology changes, the terminal updates the routing table to prepare for communication demands at all times. The disadvantage of this protocol is that it constantly uses electricity because it always communicates to exchange topology information. Also, there is a problem with network overload caused by exchanging topology information of the network.

OLSR is characterized by flooding based on MPR (Multi Point Relay)[66,67]. As shown in Figure 2.3, a MPR node repeats flooding information, but a normal node does not repeat flooding. In general flooding, a broadcast storm occurs by all adjacent nodes repeating flooding. Therefore, OLSR attempts to reduce packets by rebroadcasting a packet broadcast or rebroadcast by a certain node only with a node called MPR selected by that node. The flooding mechanism in OLSR is called MPR flooding. The Willingness parameter is used as the selection of the MPR node. Willingness uses integer values from 0 to 7. When 0, it is not selected as MPR, and in case of 7, it is positively selected as MPR node. By dynamically changing the Willingness parameter according to the remaining battery capacity of the terminal, nodes with low battery level dynamically deviate from the MPR. This has the function of suppressing battery consumption. It is also possible to statically assign the Willingness parameter. That is to say, it is designed and devised so that the parameter is set high for terminals with a power supply, and for the terminals that do not last long on battery, it is set low so that the survival time of the entire network can be extended.

In OLSR, TC (Topology Control) messages are used separately from Hello messages to communicate the topology of the entire network to each node. Since the topology is constructed from the MPR selector set of each node, unlike networks consisting of all actually existing links, the number of links to be managed is much smaller than the actual number of links. OLSR performs heuristic MPR node selection corresponding to RFC. All nodes determine the shortest path by a simple Dijkstra algorithm; however, it is unlikely that obtaining the shortest path by this method is an advantage from the viewpoint of packet error rate. Therefore, OLSRd extends Link Quality (LQ). This is the shortest path algorithm with the average of the packet error rate as the metric, which is generally called the Expected Transmission Count (ETX).

ETX[68] represents the priority to select the MPR node at the time of route selection. d_f is the packet loss probability of its own node, and d_r is the packet loss rate of the adjacent node. The lower the packet loss rate, the closer the ETX is to 1. That is, there is a high possibility of being selected as MPR at the time of route selection. In order to calculate the packet loss rate, it uses the HELLO message, where the rejection rate varies depending on the number of the LQWS (Link Quality Window Size). Since each attempt to send a packet can be viewed as a Bernoulli trial, the expected number of transmissions of the link is approximated as follows.

$$\text{ETX} = \frac{1}{d_f \times d_r}. \tag{2.1}$$

The lower the packet loss rate, the higher the ETX value and the higher the priority when selecting the route. Douglas S. J. De Couto reports that the packet delivery rate has greatly increased due to the expansion of LQ[69].

There are several implementations of OLSR, but most of them have been improved many times from RFC 3626 and improvements have been made to construct a mesh network covering the entire city. However, in this Link State type algorithm, there is a report that it takes several seconds to reconstruct the topology graph in a network composed of a large number of nodes, where the number of nodes exceeds 450 nodes[59,70]. Therefore, ETX etc. mentioned above was added, but Link State type algorithm has a problem in scalability.

Better Approach to MANET

Better Approach to MANET (B.A.T.M.A.N.)[71,72] is a protocol that has been designed to be considered for selecting simple and robust multihop routes. The features of this protocol are low process, guaranteed low-cost/traffic, as well as adaptive and loop-free route selection. Each node of the mesh network divides and manages information on the best End-to-End (E2E) path and manages only information on the best adjacent node. As a result, there is no need to know all of the table information, as only information on the local topology changes. Furthermore, in spite of the event type, it is possible to avoid the overhead of control traffic and to prevent the flooding amounts of messages concerning different topology information to a certain extent. Also, the algorithm is designed to be compatible with networks formed by untrusted links.

Each node advertises survival information to each adjacent node by using broadcast messages (OGMs). The adjacent node will flood the message by rebroadcasting OGMs according to specific rules. OGMs are small, including IP and UDP packets, and total 52 bytes, consisting of source node address, relay node address, TTL and sequence number. OGMs forward packets over fast and reliable routes. Each node rebroadcasts only OGMs advertised from the current best relay neighbor node. It judges from the sequence number whether OGM has been received once or several times.

2.2.3 Issues in MANET

In discussing MANET, the biggest problem is matters concerning routing path determination[73]. Determining routing paths affects all aspects of network performance, reliability, throughput, QoS, and even security. In addition, there are problems, such as how much to allow the use of the energy and information of its own node for the communication of other nodes. Therefore, the selection of the routing path is so important that it can be considered a serious problem in MANET.

Application areas of MANET are expected to be wide, such as large-scale natural disasters. To realize these applications, it is necessary to build and operate a large-scale ad hoc network composed of many terminals[74)]. However, with the increasing scale of the network, there is the problem that the communication band is occupied by the control packet. The cause of the problem lies in the flooding of control packets in a large-scale ad hoc network. Basically, the existing protocol exchanges information and controls routes by using the flooding of control packets. Although AODV searches for routes by flooding RREQ packets, the number of packets to be transmitted is proportional to the number of nodes, since it requires relaying as many as the number of nodes in the network. Furthermore, since a communication request proportional to the number of nodes occurs, the amount of RREQ packets is represented by $O(n^2)$ where n is the number of nodes. OLSR uses MPR to limit the number of terminals relaying TC messages, thereby reducing the number of packets transmitted in the network. However, since the packet size of the TC message is basically $O(n^2)$, the overflow of the control packet causes a drop in the packet arrival rate. So, if the amount of control packet related to flooding can be reduced, scalable routing capable of handling large-scale ad hoc networks is also possible.

In addition, as described in Section 2.2.1, MANET is a network whose effectiveness increases as the number of terminals increases. Conversely, one problem is that of how to increase the number of users until it is widely used. In response to this problem, research and development, such as the development of a killer application assuming the use of a MANET environment is progressing.

Chapter 3

Wireless Mesh Networks

The Internet is an infrastructure of our daily lives, owing to the rapid pace of development of communications technology in recent years. The number of Internet users and the number of nodes participating in the network is increasing.

From 2015 to 2016, 281 million people joined the network, as shown in Figure 1.1. The factor that continues to cause explosive growth so far is the establishment of technology such as Mobile IP[75–78], in order to connect mobile nodes to the Internet.

However, the Kumamoto earthquakes made many people physically isolated on April 14, 2016, for some hours[79]. Also, on March 11, 2011, due to the Tohoku earthquake caused by the Tohoku Region Pacific Offshore Earthquake, multiple base stations became unusable and many people were isolated. Much of the reason for why it became unusable is due to power outages. Due to long-term power outages, the fuel in the private power generation facility was exhausted, and finally communication services ceased[80,81]. At that time, WMNs using balloons ware constructed and used as a temporary communication infrastructure. In this way, the usefulness of WMNs was reconfirmed and more attention was gathered.

3.1 Mesh Networks

A mesh network is a network in which there are nodes that always have a plurality of routing paths. Since the network topology is not a tree structure, there are cases where the network has detour routes when a sudden accident occurs. If a detour route exists, the network can autonomously repair the function of the network itself by adopting a method of automatically changing the routing path according to the settings that were made in advance. Therefore, the mesh network has the feature that it is more robust than the conventional tree network[82–85].

However, a loop always exists because the mesh network and a non-tree network. Therefore, a routing mechanism fundamentally different from the tree structure network is required. Also, the mechanism for automatically changing the routing path is also complicated compared to an ordinary tree structure network.

Routing protocols such as RIP (Routing Information Protocol) and OSPF (Open Shortest Path First) are available as dynamic routing protocols compatible with conventional wired mesh networks. RIP is a relatively old protocol that uses hop count for metrics. OSPF is a relatively new protocol using bandwidth-aware cost as a metric. Here, SPF is the Dijkstra algorithm. In fact, OSPF uses the Dijkstra algorithm to share routes with the smallest cost considering bandwidth in the entire network and perform routing.

However, all of these are protocols which assume a wired environment, and it is unexpected that the network topology will change from moment to moment. Therefore, there is a need for a mechanism to autonomously update routing paths robustly and efficiently against continuous changes in network topology.

3.2 WMNs

WMNs are a communication method standardized as IEEE802.11s[50,86,87]. Communication distance classification is generally classified as a wireless MAN (see Figure 2.1). WMANs cover an area of several square kilometers.

Wireless mesh routers are ineffective compared to base stations for cellular phones, but each mesh router gets coverage of several kilometers by multi-hop. Also, since a mesh is configured as a network topology, even when a certain wireless mesh router stops for some reason, self-repair of the network is performed by a functioning wireless mesh router. Then, a detour route is reconstructed to minimize the influence on the entire network and conceal the state change of the network to the user[28].

In a network with a mesh topology, determining the routing path to communicate is not simple. In particular, because it is constructed by radio, the links between these nodes are easily broken compared to the wired network. Therefore, even if a path breaks due to a failure or a communication failure, a certain node is required to repeatedly reconnect and reconfigure. In other words, WMNs are networks that needs to self-organize and have self-healing capability.

WMNs for connecting to the Internet at all times have been actively studied for the purpose of using as a regular infrastructure. There is also a research group that distinguishe a WMN that is always connected to the Internet as WIMNET (Wireless Internet-access Mesh Network)[88–93].

3.3 Node Classification in WMNs

WMNs can be classified into the following four kinds of nodes according to their roles:

MP (Mesh Point)

MP is a node that implements the mesh function necessary for configuring the wireless mesh network. MP does not accommodate the STA. In addition, it supports PLMP (Peer Link Management Protocol[87]) to discover neighboring nodes and to keep track of them. Due to the performance of MP, it should be noted that the number of detections of adjacent nodes is limited. Also, because it communicates with nodes that are farther than 1 hop, MP supports HWMP[94] which is a hybrid protocol for wireless mesh, and MAC addresses are used for routing. The functions of MP can be done with software, and it can be implemented in PC, information appliances, AP, portable nodes and so on. It has a role like a routing hub bridge in the mesh cloud[95] of WMN.

MAP (Mesh Access Point)

MAP is a node that implements the functions of the AP, and has a function of accommodating connections from the STAs, which are wireless LAN nodes that do not implement the mesh function. MAP functions as an AP for a node that does not have a mesh function. It can also function as an MPP by connecting to a wired network.

MPP (Mesh Portal collocated with a mesh Point)

Wireless mesh networks, which are standardized in IEEE 802.11s, can be used for various purposes. For example, it can be used for the purpose of providing Internet access at low cost. In this case, at least one node and potentially some nodes are connected to the Internet. Users connected to the WMN can access the Internet via the MPP connected to both the wireless mesh network and the Internet. As a feature, the MPP needs to have at least two interfaces to provide a gateway function.

STA (Station)

The STA is a conventional wireless LAN node that does not have a mesh function.

The WMN consists of a mesh cloud, which is a component, and an STA which is a client node. The mesh cloud consists of a mesh router. The mesh router is divided into MPP, MAP and MP. IEEE802.11s assumes that functions such as routing protocols are to be implemented in the data link layer or MAC layer of the wireless LAN, and that mesh clouds (small to medium-sized wireless LAN mesh networks) will consist of about 32 MPs[28].

Actually, since the STAs are connected to each MAP, the number of nodes accommodated in the entire network is several hundred units. In addition, it is possible to expand the scale of the mesh cloud by connecting via a plurality of wireless LAN mesh networks or directly. A comparison image between WMN and the current wireless LAN is shown in Figure 3.1. As shown in Figure 3.1, everything besides the MPP having the role of the gateway are wirelessly connected.

In a conventional single-hop wireless LAN, if a gateway that controls the entire network fails, it was supposed to fall into SPF (Single Point of Failure) with the entire wireless LAN

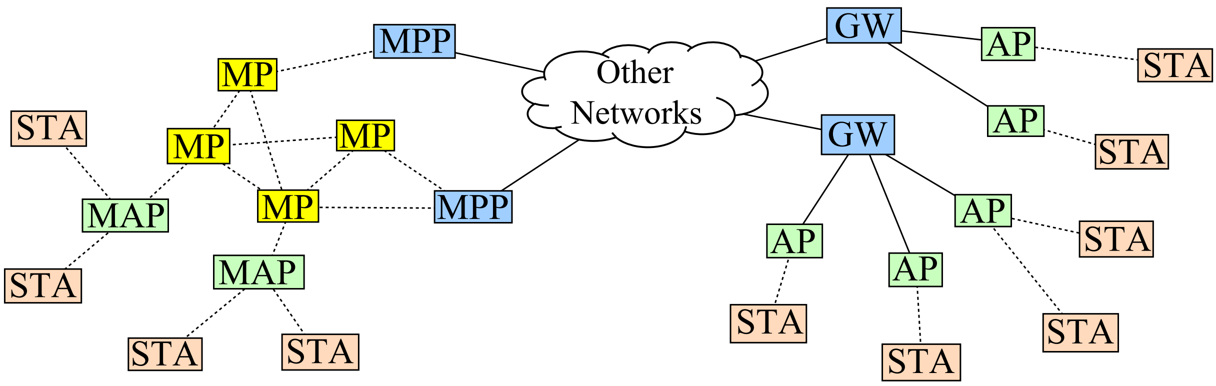


Figure 3.1: Comparison image between WMN and the conventional wireless LAN.

becoming inoperable. However, WMN has high reliability because it has a self-repairing function. Since there can be multiple MPPs that can be connected to an external network, usually one MPP is always connected. So, the other MPP's gateway function is set to the warm standby state, so that it will not fall into SPF, leading to an improvement in the reliability of the network[96)].

3.3.1 Architecture of WMNs

The architecture of WMNs can be roughly divided into the following three types.

Infrastructure/Backbone WMNs (I/B WMNs): I/B WMNs communicate with the outside using other existing networks. In the I/B WMNs, nodes other than the MPP serving as the gateway perform wireless communication. The MP has a hop function between the nodes and is used for expanding the communicable area. MAP connects with MPP and MP and provides communication to STA, which is a conventional wireless LAN terminal. As mentioned above, this architecture is based on the premise of connecting with other networks, so existing infrastructure can be used.

Client WMNs: In this architecture, each node temporarily forms a network and performs Peer to Peer (P2P) communication. With this type, there is no concept of server or client, and each node does the task for each communication. When a packet is transmitted from a node, other nodes hop the packet until the packet reaches the target node. Client WMNs are exactly the same as MANET described in Section 2.2 above when the possibility of becoming Hybrid WMNs is zero.

Hybrid WMNs: The architecture in which the I/B WMNs and the Clients WMNs are combined, as described above, are called Hybrid WMNs. This is an architecture combining the good points of I/B WMNs and Clients WMNs. In Hybrid WMNs, client nodes can connect to the network via router nodes. If a client node is not directly connected to a router, the client node can get an Internet connection via other client nodes. Thus, it is easier to improve network connectivity with a Hybrid WMN than with a conventional type of wireless LAN.

3.3.2 RM-AODV

Radio Metric AODV (RM-AODV) is a Reactive type routing protocol with improved AODV.

As mentioned in Section 2.2.2, AODV floods the RREQ message until the RREQ message arrives at a node that either has the route information of the end node or is end node. In this process, the node that received the RREQ message transmits the RREP message based on the route information of the source node in the routing table after updating the routing table. In RM-AODV, by using the transmission delay of packets for the metric, a route with less transmission delay is set as a communication route[97)].

The source node performs route searches by flooding the RREQ message to the nodes in the network. When the adjacent node receives the RREQ message, it returns the RREP message to the source of the RREQ, thereby establishing a communication route with the communication destination node. When the source node of the RREQ message receives a plurality of RREP messages, a node with a small transmission delay is selected from the metric value and set as a communication route. Since AODV uses an IP address, it operates at layer 3 of the OSI reference model and uses hop count as the routing metric. On the other hand, RM-AODV operates in Layer 2 of OSI reference model, using a MAC address, and uses the routing metric of wireless-aware, due to packet transmission delay for route selection[98,99)]. For example, when there are multiple access points, access points with low-frequency utilization rates are used. With these functions, it is possible to select a route with high communication efficiency in the wireless network.

3.3.3 RA-OLSR

Radio Aware OLSR (RA-OLSR) is a Proactive type routing protocol which has improved OLSR, which is an existing routing protocol. As mentioned in Section 2.2.2, OLSR broadcasts a Hello message in which each node includes its own address and/or neighbor address information. The node that received the Hello message can obtain the node address two hops away, in addition to the address of the neighbor node.

The RA-OLSR creates the STA list contained in the MAP and delivers the message of the STA list to all the mesh routers. According to the message of the STA list, the MAP adds the STA list accommodated in the wireless mesh network. With this, it is possible to grasp which STA is contained in which MAP.

OLSR uses the cost of considering packet loss probability as the metric and derives the shortest path, whereas the RA-OLSR uses the metric to consider the radio.

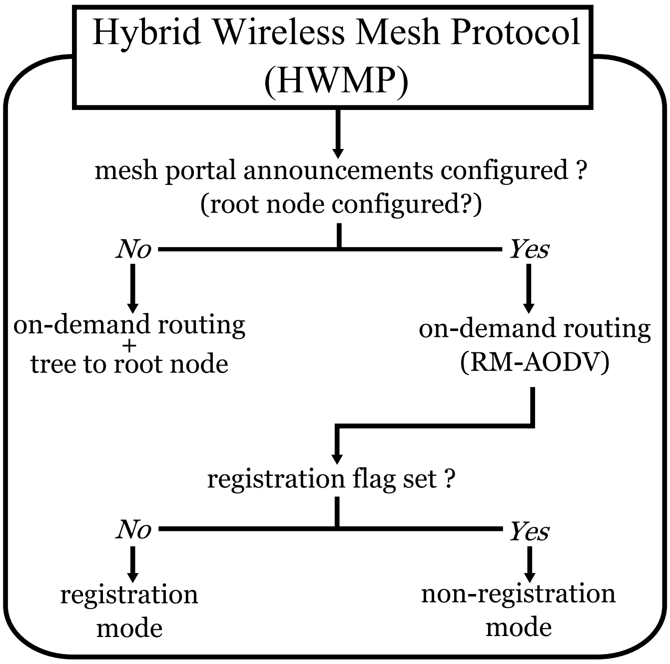


Figure 3.2: Configurability of HWMP.

3.3.4 HWMP

This section describes Hybrid Wireless Mesh Protocol (HWMP). According to the literature[94, 100], the hybrid nature and the configurability of HWMP, which is illustrated in Figure 3.2, provide good performance in all anticipated usage scenarios.

HWMP uses a sequence number to detect route information whose expiration time has passed. It discards the received sequence number if it is older than the sequence number currently registered in the MP and receives the route information having a sequence number newer than the sequence number already registered in the MP. This avoids classical problems such as infinite loops. Each entry in the routing table has a lifetime (TTL) associated with it. When the expiration date of TTL has passed, it automatically deletes unused routes. The expiration date is re-set each time a control message is sent via the route.

HWMP is a routing protocol defined as the default of WMN which is the IEEE802.11s standard. Devices compliant with all IEEE802.11s standards support this protocol. Therefore, it is possible to operate WMN mutually between devices of different vendors.

HWMP basically performs Reactive type routing by RM-AODV and adopts a well-known route discovery method by DSR[58] and AODV[59–63].

3.4 Merits of WMNs

In terms of cost, wireless communication is used to increase the number of routers in the network, so wired costs can be reduced. In heterogeneous types of network clouds, so far the cost of purchasing and maintaining LAN cables, which was essential for expansion, is hardly required by WMN. Since WMN has a mesh topology, it becomes possible to secure multiple paths, and communication can be carried out by flexibly switching paths when the radio wave environment changes or a fault occurs[101)]. Also, since the mesh cloud is a homogeneous network, device management is easier than a conventional wireless LAN.

Radio waves used for communication by an ideal antenna (isotropic antenna) spread spherically. Therefore, as Friis transmission formula shows, which is described by

$$P_R = \left(\frac{\lambda}{4\pi D}\right)^2 G_T G_R P_T,$$

where P_R is received power [W], P_T is transmission power [W], G_R is received gain [1], G_T is transmission gain [1], λ is wave length [m], and D is distance [m], derived from the Maxwell equation, the power required for communication is proportional to the square of the distance, theoretically[27)]. In fact, it is said that the transmission power required for wireless communication is proportional to the 3^{rd} to the 5^{th} power of the communication distance[102)]. Therefore, it is expected that a relay communication that hops a relatively short distance more effectively than the long distance wireless communications, like a cellular phone network, can effectively utilize power for communication.

3.5 Demerits of WMNs

Representative problems of WMNs include degradation of throughput characteristics due to hidden/exposed terminal problems, congestion control, QoS control, ensuring interconnectivity, and problems related to route tree generation. Also, IEEE802.11s assumes that the routing function is performed not on the network layer in the OSI reference model but on the data link layer or the MAC layer, causing layer violation [*].

In order to solve these problems and to take advantage of the merits of WMNs, it is important that with the routing protocol, the main functions such as the radio resource management function and radio control function implemented in the MAC layer, cooperate in real time and operate[103)].

Furthermore, research on routing in WIMNET which consider the use of WMNs for Internet always-on access is being actively conducted[90)]. Considering that WMNs are always connected to the Internet, it is a disadvantage that constraining conditions increase. However, it goes without saying that it is preferable to use WMNs as one of the usual infrastructures.

It is effective to have redundancy when placing a mesh router to improve the reliability of

[*] Violation related to layered design: The flexibility of problem-solving obtained by layer violation is attractive, although the flexibility obtained by layer violation brings about complications in managing the system.

links between nodes in WMNs and failures of the mesh routers. However, when all the mesh routers in the network are in operation, the problem of performance degradation arises due to radio wave interference and an increase in the cost of electricity. Therefore, when selecting an operating mesh router in practice, we aim to improve throughput characteristics by formulating the selection problem and using algorithms. In addition, proposals and research for minimizing the number of mesh routers to be operated are being actively conducted[104)].

WMNs construct a mesh network by establishing GW as the entrance of the external network. HWMP is adopted by default for WMN route construction. However, as access to the Internet increases, traffic concentrates on the GW, which increases the load. To solve this problem, by arranging multiple GWs, traffic is distributed so as not to concentrate. At that time, it is necessary to select an appropriate GW from a plurality of GWs.

However, in HWMP, it is difficult to calculate which GW is selected and determined as a passing point, and there is no guarantee that the optimum GW can be practically selected. Therefore, at the present stage, it is impossible to construct an optimal route tree considering load balancing.

The problem of route tree generation is introduced in Section 3.5.1. Then, the hidden node/exposed terminal problem is explained in Section 3.5.2.

3.5.1 Problems of Route Tree Generation

Route tree generation in WIMNET is for generating a tree-structured route based on a certain metric among a plurality of nodes having a certain number of links.

Definition of the Decision Problem of Route Tree Generation Problem

The decision problem is defined by changing the problem on the route tree generation problem in WIMNET as follows.

Problem

Does there exist a route tree T with the objective function $E^T \leq E_0$?

Here, the objective function E^T is the maximum value of the traffic amount for the link between the MPP and its adjacent mesh router (MP), and E_0 is the delay tolerance, which is a constant given by input. NP-completeness of the decision problem of route tree generation problem is proved by the return from the Bin Packing Problem which is known to be NP-complete.

Definition of the Bin Packing Problem

The Bin Packing Problem is a problem of determining the existence of assignments that can be made when items of various sizes are allocated to a plurality of containers of constant

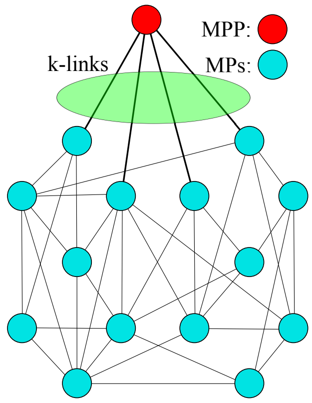


Figure 3.3: Mesh routers network.

size[105–107]. Also, in such a case, one item must be assigned to one container without being divided. The size of the item u will be a positive number $s(u)$ and let U be the set. Also assume that there are K containers whose size is a positive number B, and that set is V. Then, the Bin Packing Problem is defined as follows.

Problem

Is exist a way to assign each item to K containers so that the sum of the item sizes in each container is less than or equal to size B?

Proof of NP-completeness

The route tree generation problem clearly belongs to the class NP. Also, any instance of the Bin Packing Problem can return to the following instances of the route tree generation problem.

- Mesh router to mesh router network
  - Number of Mesh Routers: $N = 1 + K + |U|$ (U is an amount number of MP);
  - Classification for each mesh router: every mesh router is MP;
  - Link set between mesh routers: MPP connects (there are links) with K mesh routers. Other interconnections between U mesh routers are as shown in Figure 3.3.
  - The communication band of the mesh router to mesh router links: $s_{ij} = 1$
- Communication load
  - Maximum number of connected hosts per mesh router
    - MPP: $h_0 = 0$
    - K mesh router connected to MPP: $h_i = 1 \quad (i = 1, \ldots, K)$
    - Others: $h_i = s(i - K) \quad (i = K + 1, \ldots, K + |U|)$
  - Average transmit traffic per host: $S = 1$

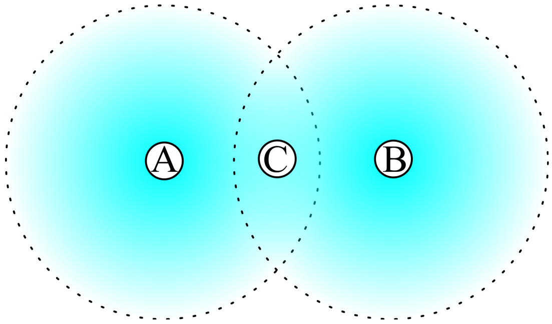


Figure 3.4: Example of hidden terminal problem.

  - Average received traffic per host: $R = 0$
- WIMNET design constraints
  - Total NIC count: $B = N$
  - Maximum MP number in WDS cluster: $WSIZE = \infty$
  - Maximum number of NICs per mesh router: $b_i = 1$
  - Maximum number of channels: $M = 1$
  - Channel interference rate matrix: $C(i, j) = 0$
- Delay tolerance: $E_0 = B + 1$
- Propagation delay correction coefficient of objective function E^T: $\alpha = 0$

In this instance of the route tree generation problem, the objective function E^T is the maximum value of the traffic of the link between the MPP and its adjacent mesh router (MP). This traffic matches the sum of the traffic (item size) from all the mesh routers connected to the link. As a result, the container assignment of items whose capacity is less than or equal to the capacity B due to the Bin Packing Problem coincides with the route tree T in which the evaluation function is equal to or less than E_0 in the route tree generation problem.

Therefore, the route tree generation problem in WIMNET is NP-complete, so it is not realistic to reach a reliable exact solution in real time. K. Uemura et, al.[90)] have proposed clustering of nodes and have approached it based on a reduction of solution space.

3.5.2 Hidden/Exposed Terminal Problem

In this section, we describe the Hidden Terminal Problem and Exposed Terminal Problem.

Hidden Terminal Problem

An example of the hidden terminal problem is shown in Figure 3.4. The hidden terminal problem is a situation in which two nodes A and B are unrecognizable from each other and when

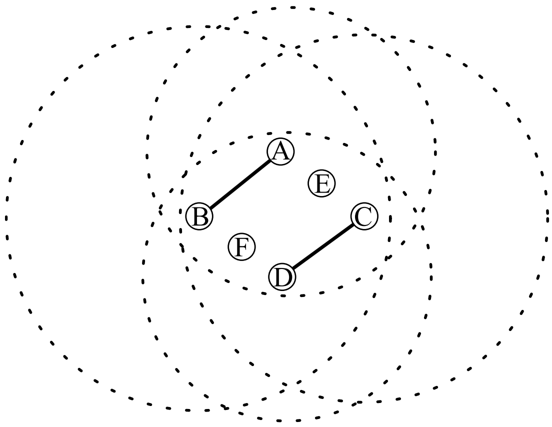


Figure 3.5: Example of exposed terminal problem.

node A and node B simultaneously transmit radio signals, a signal collision occurs in reception node C. From node A, there is no way to know whether node B is transmitting or not. Likewise, even from the standpoint of node B, there is no way to know whether node A is transmitting or not. Therefore, the nodes A and B may transmit signals to the receiving node C at the same time. When node A and node B transmit signals at the same time, a collision of packets occurs at reception node C, and furthermore, the collision can not be detected, which causes a considerable decrease in throughput.

There is a method called CSMA/CA with RTS/CTS that establishes a connection in advance between transmitting and receiving nodes as a countermeasure against the hidden terminal problem[108)]. In order to prevent data from being sent to the destination node simultaneously with other nodes, the RTS/CTS first transmits an RTS (Request to Send) message from the transmitting node to the destination node and requests permission for data transmission. After the destination node receives the RTS message, the destination node responds to the sending the node with a CTS (Clear to Send) message for permitting data communication. With the above procedure, a connection is established in advance between transmitting and receiving nodes. By establishing the connection in advance of data transmission, the collision of frames with other transmitting nodes is avoided.

On the other hand, a disadvantage of RTS/CTS is that there is a possibility of suppressing the frame transmission of other nodes. If a plurality of nodes existing within a range where carrier wave detection is possible to transmit frames to different destinations, frame collision does not occur. However, when one transmitting node transmits a frame earlier, the other node detects the carrier wave and suppresses the frame transmission. This further exacerbates the exposed terminal problem described later. In addition, since the procedure of RTS/CTS is followed, a slight delay occurs at the start of data transmission.

Exposed Terminal Problem

The exposed terminal problem is a problem where a certain node intercepts the communication of another adjacent node, suppressing transmission to the target node, and lowering the throughput. An example of the exposed terminal problem is shown in Figure 3.5. In Figure 3.5, all the nodes (A to F) are intercepting the communications of all the other nodes. Node A and node B, node C and node D communicate with each other in Figure 3.5. At this time, although node E and node F want to communicate, communication frequency is suppressed in order to avoid packet collision with other nodes, resulting in lower throughput.

3.6 Node Placement Problem in WMNs

The placement of mesh routers in WMNs becomes a multi-objective optimization facility placement problem, which is a very complicated problem called NP-hard.

Here, NP-hard is a problem which is at least equal to or more difficult than the problems belonging to class NP in computational complexity theory. NP stands for Nondeterministic Polynomial time, and the NP problem is “a problem that can be solved in polynomial time by a nondeterministic Turing machine”. A nondeterministic Turing machine is a fantasy theoretical machine that can always select an option that approaches a solution when there are multiple choices that go from the current state to the next state. When the problem space is considered as a search tree, it is a problem that can be reached in polynomial time when we believe that it is possible to reach a child node with a solution by an ideal heuristic function. Even in this problem space, computers are deterministic Turing machines, and there is no choice but to search trees. Therefore, the calculation time order is expressed by $O(c^n)$, and the order becomes an exponent. Where, c is the number of branches, and n is the depth of solutions. Then, if $P \neq NP$ prediction is affirmed, it is effective to find an optimal solution or a suboptimal solution by using intelligent algorithms for the node placement problem in WMNs. This has become a practical method with the development of computer technology in recent years[109)]. Therefore, node placement problem in WMNs is a “difficult” problem also from the viewpoint of computational complexity theory.

However, the merit of mesh router placement optimization in WMN is immeasurable. As mentioned above, energy efficiency improves because it does not pass unnecessary packets, and such as reduces the cost by effectively using resources such as routers. Also, it is possible to construct a network that can withstand sudden accidents. Therefore, in order to solve this problem, the intelligent algorithm which is considered effective for the theoretically “difficult” problem in terms of the complexity computational complexity will be described in the following Chapter 4.

Chapter 4

Intelligent Algorithms

In this chapter, Intelligent Algorithms are described. The definitions of an intelligent algorithm is diverse, and differs from field to field. "A thing which organically combines heuristics" is also one definition of an intelligent algorithm. There are also research groups that incorporate "A thing which has analogues in natural phenomena" in the definition of intelligent algorithms. There are also research groups that classify intelligent algorithms by "Optimization method by neighborhood search", "Optimization method by dynamic system model", "Evolutionary optimization method", "Multiagent type optimization method" and "hybrid method" which combines them.

Intelligent algorithms are frequently applied to more difficult class combinatorial optimization problems. Combinatorial Optimization Problem (COP) is a group of optimization problems whose solution space and possible areas are combinable [*]. Specifically, it includes an extremely wide range, such as: integer programming problems with discrete variables and n queen problems leading to very complex combination solutions, Traveling Salesman Problem (TSP) for finding the optimum visiting order at n locations, optimization problems on graphs and networks, scheduling problems for the finite number of tasks to determine the optimal order.

There is an approximate solution as a similar concept of intelligent algorithms. The approximate solution is a technical term used in contrast to the exact solution. While the exact solution refers to an algorithm with an assurance of optimality, whereas the approximate solution is an algorithm without guarantee of optimality. There is no guarantee in the intelligent algorithm of strict optimality, which is the similarity it shares with the approximate solution. The termination criterion of the approximate solution is not clear; however, the intelligent algorithm is a method that can obtain a good solution according to the calculation time at any time. This is the difference between the intelligent algorithm and the approximate solution.

In this chapter, No Free Lunch theorem is explained in Section 4.1.

[*] Combinable: It reflects the mathematical properties of a discrete or finite (or enumerable infinite) set. Discrete optimization and discrete programming have similar meanings.

4.1 No Free Lunch Theorem

A universal optimization algorithm has been proven not to exist[110]. The No Free Lunch theorem says that "when designing a system that performs any optimization, the expected value for optimization in each algorithm is equivalent." Therefore, it is necessary to design the system using algorithms suitable for certain problems, taking into consideration the characteristics of each algorithm and making use of the merits of each algorithm.

4.2 Local Search Algorithms

4.2.1 Hill Climbing Algorithm

Hill Climbing (HC) is a local search algorithm that is based on incremental improvements of solutions, as follows. It starts with a solution (which may be randomly generated) considered as the current solution in the search space. HC examines its neighboring solutions and if a neighbor is better than the current solution then it can become the current solution. HC keeps moving from one solution to another one in the search space until no further improvements are possible. HC is actually a very simple algorithm. Also, it should be noted that HC usually ends up in local optima.

The solution search process of HC is often compared to a climber. The solution space with multimodality is shown in Figure 4.1. In Figure 4.1, the height (altitude) is determined by the combination of the horizontal axis (latitude) and the vertical axis (longitude) †. By considering the height here as the value of the fitness function (the higher it is, the better the solution), it can be compared to a climber's point of view.

Depending on the start point, HC may reach a different hilltop. Thus, when the solution space is unimodal, HC is a very powerful algorithm. HC algorithm is a very important mechanism for intelligent algorithms. In other words, HC is a basis for intelligent algorithms.

4.2.2 Simulated Annealing Algorithm

Simulated Annealing (SA) is an improved version of HC. SA is said to be independently proposed by S. Kirkpatrick et al.[111] and V. Černỳ[112]. The design basis of SA was already built by Metropolis et al.[113] in 1953.

SA is one of the probabilistic approximate solutions that exerts power against NP-hard problems, such as optimization problems, and its principle is inspired by the annealing phenomenon. In annealing, the energy of particles of high-temperature material initially spread randomly.

†Although the solution space here is represented by two variables, the actual problem is often determined by the height of the multidimensional element.

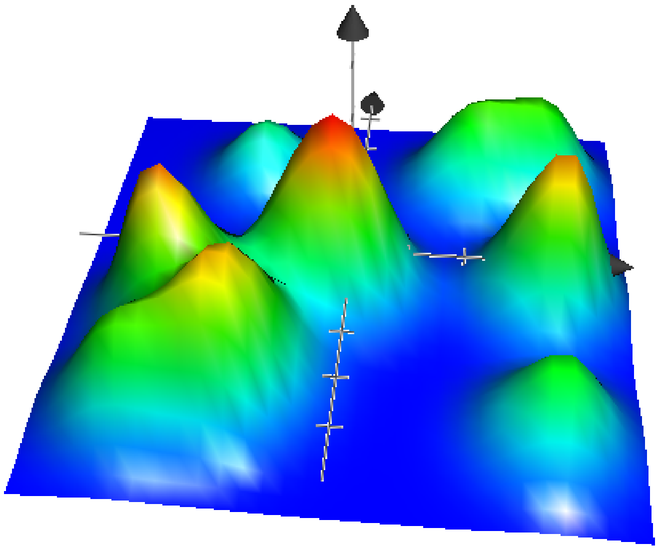


Figure 4.1: The solution space with multimodalit.

Energy is scattered, but by lowering the temperature slowly, the particles converge to a well-ordered state and reach an aligned ground state, that is, the lowest (stable) state of energy. The energy here, which is regarded as the cost of optimization, composes the SA. SA can be structured in various styles by organically combining and repeating various strategies. Intelligent algorithms are a technical technique that solves a problem skillfully by using degrees of freedom generated by such a configuration. Furthermore, by devising one, it becomes a robust and practical tool against the combination optimization problem.

Interestingly, SA has the property that it can theoretically show stochastic convergence to optimal solution. In fact, it is possible to obtain a solution with high approximation, and it is a representative method of an effective intelligent algorithm.

Compared to HC, SA uses a temperature parameter to prevent falling into a local optimal solution. SA is also often compared to climbers. SA is similar to climbers searching for the highest altitude point of a certain mountain range before the sun rises after a misty night. SA keeps searching for a position higher than the present position. And even if you reach a certain mountain peak, the peak is not necessarily the highest point in the mountain range. Therefore, the SA prevents a locally optimal solution by using the temperature parameter.

The temperature slowly falls towards the morning, and while it is still warm, the climber does as much movement as possible. In order to find mountains with a higher peak, the climber sometimes moves to a lower altitude. As climbers get colder they learn that the morning is getting closer and they aim to reach a peak of a hill that is as close as possible to where they are now. SA moves to the termination condition while using the temperature parameter.

Process of Simulated Annealing

The process of SA is given a solution P_n and its cost is $f(P_n)$. Next, a neighbor solution P_{n+1} is generated from the solution P_n, and the cost of the solution is $f(P_{n+1})$. Here, when the cost $f(P_{n+1})$ of the neighbor solution P_{n+1} is improved from the cost $f(P_n)$ of the current solution P_n, it moves to the neighbor solution P_{n+1}. If it is not improved, using the probability corresponding to $f(P_{n+1}) - f(P_n)$ and the temperature parameter, it decides whether it moves to the neighbor solution P_{n+1} or not.

By lowering the temperature parameter gradually in the process of this iteration, the sequence of solutions will change to a minimized cost. At this time, by lowering the temperature parameter, a process approaching the optimal solution is realized. What is playing an important role for this is the acceptance criteria for the neighbor solution shown in

$$\Pr\{\text{accept}\,(P_{n+1})\} = \begin{cases} 1 & \text{if } f(P_{n+1}) \leqq f(P_n) \\ \exp\left[\frac{-(f(P_{n+1})-f(P_n))}{T}\right] & \text{if } f(P_{n+1}) > f(P_n) \end{cases} \tag{4.1}$$

to decide whether to move. Where, T represents a temperature parameter, and satisfies $T > 0$. The value of the probability of accepting the neighbor solution is determined by the temperature parameter and the cost difference, and based on it, the solution is allowed to move to a solution which is going to be worse. By introducing this mechanism, it plays the role of kick-up to prevent a drop in the local solution in the neighbor search algorithm, and provides a mechanism for finding a global optimum solution.

Convergence of Solutions

Stochastic convergence to a strict optimal solution can be recognized by treating the solution movement sequence of SA as a Markov chain as a stochastic process. The process of repeating the iteration with constant temperature can be modeled as a homogeneous Markov chain with no change in transition probability. Using this model, the equilibrium state is given by

$$\omega_{P_i}(T) = \frac{\exp\left[\frac{-f(P_i)}{T}\right]}{\sum_{P_j \in X} \exp\left[\frac{-f(P_j)}{T}\right]}, \qquad \forall P_i \in X, \tag{4.2}$$

which is a canonical distribution[114)]. Where, $\omega_{P_i}(T)$ shows the probability that solution P_i will finally distribute after solution $P_i \in X$ has infinite iterations at temperature T, and $\Omega(T) = (\omega_{P_1}(T), \omega_{P_2}(T), \dots, \omega_{P_i}(T), \dots)$ is a vector containing them as elements, and expresses the stationary distribution itself.

If P_{opt} is the global best solution here, and the temperature parameter T gradually approaches 0 with respect to the stationary probability distribution of the Eq. (4.2), each element converges to

$$\lim_{T\to 0}\omega_{P_{opt}}(T) = \lim_{T\to 0}\frac{\exp\left[\frac{-f(P_{opt})}{T}\right]}{\sum_{j\in X}\exp\left[\frac{-f(P_j)}{T}\right]} = \lim_{T\to 0}\frac{\exp\left[\frac{f_{opt}-f(P_{opt})}{T}\right]}{\sum_{j\in X}\exp\left[\frac{f_{opt}-f(P_j)}{T}\right]} = \frac{1}{|X_{opt}|}, \quad (4.3)$$

where, $Xopt$ is a set of optimal solutions. Also, if the solution P_i is not the optimal solution, the solution distribution is given by

$$\lim_{T\to 0}\omega_{P_i}(T) = \lim_{T\to 0}\frac{\exp\left[\frac{f_{opt}-f(P_i)}{T}\right]}{\sum_{j\in X}\exp\left[\frac{f_{opt}-f(P_j)}{T}\right]} = 0. \quad (4.4)$$

For that reason, iteration is performed until the steady state is reached, and in the case of temperature $T \longrightarrow 0$, the probability converges to the distribution of the optimum solution P_{opt}. Assuming that $X(k)$ is a random variable representing the solution obtained after the k^{th} iteration, it is expressed by

$$\lim_{T\to 0}\lim_{k\to\infty}\Pr\{X(k)\in X_{opt}\} = 1. \quad (4.5)$$

At this time, if the given assumption is satisfied, the asymptotic convergence to the strict optimum solution is guaranteed[115)].

In this case, it is a model of a homogeneous case in which temperature is fixed, an infinite movement is repeated, and the temperature is gradually lowered. However, the condition for satisfying the Eq. (4.2) must have sufficient conditions for converging to the optimal solution. Therefore, a limit is given to the number of iterations at a certain temperature, and the temperature is gradually decreased. A model with an inhomogeneous Markov chain in which the transition probability changes is shown. According to B. Hajek[116)], based on some assumptions, convergence of the SA is guaranteed when the temperature parameter sequence is given by

$$T_k = \frac{\Gamma}{\log(k+2)} \qquad (k = 0, 1, 2, \dots) \quad (4.6)$$

for a certain constant Γ or slowly cooled more than Eq. (4.6).

4.3 Optimization Method by Dynamical System Model

In recent years, computer development has made it possible to model a specific phenomenon group and analyze its behavior by computer simulation[117)]. As a result, an optimization algorithm emulating those phenomena has come about by constructing the mathematical model in the computer. It is the optimization method by dynamical system model[118)].

Specifically, it is an optimization method using models of neurophysiology and equilibrium statistical mechanics, and associative memory applying these functions. In particular, phenomena described by nonlinear dynamical models have various unique features due to their nonlinearity. For this reason, the characteristics developed from the inherent functions of nonlinearity caused by the instability of the system are effectively utilized as a global optimization method [‡].

In this optimization method, there is the steepest descent gradient system and a gradient system with an inertia term. If there are further constraints, nonlinear oscillations, chaotic phenomena, and stability analysis are applied to global optimization to strictly satisfy them.

4.4 Genetic Algorithm

The Genetic Algorithm (GA) itself is an algorithm that simulates the process of evolution of living things introduced by Holland[119)] in the 1960s. It has been studied vigorously since the 1980s[120–123)]. A characteristic of GA is that there is flexibility in algorithms, and it can be applied to a wide variety of problems. One of its other features is that it is an iterative calculation method that updates multiple solution candidates simultaneously and in parallel.

GA classified as Evolutionary Algorithms (EA) is an optimization method based on the theory of evolution of living organisms proposed by Darwin. According to Darwin's theory of evolution[124)], living things change their bodies little by little to adapt to the environment.

The process of GA is shown in Figure 4.2. At first, GA generates initial solutions somehow [§]. Then, GA gives a fitness value to a gene by calculating a fitness function. After that, GA selects genes for a later generation, crossovers some genes and mutates a few genes. GA iterates the cycle of the process and terminates if the termination condition is satisfied.

4.5 Multi-agent Algorithms

This is mainly a model of Swarm Intelligence Algorithm (SIA). It is a model that incorporates ideas to mimic the collective behavior of self-organized systems. For example, in a group of

[‡]The global optimization method is a method in which the global optimality of the local optimal solution is caused by the multipoint property of the objective function or the irregular shape of the constraint condition when there is no convexity assumption in the objective function or the constraint region. It is an optimization method that gives a function to avoid the stationary to the local optimum solution when it cannot be guaranteed.

[§]Most of the case, initial solutions are generated by randomly.

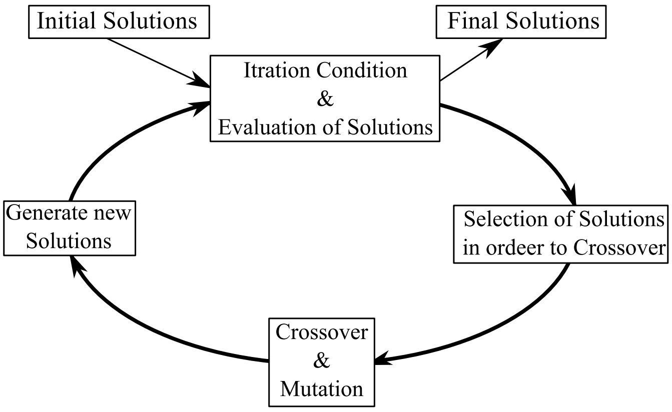


Figure 4.2: Basic GA process.

ants, if one finds a route to a safe route or bait by chance, the remaining group imitates it and increases the overall efficiency. Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO), etc., are classified as a multi-agent type optimization method. The Intelligent Water Drops (IWD) has also been proposed, which hints at how natural rivers almost always find the optimal route.

4.5.1 Ant Colony Optimization

Ants and bees are called social insects and form and live in colonies of a large number of members with various roles, including a queen[125)].The colony is huge and even the queen is simply one of the members. Even the queen is unable to comprehend the overall situation of the colony. Therefore, the maintenance of the colony is done as a collective act of individual judgments and the corresponding behavior of its members.

Many activities, such as defense against surprise attacks by enemies, repair of sudden nest collapses, foraging to feed larvae, etc., that have to be done to maintain the colony is done with the cooperation of several members. Furthermore, as a whole colony, it is also necessary to properly distribute the labor force for these roles. Therefore, it would not be easy to survive in the natural world as a colony species consisting of huge members such as ants and bees if they did not properly divide roles while communicating with each other according to the situation.

Many other creatures besides insects are known to perform indirect communication via chemical substances called pheromone (Pheromone), in addition to direct communication methods through sound, light, touch and such. A pheromone is a chemical substance with a so-called “smell”, and it is released into the environment from a signal sender who expects that other peers will perceive it. The recipient who receives the pheromone causes a specific change in its behavior, the state of the body, etc. according to the pheromone.

Next, the author explains ant feeding behavior, which is a famous example of stigmergy by pheromone. Many kinds of ants start variously exploring from the nest during foraging, and

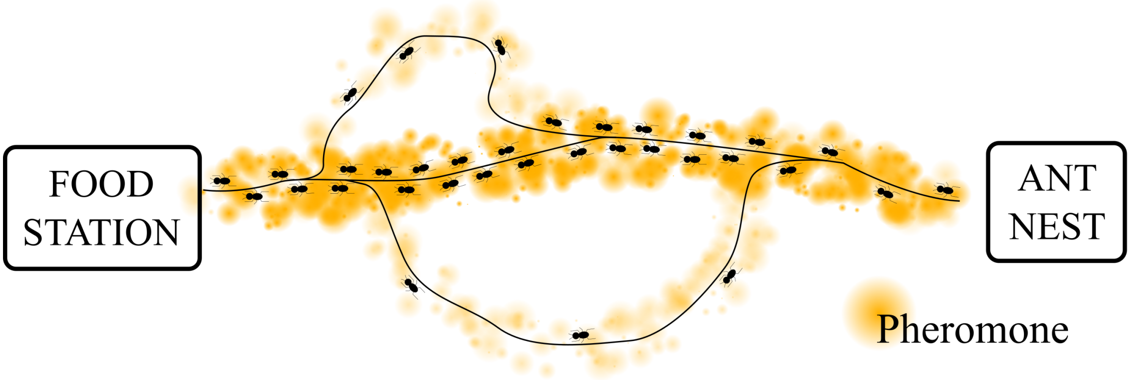


Figure 4.3: Multi-paths from the nest to the feed station.

the searching range widens until the discovery of bait. When the exploring ant successfully discovers a feeding site, it returns to the nest while scattering a chemical substance called the trail marking pheromone on the ground. When an ant near the nest senses the trail marking pheromone, it can be expected to reach the bait efficiently through its characteristic of going in the direction of denser pheromone. In addition, the ant also scatters the trail marking pheromone. Therefore, when the feeding site is rich in food, the trail marking pheromone becomes thicker, and many ants head towards the feed station. After exhausting the bait from the feeding site, the trail marking pheromone evaporates because there are no ants to spread the pheromone. In this manner, food is efficiently taken to the nest while properly arranging the members.

Deneubourg's experiments using Argentine ants revealed that ant feeding behavior has a remarkable characteristic that when there are multiple paths from the nest to the feed station as shown in the Figure 4.3, the path through which the ant goes finally converges to the shortest path[126)].

It is impossible for ants with poor eyesight to see what is going on at each branch point. Also, at each branch point, there are no ants doing things like traffic control. Therefore, it is thought that there is an interesting mechanism at work between the method of realizing the shortest path and the signpost hormone.

The prediction is as follows. First, when starting to secure bait, there is no special difference to each route other than the way. Also, at the bifurcation point on the way home from where bait was placed, the number of ants selecting each route, per unit time, is about the same. At this time, as the same number of ants still pass through each route, there is no difference in the concentration of the trail making pheromone. However, after a short period of time, at the branch point on the opposite side of the path, the ant choosing a shorter route will quickly pass through the fork. For ants leaving the nest to take food, there is a difference in the concentration of the trail making pheromone at the branch point. Ants prefer strong trail making pheromone, so it is more likely that ants departing from the nest side will choose short paths. Here, if an ant that is involved in the feeding work further works and sprays pheromone, the short path will become more concentrated with pheromone. On the other hand, pheromone evaporates on the path not selected, so the concentration of pheromone decreases. As a result, at each branch point, the selection of the shorter search path is self-reinforcing, with the expectation that the shortest route can be selected by the group as a whole.

M. Dorigo, et. al. developed a series of optimization algorithms called Ant Colony Optimization (ACO), focusing on the shortest route selection behavior of these ants[127–131]. ACO is an intelligent algorithm mainly for the combinatorial optimization problem, but it can adapt to various problems depending on ingenuity. Theoretical considerations are also made for the behavior and convergence in the search of ACO, and also guarantees convergence to the optimal solution under the circumstances of the ideal[130,132,133]. In addition, ACO has reported that the concept of ACO works effectively to set the optimum routing table as the load distribution dynamically changes on the Internet, by setting a virtual pheromone on the network[127,130,131]. Although it cannot be said that ACO is as versatile as other intelligent algorithms such as GA, SA, and PSO, it is known to demonstrate powerful performance by specializing on target problems[109].

4.5.2 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an intelligent algorithm developed by J. Kennedy and R. Eberhart in 1995 through the simulation of a simplified social model[134].

The basic idea of PSO is based on the assumption of “information sharing through swarming” guided by a behavioral research into flocks of birds searching for bait. This is a concept where the individuals constituting the group do not act independently, but combine individual pieces of information from individuals constituting the group and the common information of the whole group and act according to certain rules.

The features of PSO as an optimization algorithm are multi-point search algorithms in which there is a plurality of search points, that information on the best solutions are shared among multiple points, and that a solution space is searched based on the information. Through analytical and numerical experimental studies on PSO so far, it has become clear that it is possible to obtain an optimal solution or a suboptimal solution of a global optimization problem having multimodality within real time[134–143]. Furthermore, PSO has been confirmed to be useful for various problems including application to neural network learning algorithms, application to the voltage reactive power control of a power system, application to control system design problems, and so on.

Chapter 5

Particle Swarm Optimization

PSO was originally developed from the premise of simulating the movement of a group on a two-dimensional space. However, PSO as an optimization algorithm can be extended to multi-dimensional space. The position of one search point in the n-dimensional space is represented as $\boldsymbol{x}_i = (x_{i1}, x_{i2}, x_{i3}, \ldots, x_{ij}, \ldots, x_{in})^T$ by the n-dimensional vector, where i is the subscript number of the particle. For example, x_{ij} denotes the j-dimensional component of the i^{th} particle. In addition, each particle has a velocity vector $\boldsymbol{v}_i = (v_{i1}, v_{i2}, v_{i3}, \ldots, v_{ij}, \ldots, v_{in})^T$. Furthermore, each particle retains the position of the best solution $\boldsymbol{PBest}_i$ found by the previous search and the value of the evaluation value $f(\boldsymbol{PBest}_i)$ at that time. In the swarm, we hold the best solution position $\boldsymbol{GBest}$ and the value of the evaluation value $f(\boldsymbol{GBest})$ at that time among all the solutions discovered by all the particles in previous searches.

5.1 Process of Particle Swarm Optimization

The velocity vector of each particle moving from the current position $\boldsymbol{x}_i^t$ at a certain time t is determined by

$$\boldsymbol{v}_{ij}^{t+1} = \omega \cdot \boldsymbol{v}_{ij}^t + C_1 \cdot \text{rand()} \cdot (PBest_{ij}^t - x_{ij}^t) + C_2 \cdot \text{rand()} \cdot (GBest_j^t - x_{ij}^t) \tag{5.1}$$

where, rand() is an uniform random number from 0 to 1. Also, $omega, C_1, C_2$ is a weighting parameter for each term. A model with an inertial parameter (ω) is called IWM (Inertia Weight Method). In fact, some other formulas for determining the velocity vector of PSO have been proposed.

The velocity vector is determined by the term by the inertial force so far, the term toward each best solution, and the term heading to the best solution. Once the velocity vector is determined, the particle moves. Movement of the particle is represented by

$$\boldsymbol{x}_{ij}^{t+1} = \boldsymbol{x}_{ij}^t + \boldsymbol{v}_{ij}^{t+1}. \tag{5.2}$$

In addition to the IWM mentioned above, a number of models have been proposed for PSO.

Gbest Model (GM)

GM is a model that shares the group as a whole with the best consent found in the group as $GBest$.

Lbest Model (LM)

LM is a model that divides a group into several groups and shares the best solution found in each group as $LBest$ within each swarm.

Fully Informed Particle Swarm (FIPS)

FIPS is a model that uses vectors in the PBest direction of all swarm (or some swarms) for generating the search direction vector $\boldsymbol{v}_i^{t+1}$ of each particle.

Constriction Coefficient Method (CCM)

The CCM is a model for determining the velocity vector by

$$\boldsymbol{v}_{ij}^{t+1} = \chi \left\{ \cdot \boldsymbol{v}_{ij}^{t} + C_1 \cdot \text{rand()} \cdot (PBest_{ij}^{t} - x_{ij}^{t}) + C_2 \cdot \text{rand()} \cdot (GBest_{j}^{t} - x_{ij}^{t}) \right\} \quad (5.3)$$

using the inclusive parameter χ instead of the inertial parameter ω.

The first term of Eq. (5.1) ($\omega \cdot \boldsymbol{v}_{ij}^{t}$) is called an inertia term and is also used in methods such as the moment method and it is known to be useful for the suppression of search vibration and search efficiency. The second and third terms correspond to the correction term of the motion vector in the gradient method. Although the gradient method presupposes the differentiability possibility, since PSO does not use gradient information, it can be applied to a wide range of problems including not necessarily guaranteed differential possibility.

In other intelligent algorithms such as SA and GA, it is widely known that it is important to realize appropriate diversification/concentration in the search process to improve the search performance. In order to quantitatively grasp the situation of the search, it is necessary to newly define an index that can quantitatively evaluate how much diversification / concentration in the search of PSO is realized.

The search of PSO is realized by moving individual particles around the search space. The motion of this particle can be seen as analogous to the movement of gas molecules in thermodynamics. The group activity of PSO (the degree of how each particle moves) is defined using the mean square velocity of each particle. By lowering the group activity of PSO slowly, the same effect as the SA temperature parameter described in Section 4.2.2 can be obtained. When the group activity of PSO is high, each particle moves around for diversification, and PSO searches widely. When the group activity of PSO is low, each particle concentrates and searches more intensively around the current solution.

5.2 Analytical stability analysis of PSO

As shown in Eq. (5.1) and Eq. (5.2), the search dynamics of PSO can be described as a discrete dynamical system. Therefore, it is possible to discuss the stability and instability of the system. The dynamical system of PSO contains random elements, and at the same time $PBest$ and $GBest$, which are the best solution information, have time variability which changes with computation. Since it is difficult to theoretically analyze in this form, a simplified model[134, 144] with $PBest$ and $GBest$ as constants has been proposed. In this model, it is expressed as a linear time-invariant system. Therefore, the stability and instability of the system can be analytically evaluated by eigenvalue analysis[144–147].

By considering ϕ_1 and ϕ_2 defined as

$$\phi_1 = C_1 \cdot \text{rand}(), \qquad \phi_2 = C_2 \cdot \text{rand}(), \tag{5.4}$$

Eq. (5.1) can be described as

$$\boldsymbol{v}_{ij}^{t+1} = \omega \cdot \boldsymbol{v}_{ij}^{t} + \phi_1 \cdot (PBest_{ij}^{t} - x_{ij}^{t}) + \phi_2 \cdot (GBest_{j}^{t} - x_{ij}^{t}). \tag{5.5}$$

Also, by defining p as

$$p = \frac{\phi_1 \cdot PBest_{ij}^{t} + \phi_2 \cdot GBest_{j}^{t}}{\phi_1 + \phi_2}, \tag{5.6}$$

Eq. (5.5) is represented by

$$\boldsymbol{v}_{ij}^{t+1} = \omega \cdot \boldsymbol{v}_{ij}^{t} + (\phi_1 + \phi_2)\left(p - x_{ij}^{t}\right). \tag{5.7}$$

In addition, by defining ϕ and y^tas

$$\phi = \phi_1 + \phi_2, \tag{5.8}$$

$$y^t = p - x^t, \tag{5.9}$$

Eq. (5.7) can be transformed into

$$\boldsymbol{v}_{ij}^{t+1} = \omega \cdot \boldsymbol{v}_{ij}^{t} + \phi y^t, \tag{5.10}$$

$$y^{t+1} = -\omega \cdot \boldsymbol{v}_{ij}^{t} + (1 - \phi) \cdot y^t. \tag{5.11}$$

In the above-simplified model, if p is regarded as a constant and it is represented in a matrix form, it can be expressed as

$$\begin{bmatrix} \boldsymbol{v}_{ij}^{t+1} \\ y^{t+1} \end{bmatrix} = \begin{bmatrix} \omega & \phi \\ \omega & 1-\phi \end{bmatrix} \begin{bmatrix} \boldsymbol{v}_{ij}^{t} \\ y^{t} \end{bmatrix} = M \begin{bmatrix} \boldsymbol{v}_{ij}^{t} \\ y^{t} \end{bmatrix}. \tag{5.12}$$

This model is a linear time-invariant free system without inputs. Let λ_1 and λ_2 be the eigenvalue of this matrix M, then λ_1 and λ_2 are given by

$$\lambda_1, \lambda_2 = \frac{\omega + 1 - \phi \pm \sqrt{(\omega + 1 - \phi)^2 - 4\omega}}{2}. \tag{5.13}$$

The condition under which the particle is asymptotically stable ($|\lambda_1|$ and $|\lambda_2|$) is given by.

$$0 \leq \phi < 2\omega + 2, \tag{5.14}$$

$$0 \leq \omega < 1. \tag{5.15}$$

The stability/instability of the system is defined by whether the state variable stays in the vicinity of the equilibrium point or not. This corresponds to whether the velocity of the particle stays within a certain range in PSO or not. According to Lyapunov's stability theory[148, 149], the stability and instability of the system are classified into three types: stable, asymptotic stable, and unstable.

As described above, it is widely known that it is also important for other intelligent algorithms, such as SA and GA, to realize appropriate diversification and concentration in the search process for the improvement of search performance. In PSO, it is possible to correlate the increase/decrease in velocity of each particle (unstable state/stable state) to global / local search (diversification/centralization). PSO is drawing attention as a global search optimization method of the direct search type. PSO is applied to various engineering systems such as that of an extension to constrained problems[125], discrete optimization problems, application to multiobjective optimization problems making full use of multi-point search merit[138], and voltage reactive power control of power systems[139].

Chapter 6

Implementation of Intelligent and Hybrid Systems

In this chapter, we describe our proposal and implement three intelligent systems so that we can solve the node placement problem in wireless mesh networks. First, we show an intelligent system based on Particle Swarm Optimization. Second, we explain two intelligent systems based on hybrid method.

6.1 WMN Optimization Problem

As mentioned in Section 3.6, the placement of mesh routers in WMNs becomes a multi-objective optimization facility placement problem, which is a very complicated problem called NP-hard. Also, the placement of mesh routers in WMNs is a combination optimization problem. Each mesh router has a position and communication distance. Therefore, the connectivity and user coverage are decided by position and mesh router performance.

As a problem of maximizing the objective function $f(\boldsymbol{x})$ for the element $\boldsymbol{x}$ of the solution space X, the combinatorial optimization problem is defined as

$$\begin{aligned} &\text{maximize} && f(\boldsymbol{x}), \\ &\text{s.t.} && \boldsymbol{x} \in X. \end{aligned} \tag{6.1}$$

Here, $\boldsymbol{x}$ that satisfies $\boldsymbol{x} \in X$ is called an executable solution. The exact solution is the solution $\boldsymbol{x}$ that satisfies Eq. (6.1). The exact solution of the combinatorial optimization problem is defined. The exact solution satisfies the following properties from Eq. (6.1).

- The objective function value is the largest in executable solutions.
- The solution $\boldsymbol{x}$, having an objective function value larger than its objective function value is not an executable solution. For this reason, the exact solution of the combinatorial

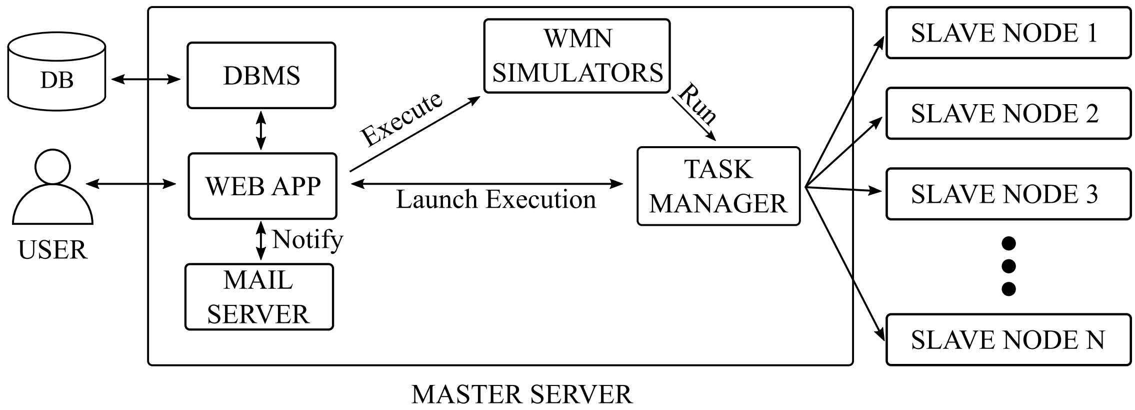


Figure 6.1: System structure for web interface.

optimization problem can be obtained by the following two methods correspondingly.

1. Enumerate feasible solutions and find executable solutions with the highest objective function value.
2. We prove that all solutions $\boldsymbol{x}$ with smaller objective function values than some feasible solutions are $\boldsymbol{x} \in X$.

Although these methods cannot be distinguished in some cases, 1 is a method of finding an exact solution by using a heuristic search of the state transition space and it can be used when the state transition space can be enumerated. In this method, reducing the solution space that must be actually searched leads to efficient solution determination.

6.2 Web Interfaces

The Web application[150)] follows a standard Client-Server architecture and is implemented using LAMP (Linux + Apache + MySQL + PHP) technology (see Figure 6.1). Remote users (clients) submit their requests by first completing the parameter setting. The parameter values to be provided by the user are classified into three groups, as follows.

- Parameters related to the problem instance: These include parameter values that determine a problem instance to be solved and consist of number of router nodes, number of mesh client nodes, client mesh distribution, radio coverage interval and size of the deployment area.
- Parameters of the resolution method: Each method has its own parameters.
- Execution parameters: These parameters are used as a stopping condition of the resolution methods and include the number of iterations and number of independent runs. The former is provided as a total number of iterations and depending on the method is also

divided per phase (e.g., number of iterations in a exploration). The later is used to run the same configuration for the same problem instance and parameter configuration a certain number of times.

6.3 Network Simulator 3

The ns-3 simulator[151)] is developed and distributed completely in the C++ programming language, because it better facilitated the inclusion of C-based implementation code. The ns-3 architecture is similar to Linux computers, with internal interface and application interfaces such as network interfaces, device drivers and sockets. The goals of ns-3 are set very high: to create a new network simulator aligned with modern research needs and develop it in an open source community. Users of ns-3 are free to write their simulation scripts as either *C++ main()* programs or *Python* programs. The ns-3 simulator's low-level API is oriented towards the power-user, but more accessible "helper" APIs are overlaid on top of the low-level API.

In order to achieve scalability of a very large number of simulated network elements, the ns-3 simulation tools also support distributed simulation. The ns-3 simulator supports standardized output formats for trace data, such as the pcap format used by network packet analyzing tools such as tcpdump, and a standardized input format such as importing mobility trace files from ns-2.

The ns-3 simulator is equipped with *Pyviz* visualizer, which has been integrated into mainline ns-3, starting with version 3.10. It can be most useful for debugging purposes, i.e. to figure out if mobility models are what you expect and where packets are being dropped. It is mostly written in Python and it works both with Python and pure C++ simulations. The ns-3 visualizer function is more powerful than the ns-2 simulator's network animator (*nam*).

The ns-3 simulator has models for all the network elements that comprise a computer network. For example, network devices represent the physical device that connects a node to the communication channel. This might be a simple Ethernet network interface card or a more complex wireless IEEE 802.11 device.

The ns-3 simulator is intended as an eventual replacement for the popular ns-2 simulator. The ns-3's wifi models a wireless network interface controller based on the IEEE 802.11 standard. The ns-3 provides models for these aspects of 802.11:

1. Basic IEEE802.11 DCF with infrastructure and ad hoc modes.

2. IEEE802.11a, IEEE802.11b, IEEE802.11g and IEEE802.11s physical layers.

3. QoS-based EDCA and queueing extensions of IEEE802.11e.

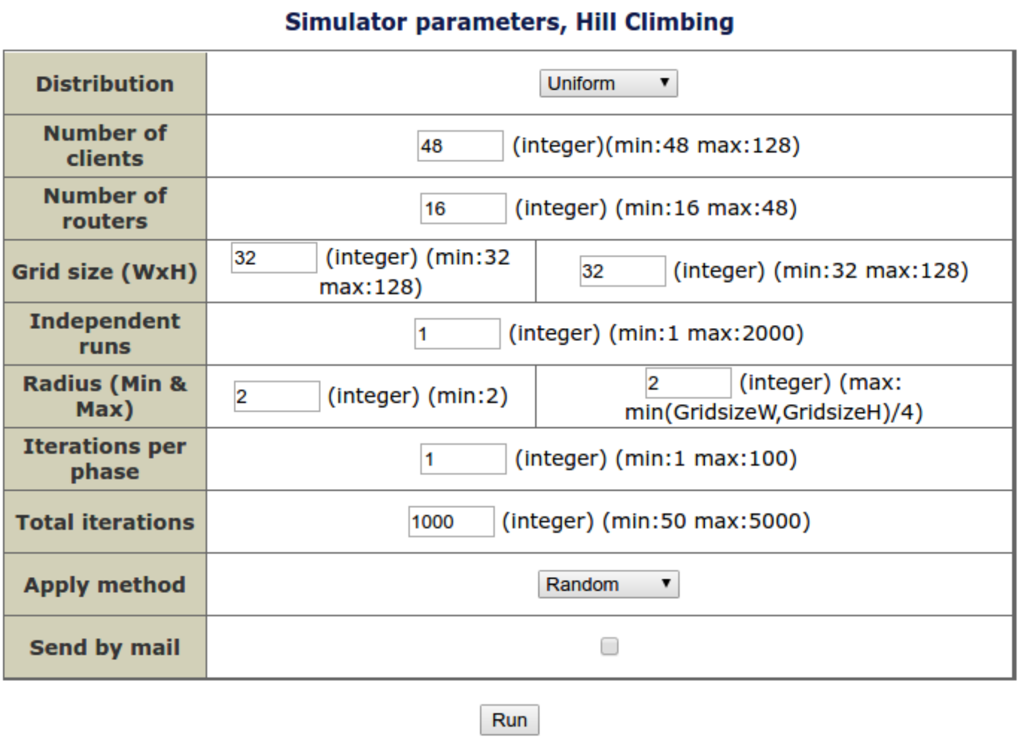


Figure 6.2: Web-interface tool of WMN-HC system.

4. Various propagation loss models including Nakagami, Rayleigh, Friis, LogDistance, FixedRss, and so on.

5. Two propagation delay models, a distance-based and random model.

6. Various rate control algorithms, including Aarf, Arf, Cara, Onoe, Rraa, ConstantRate, and Minstrel.

6.4 Hill Climbing Based Intelligent System

We propose and implement a new simulator that uses the HC algorithm to solve the problem of node placement in WMNs. We call this simulator WMN-HC. Our system can generate instances of the problem using different iterations per phase of client and mesh routers. The web-interface tool of WMN-HC is shown in Figure 6.2.

We present the particularization of the Hill Climbing algorithm (see Algorithm 1) for the mesh router node placement problem in WMNs.

Initial solution The algorithm starts by generating an initial solution either random or by *ad hoc* methods[152)].

Algorithm 1 Pseudo code for Hill Climbing algorithm.

Start: Generate an initial solution s_0;
$s = s_0$; $s^* = s_0$; $f^* = f(s_0)$;
repeat
  Movement Selection: Choose a movement $m = select\_movement(s)$;
  Evaluate & Apply Movement:
  if $\delta(s, m) \geq 0$ **then**
    $s' = appply(m, s)$;
    $s = s'$;
  end if
  Update Best Solution:
  if $f(s') > f(s^*)$ **then**
    $f^* = f(s')$;
    $s^* = s'$;
  end if
  Return s^*, f^*;
until (stopping condition is met)

Algorithm 2 Radius movement.

Choose Values H_g and W_g for height and width of a small grid area.
Compute the densest $H_g \times W_g$ area and (x_{dense}, y_{dense}) its central cell point.
Compute the position of the router of largest radio coverage $(x_{largest\_cov}, y_{largest\_cov})$.
Move router at $(x_{largest\_cov}, y_{largest\_cov})$ to new position (x_{dense}, y_{dense}).
Re-establish mesh nodes network connections.

Algorithm 3 Swap movement.

Choose Values H_g and W_g for height and width of a small grid area.
Compute the position of densest $H_g \times W_g$ area.
Compute the position (x_{dense}, y_{dense}) of the least powerful router within the dense area.
Compute the position of sparsest $H_g \times W_g$ area.
Compute the position of (x_{sparse}, y_{sparse}) of the most powerful router in the sparse area.
Swap routers in (x_{dense}, y_{dense}) and (x_{sparse}, y_{sparse}) positions.
Re-establish mesh nodes network connections.

Evaluation of fitness function One important aspect is the determination of an appropriate objective function and its encoding. In our case, the fitness function follows a hierarchical approach in which the main objective is to maximize the size of giant components in a WMN.

Neighbor selection and movement types The neighborhood $N(s)$ of a solution s consists of all solutions that are accessible by a local move from s. In the implementation of HC, we defined three different types of movements: Random, Radius and Swap. We also considered a fourth movement type, which is a combination of Random, Radius and Swap movements.

Random: This movement chooses a router at random and places it in a new position selected at random in the grid area.

Radius: This movement selects the router of largest radio coverage and places it in the densest area in terms of the number of client mesh nodes in the grid area (see Algorithm 2). This movement could yield better performance, but it has the drawback of concentrating mesh routers in the densest area of clients.

Swap: This movement consists of exchanging the placement of two routers (see Algorithm 3). More precisely, the worst router (that with the smallest radio coverage) in the densest area (in terms of number of client mesh nodes) is exchanged with the best router (that of largest radio coverage) of the sparsest area. The idea is to promote the placement of the best routers in the densest areas of the grid area.

Combination: In this movement, we consider a composition of previous movements in blocks yielding to a larger sequence:

$$< Rand_1, \ldots, Rand_k; Radius_1, \ldots, Radius_k; Swap_1, \ldots, Swap_k >,$$

where k is a user specified parameter.

Acceptability criteria The acceptability criteria for newly generated solutions can be done in different ways (simple ascent, steepest ascent, or stochastic). In our case, we have adopted the simple ascent. That is, if s is the current solution and m is a movement, the resulting solution s' obtained by applying m to s will be accepted, and hence become the current solution, if the fitness of s' is at least as good as fitness of solution s. In terms of the δ function, s' is accepted and becomes the current solution if $\delta(s, m) \geq 0$. It should be noted that in this definition we are also accepting solutions that have the same fitness as the previous solution. The aim is to give the search chances to move towards better solutions in the solution space. A more strict version would be to accept only solutions that strictly improve the fitness function ($\delta(s, m) > 0$).

6.5 Simulated Annealing Based Intelligent System

In this section, we present a WMN-SA simulation system. Our system can generate instances of the problem using different distributions of clients and mesh routers.

We set the network configuration parameters, such as distribution, number of clients, number of mesh routers, grid size, radius of transmission distance and the size of subgrid. The web-interface tool of WMN-SA is shown in Figure 6.3.

SA algorithm[111)] is a generalization of the metropolis heuristic. Indeed, SA consists of a sequence of executions of metropolis with a progressive decrement of the temperature starting from a rather high temperature, where almost any move is accepted, to a low temperature, where the search resembles Hill Climbing. In fact, it can be seen as a hill-climber with an internal mechanism to escape local optima (see pseudo-code in Algorithm 4). In SA, the solution

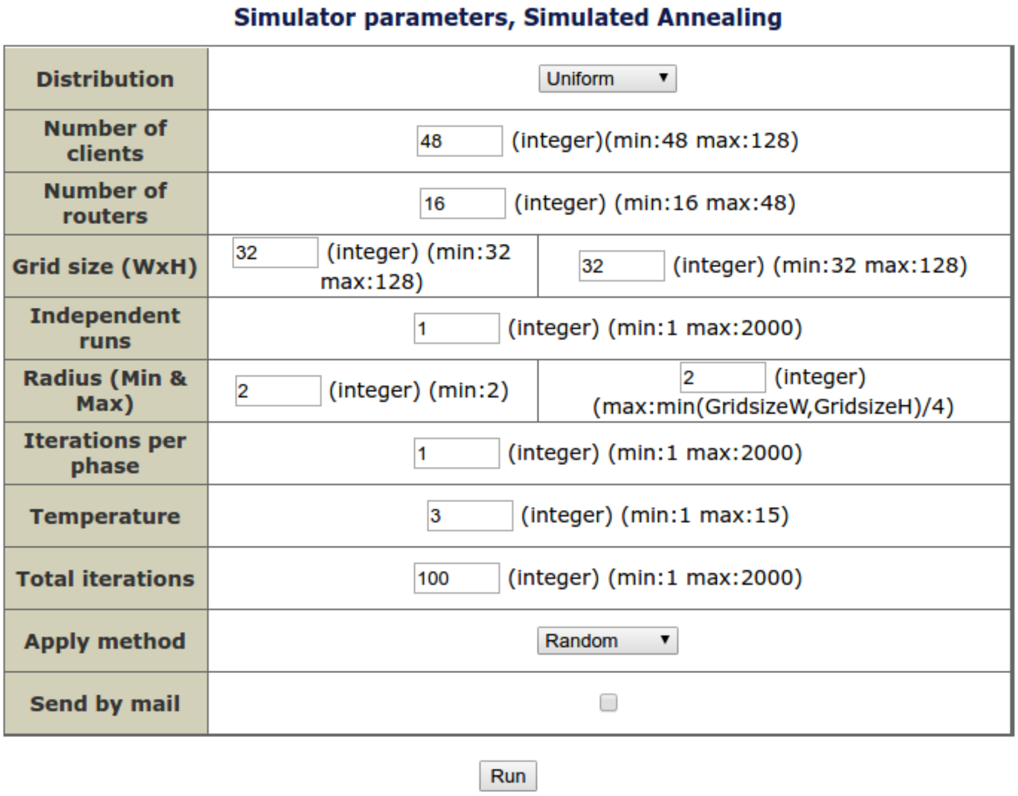


Figure 6.3: Web-interface tool of WMN-SA system.

Algorithm 4 Pseudo-code of SA.

```
t := 0
Initialize T
s0 := Initial_Solution()
v0 := Evaluate(s0)
while (stopping condition not met) do
    while t mod MarkovChainLen = 0 do
        t := t+1
        s1 := Generate(s0,T)    //Move
        v1 := Evaluate(s1)
        if Accept(v0,v1,T) then
            s0 := s1
            v0 := v1
        end if
    end while
    T := Update(T)
end while
return s0
```

s' is accepted as the new current solution if $\delta \leq 0$ holds, where $\delta = f(s') - f(s)$. To allow escaping from a local optimum, the movements that increase the energy function are accepted with a decreasing probability $\exp(-\delta/T)$ if $\delta > 0$, where T is a parameter called the "temperature". The decreasing values of T are controlled by a *cooling schedule*, which specifies the

Algorithm 5 Pseudo code for Genetic Algorithm.

Generate the initial population P^0 of size μ; $t = 0$.
Evaluate P^0;
while not termination-condition **do**
  Select the parental pool
  T^t of size λ;
  $T^t := Select(P^t)$;
  Perform crossover procedure on pairs of individuals in
  T^t with probability p_c; $P^t_c := Cross(T^t)$;
  Perform mutation procedure on individuals in P^t_c with
  probability p_m; $P^t_m := Mutate(P^t_c)$;
  Evaluate P^t_m ;
  Create a new population P^{t+1} of size μ from
  individuals in P^t and/or P^t_m;
  $P^{t+1} := Replace(P^t; P^t_m)$
  $t := t + 1$;
end while
return Best found individual as solution;

temperature values at each stage of the algorithm and what represents an important decision for its application (a typical option is to use a proportional method, like $T_k = \alpha \cdot T_{k-1}$). SA usually gives better results in practice, but uses to be very slow. The most striking difficulty in applying SA is to choose and tune its parameters such as initial and final temperature, decrements of the temperature (cooling schedule), equilibrium and detection.

For further details on initial solution, fitness evaluation and movement types refer to[153)]. However, the acceptability criteria of neighboring solutions are different [*], as explained next.

Acceptability Criteria

The acceptability criteria for newly generated solutions are based on the definition of a threshold value (accepting threshold) as follows. We consider a succession t_k such that $t_k > t_{k+1}$, $t_k > 0$ and t_k tends to 0 as k tends to infinity. Then, for any two solutions s_i and s_j, if $fitness(s_j) - fitness(s_i) < t_k$, then accept solution s_j.

For the SA, t_k values are taken as an accepting threshold, but the criterion for acceptance is probabilistic:

- If $fitness(s_j) - fitness(s_i) \leq 0$ then s_j is accepted.
- If $fitness(s_j) - fitness(s_i) > 0$ then s_j is accepted with probability $\exp[(fitness(s_j) - fitness(s_i))/t_k]$ (at iteration k the algorithm generates a random number $R \in (0, 1)$ and s_j is accepted if $R < \exp[(fitness(s_j) - fitness(s_i))/t_k]$).

[*]Initial solution, fitness evaluation and movement types are the same for Hill Climbing and Simulated Annealing.

In this case, each neighbor of a solution has a positive probability of replacing the current solution. The t_k values are chosen in a way that solutions with a large increase in the cost of the solutions are less likely to be accepted (but there is still a positive probability of accepting them).

6.6 Genetic Algorithm Based Intelligent System

GA has shown its usefulness for the resolution of many computationally hard combinatorial optimization problems. Their main features are briefly described next (see Algorithm 5 for a template). The web-interface tool of WMN-GA is shown in Figure 6.4.

Population of individuals: Unlike local search techniques that construct a path in the solution space jumping from one solution to another one through local perturbations, GA use a population of individuals, thus giving the search a larger scope and chance to find better solutions. This feature is also known as the "exploration" process in contrast to the "exploitation" process of local search methods.

Fitness: The determination of an appropriate fitness function, together with chromosome encoding are crucial to the performance of GA. Ideally we would construct objective functions with "certain regularities", i.e. objective functions that verify that for any two individuals which are close in the search space, their respective values in the objective functions are similar.

Selection: The selection of individuals to be crossed is another important aspect in GA, as it impacts the convergence of the algorithm. Several selection schemes have been proposed in the literature for selection operators trying to cope with premature convergence of GA.

Crossover operators: Use of crossover operators is one of the most important characteristics. The crossover operator is the means of the GA to transmit the best genetic features of parents to its offspring during generations of the evolution process.

Mutation operators: These operators intend to improve the individuals of a population by small local perturbations. They aim to provide a component of randomness in the neighborhood of the individuals of the population.

Escaping from local optima: GA has the ability to avoid falling prematurely into local optima and can eventually escape from them during the search process.

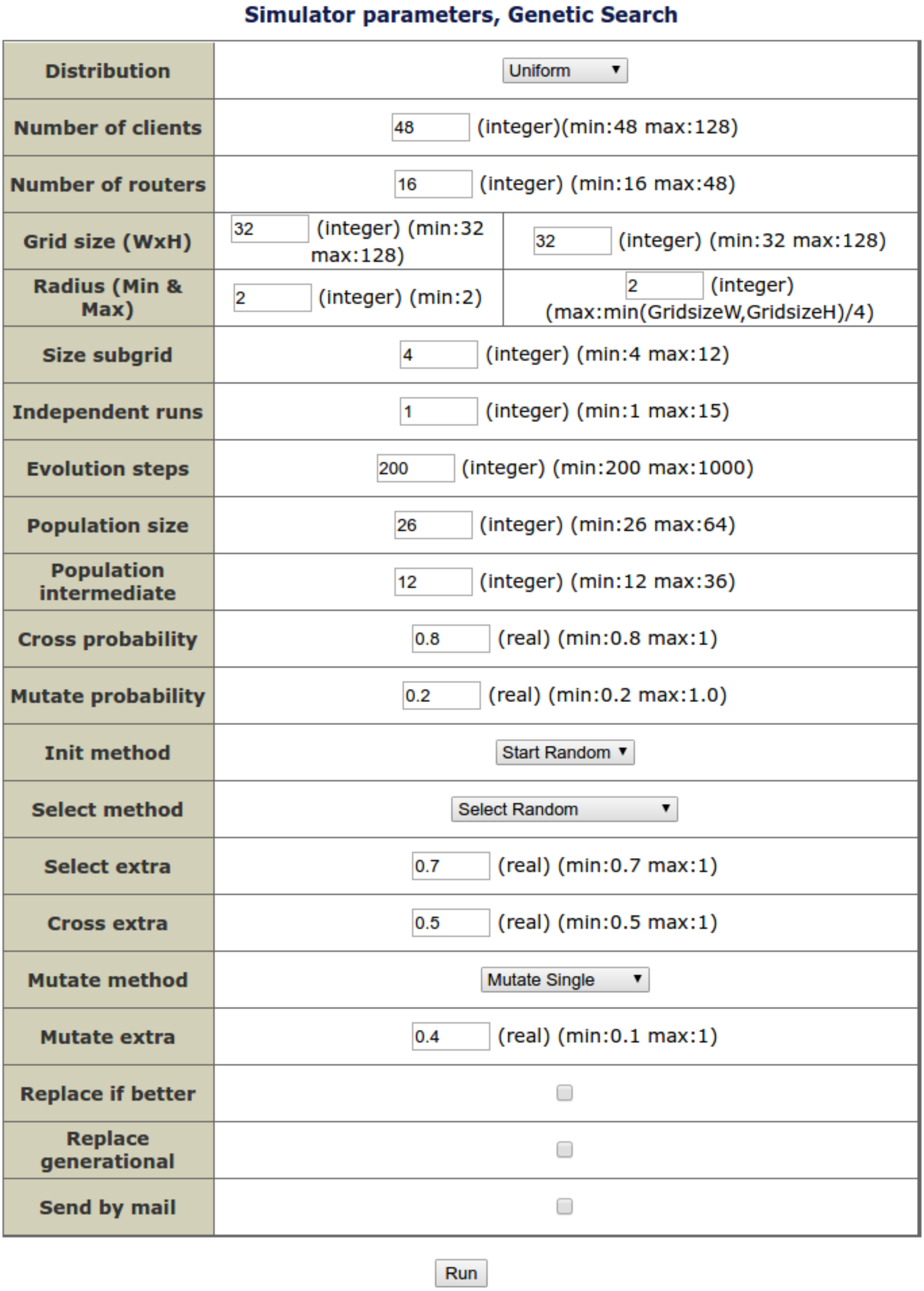


Figure 6.4: Web-interface tool of WMN-GA system.

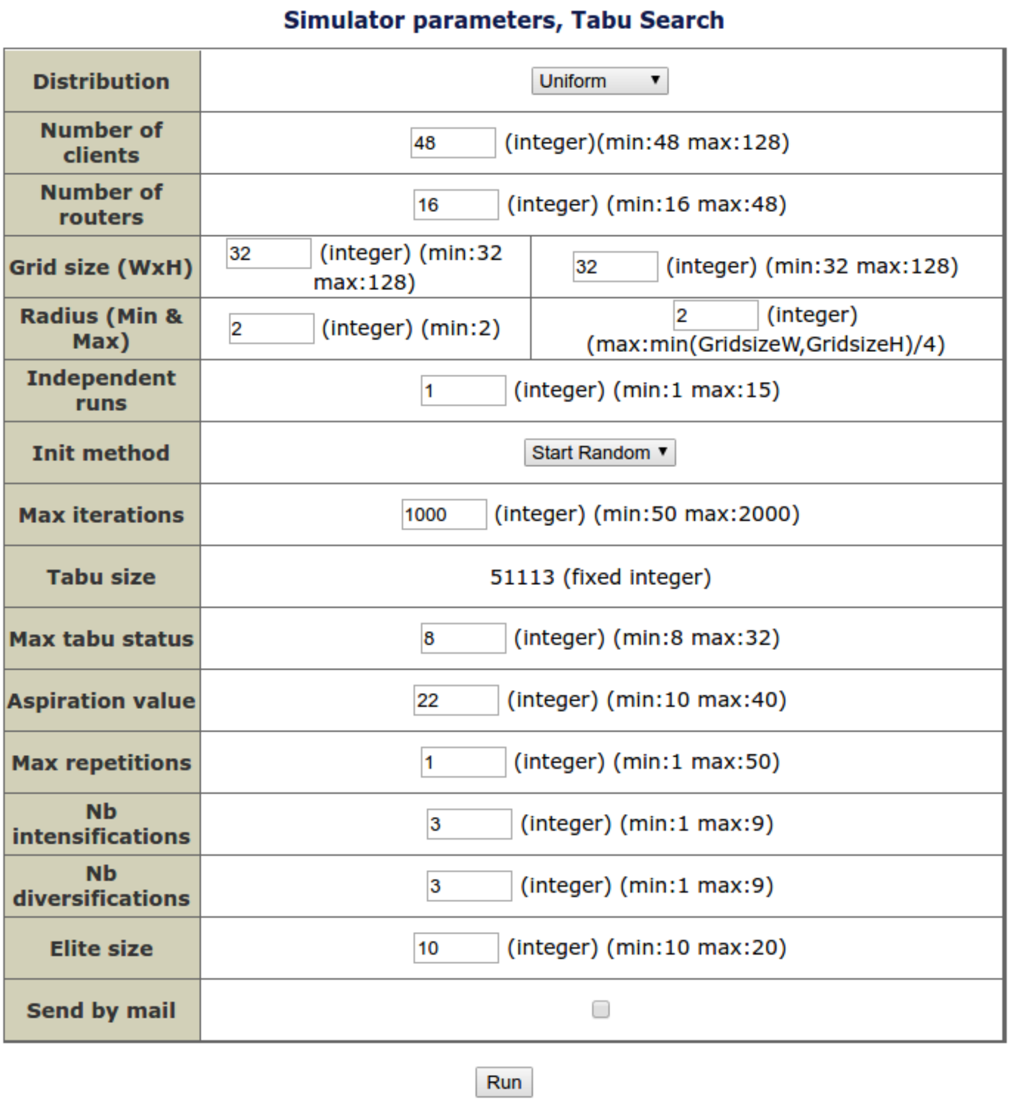


Figure 6.5: Web-interface tool of WMN-TS system.

Convergence: The convergence of the algorithm is a mechanism of GA for reaching good solutions. A premature convergence of the algorithm would cause all individuals of the population to be similar in their genetic features and thus the search would have ineffective results and the algorithm would get stuck in local optima. Maintaining the diversity of the population is therefore very important to this family of evolutionary algorithms.

6.7 Tabu Search Algorithm Based Intelligent System

The Tabu Search (TS) method was introduced by Glover[154)] as a high-level algorithm that uses other specific heuristics to guide the search. The objective is to perform an intelligent exploration of the search space that would eventually allow one to avoid getting trapped in local optima. The objective is thus to remedy one of the main issues of local search methods: namely the useless search in a neighborhood of local optima without further improvements due to re-

Algorithm 6 Pseudo code for Tabu Search

```
Compute an initial solution s;
let ŝ ← s;
Reset the tabu and aspiration conditions;
while not termination-condition do
    Generate a subset N*(s) ⊆ N(s) of solutions such that:
(none of the tabu conditions is violated) or (the aspiration criteria hold)
    Choose the best s′ ∈ N*(s) with respect to the cost function;
    ŝ ← s′ ;
    if improvement(s′ , ŝ) then
        ŝ ← s′ ;
    end if
    Update the receness and frequency;
    if (intensification condition) then
        Perform intensification procedure;
    end if
    if (diversification condition) then
        Perform diversification procedures;
    end if
end while
return ŝ;
```

visiting solutions or paths of solutions already explored. This is achieved by giving the tabu status to solutions visited in the recent search. TS is also designed to be a flexible method, so the tabu status of solutions can be waived in case they have been prohibited for a long while or if they satisfy some aspirational criteria. The classification of some solutions as tabu is achieved through the intelligent use of adaptive memory, which is allowed to evolve and eventually change the status of tabu solutions. The main features of the TS method are adaptive memory and responsive exploration. Again, adaptive memory is the basis to guide the search in taking intelligent decisions. This gives the TS method advantages with regard to other memoryless methods, those being local search methods (HC, SA, etc.) or population based methods (GAs, Memetic Algorithms, etc.). On the other hand, responsive exploration enables the method to select some solutions which although not so good at the current search iteration might in the long run lead to promising areas of good solutions in the search space (see Algorithm 6). The web-interface tool of WMN-TS is shown in Figure 6.5.

6.8 Particle Swarm Optimization Based Intelligent System

Here, a simulator that uses PSO algorithm to solve the node placement problem in WMNs (WMN-PSO) is proposed and implemented. The system can generate instances of the problem using different iterations of clients and mesh routers.

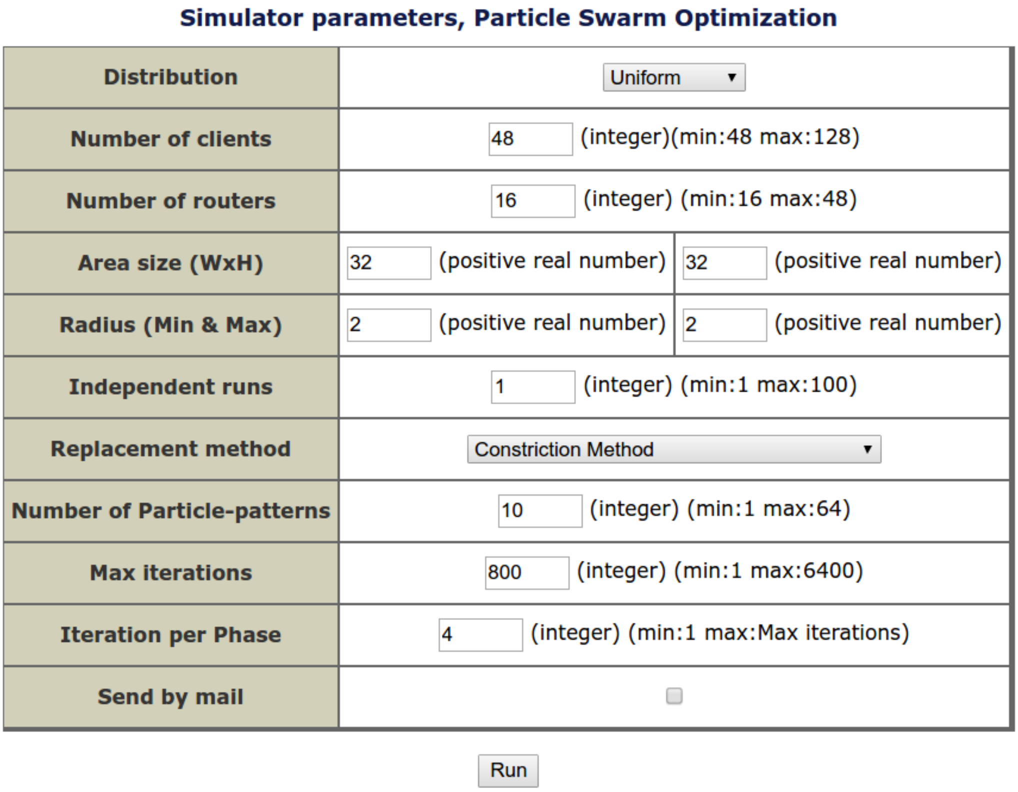


Figure 6.6: Web-interface tool of WMN-PSO system.

We present here the particularization of the PSO algorithm (see Algorithm 7) for the mesh router node placement problem in WMNs. The web-interface tool of WMN-PSO is shown in Figure 6.6.

Initialization Our proposed system starts by generating an initial solution randomly. We decide the velocity of particles by a random process considering the area size. For instance, when the area size is $W \times H$, the velocity is decided randomly from $-\sqrt{W^2 + H^2}$ to $\sqrt{W^2 + H^2}$.

Particle-pattern In order to apply PSO to the node placement problem in WMNs, particle-patterns are defined. A particle is a mesh router. A fitness value of a particle-pattern is computed by a combination of mesh routers and mesh client positions. In other words, each particle-pattern is a solution as shown is Figure 6.7. Therefore, the number of particle-patterns is the number of solutions.

Fitness function One of most important thing in the PSO algorithm is to decide the determination of an appropriate objective function and its encoding. In our case, each particle-pattern has its own fitness value and compares other particle-patterns' fitness values in order to share information of a global solution. The fitness function follows a hierarchical approach in which the main objective is to maximize the SGC in WMN. The fitness function of this scenario is

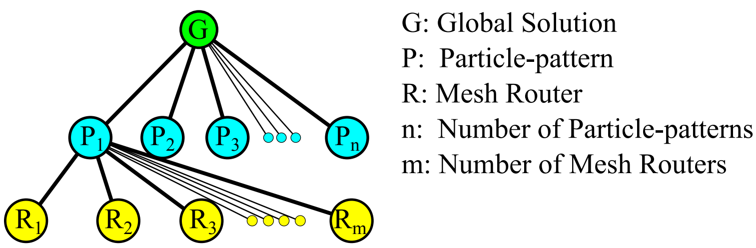


Figure 6.7: Relationship among global solution, particle-patterns and mesh routers.

Algorithm 7 Pseudo code for PSO.

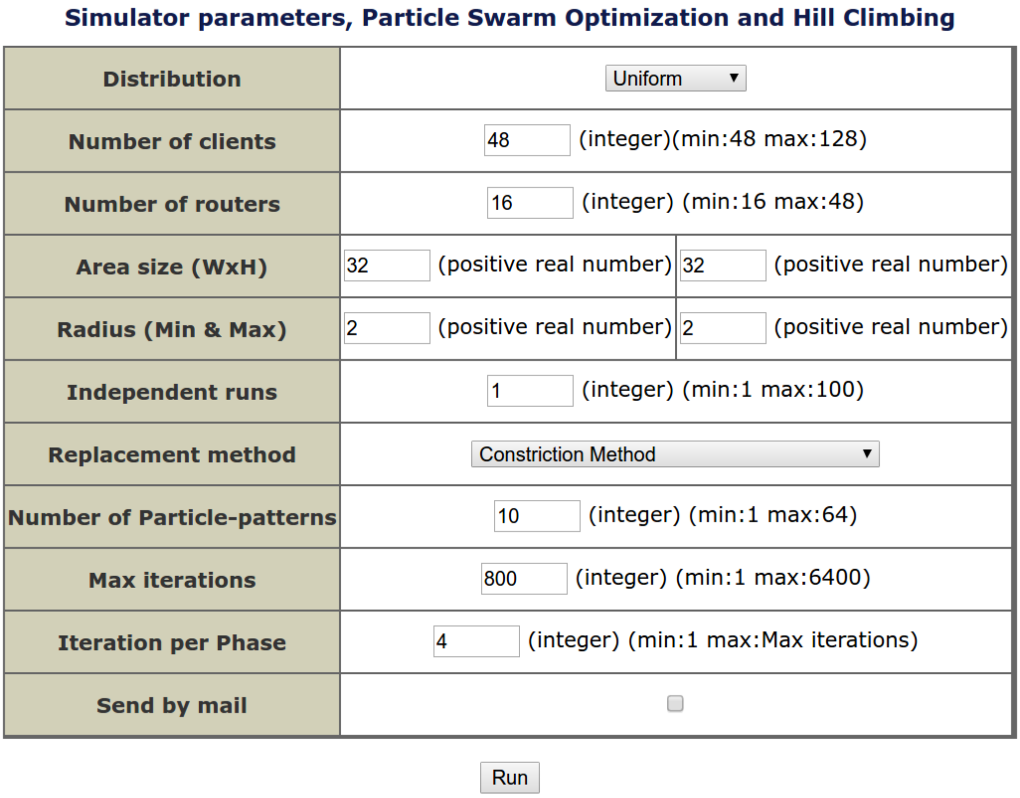
/* Generate the initial solutions and parameters */
Computation maxtime:= T_{max}, $t = 0$;
Number of particle-patterns:= m, $2 \le m \in \boldsymbol{N}^1$;
Particle-patterns initial solution:= $\boldsymbol{P}_i^0$;
Global initial solution:= $\boldsymbol{G}^0$;
Particle-patterns initial position:= $\boldsymbol{x}_{ij}^0$;
Particles initial velocity:= $\boldsymbol{v}_{ij}^0$;
PSO parameter:= ω, $0 < \omega \in \boldsymbol{R}^1$;
PSO parameter:= C_1, $0 < C_1 \in \boldsymbol{R}^1$;
PSO parameter:= C_2, $0 < C_2 \in \boldsymbol{R}^1$;
/* Start PSO */
Evaluate($\boldsymbol{G}^0$, $\boldsymbol{P}^0$);
/* "Evaluate" does calculate present fitness value of each Particle-patterns. */
while $t < T_{max}$ **do**
    /* Update velocities and positions */
    $\boldsymbol{v}_{ij}^{t+1} = \omega \cdot \boldsymbol{v}_{ij}^t$
        $+C_1 \cdot \text{rand}() \cdot (best(P_{ij}^t) - x_{ij}^t)$
        $+C_2 \cdot \text{rand}() \cdot (best(G^t) - x_{ij}^t)$;
    $\boldsymbol{x}_{ij}^{t+1} = \boldsymbol{x}_{ij}^t + \boldsymbol{v}_{ij}^{t+1}$;
    Update_Solutions($\boldsymbol{G}^t$, $\boldsymbol{P}^t$);
    /* "Update_Solutions" compares and updates the Particle-pattern's best solutions and the global best solutions if their fitness value is better than previous. */
    Evaluate($\boldsymbol{G}^{(t+1)}$, $\boldsymbol{P}^{(t+1)}$);
    $t = t + 1$;
end while
return Best found pattern of particles as solution;

considered as Where α and β are weight-coefficients of SGC and NCMC, respectively.

Router replacement method A mesh router has x, y positions and velocity. Mesh routers are moved based on velocities. There are many moving methods in PSO field, such as:

Constriction Method (CM)

CM is a method in which PSO parameters are set to a weak stable region ($\omega = 0.729$, $C_1 = C2 = 1.4955$) based on the analysis of PSO by M. Clerc et. al.[137,144]. It is expected that the particle speed decreases as the search progresses.



Simulator parameters, Particle Swarm Optimization and Hill Climbing

Distribution	Uniform ▾
Number of clients	48 (integer)(min:48 max:128)
Number of routers	16 (integer) (min:16 max:48)
Area size (WxH)	32 (positive real number) 32 (positive real number)
Radius (Min & Max)	2 (positive real number) 2 (positive real number)
Independent runs	1 (integer) (min:1 max:100)
Replacement method	Constriction Method ▾
Number of Particle-patterns	10 (integer) (min:1 max:64)
Max iterations	800 (integer) (min:1 max:6400)
Iteration per Phase	4 (integer) (min:1 max:Max iterations)
Send by mail	☐

Run

Figure 6.8: Web-interface tool of WMN-PSOHC system.

Random Inertia Weight Method (RIWM)

In RIWM, the ω parameter is changing randomly from 0.5 to 1.0. The C_1 and C_2 are kept at 2.0. The ω can be estimated by the weak stable region. The average of ω is 0.75[137]. One adds random elements by setting ω to cross the boundary between stability and instability. Since the frequency of occurrence of the stable region is high, like the CM, it is expected that the particle speed decreases as the search progresses.

Linearly Decreasing Inertia Weight Method (LDIWM)

In LDIWM, C_1 and C_2 are constantly set to 2.0. On the other hand, the ω parameter is changed linearly from unstable region ($\omega = 0.9$) to stable region ($\omega = 0.4$) with an increase of iterations of computations[137, 155]. The parameters are gradually changed to the stable region as the calculation progresses. For this reason, this method searches for solutions globally at the beginning of the search. As the search progresses, the velocity of particles decreases gradually in order to centralize the search.

Linearly Decreasing Vmax Method (LDVM)

In LDVM, PSO parameters are set to unstable region ($\omega = 0.9$, $C_1 = C_2 = 2.0$). A value of V_{max} which is the maximum velocity of particles, is considered. With an increase of iterations of computations, the V_{max} is kept decreasing linearly[139]. In this work, we apply this method to optimize the weight-coefficients of SGC and NCMC.

Algorithm 8 Pseudo code for PSO-HC.

/* Generate the initial solutions and parameters */
Computation maxtime:= T_{max}, $t := 0$;
Number of particle-patterns:= m, $2 \leq m \in \boldsymbol{N}^1$;
Particle-patterns initial solution:= $\boldsymbol{P}_i^0$;
Global initial solution:= $\boldsymbol{G}^0$;
Particle-patterns initial position:= $\boldsymbol{x}_{ij}^0$;
Particles initial velocity:= $\boldsymbol{v}_{ij}^0$;
PSO parameter:= ω, $0 < \omega \in \boldsymbol{R}^1$;
PSO parameter:= C_1, $0 < C_1 \in \boldsymbol{R}^1$;
PSO parameter:= C_2, $0 < C_2 \in \boldsymbol{R}^1$;
/* Start PSO-HC */
Evaluate($\boldsymbol{G}^0, \boldsymbol{P}^0$);
while $t < T_{max}$ **do**
  /* Update velocities and positions */
  $\boldsymbol{v}_{ij}^{t+1} = \omega \cdot \boldsymbol{v}_{ij}^t$
    $+C_1 \cdot$ rand() $\cdot (best(P_{ij}^t) - x_{ij}^t)$
    $+C_2 \cdot$ rand() $\cdot (best(G^t) - x_{ij}^t)$;
  $\boldsymbol{x}_{ij}^{t+1} = \boldsymbol{x}_{ij}^t + \boldsymbol{v}_{ij}^{t+1}$;
  /* if fitness value is increased, a new solution will be accepted. */
  if Evaluate($\boldsymbol{G}^{(t+1)}, \boldsymbol{P}^{(t+1)}$) >= Evaluate($\boldsymbol{G}^{(t)}, \boldsymbol{P}^{(t)}$) **then**
    Update_Solutions($\boldsymbol{G}^t, \boldsymbol{P}^t$);
    Evaluate($\boldsymbol{G}^{(t+1)}, \boldsymbol{P}^{(t+1)}$);
  else
    /* "Reupdate_Solutions" makes particle back to previous position */
    Reupdate_Solutions($\boldsymbol{G}^{(t+1)}, \boldsymbol{P}^{(t+1)}$);
  end if
  $t = t + 1$;
end while
Update_Solutions($\boldsymbol{G}^t, \boldsymbol{P}^t$);
return Best found pattern of particles as solution;

Rational Decrement of Vmax Method (RDVM)

In RDVM, PSO parameters are set to unstable region ($\omega = 0.9$, $C_1 = C_2 = 2.0$). The V_{max} is kept decreasing with the increase of iterations as

$$V_{max}(x) = \sqrt{W^2 + H^2} \times \frac{T - x}{x}, \tag{6.2}$$

where W and H are the width and the height of the considered area, respectively. Also, T and x are the total number of iterations and a current number of the iteration, respectively[156).

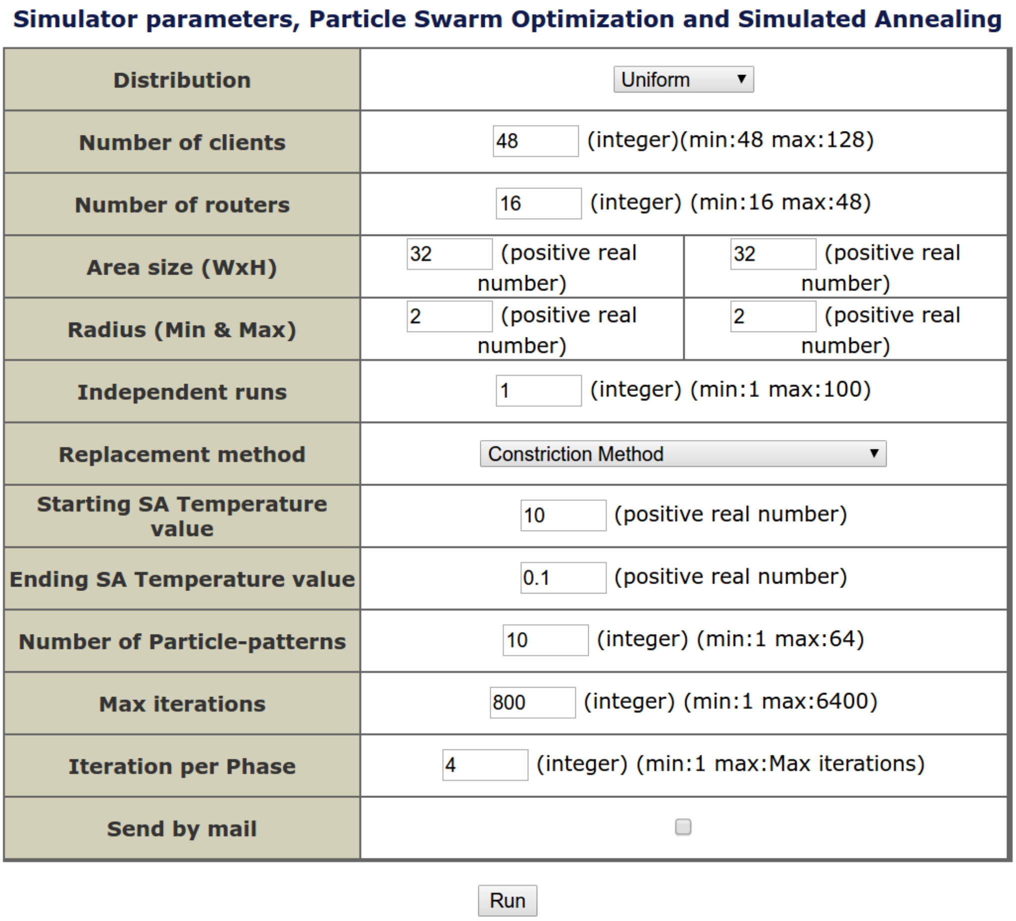


Figure 6.9: Web-interface tool of WMN-PSOSA system.

6.9 Particle Swarm Optimization and Hill Climbing Based Intelligent Hybrid System

We propose and implement a PSO and HC based simulation systems called WMN-PSOHC for solving the node placement problem in WMNs. When PSO decides the positions of its own particle-pattern, HC interrupts and evaluate a fitness value of the particle-pattern. Then, the system accepts the move if the fitness value is increased; however, the system does not accept it if the fitness value is decreased, comparing with previous particle-patterns' fitness values.

We show pseudo code for WMN-PSOHC in Algorithm 8. The web-interface tool of WMN-PSOHC is shown in Figure 6.8.

6.10 Particle Swarm Optimization and Simulated Annealing Based Intelligent Hybrid System

We propose and implement a PSO and SA based simulation system called WMN-PSOSA for solving the node placement problem in WMNs. When PSO decides the positions of its own

Algorithm 9 Pseudo code for PSO-SA.

```
/* Generate the initial solutions and parameters */
Computation maxtime:= T_max, t := 0;
Number of particle-patterns:= m, 2 ≤ m ∈ N^1;
Starting SA temperature:= Temp;
Decreasing speed of SA temperature:= T_d;
Particle-patterns initial solution:= P_i^0;
Global initial solution:= G^0;
Particle-patterns initial position:= x_ij^0;
Particles initial velocity:= v_ij^0;
PSO parameter:= ω, 0 < ω ∈ R^1;
PSO parameter:= C_1, 0 < C_1 ∈ R^1;
PSO parameter:= C_2, 0 < C_2 ∈ R^1;
/* Start PSO-SA */
Evaluate(G^0, P^0);
while t < T_max do
    /* Update velocities and positions */
    v_ij^{t+1} = ω · v_ij^t
        +C_1 · rand() · (best(P_ij^t) − x_ij^t)
        +C_2 · rand() · (best(G^t) − x_ij^t);
    x_ij^{t+1} = x_ij^t + v_ij^{t+1};
    /* if fitness value is increased, a new solution will be accepted. */
    if Evaluate(G^(t+1), P^(t+1)) >= Evaluate(G^(t), P^(t)) then
        Update_Solutions(G^t, P^t);
        Evaluate(G^(t+1), P^(t+1));
    else
        /* a new solution will be accepted, if condition is true. */
        if Random() > e^((Evaluate(G^(t+1), P^(t+1)) − Evaluate(G^(t), P^(t))) / Temp) then
            /* "Reupdate_Solutions" makes particle back to previous position */
            Reupdate_Solutions(G^{t+1}, P^{t+1});
        end if
    end if
    Temp = Temp × t_d;
    t = t + 1;
end while
Update_Solutions(G^t, P^t);
return Best found pattern of particles as solution;
```

particle-pattern, SA interrupts and evaluates a fitness value of the particle-pattern. Then, the system accepts the move if the fitness value is increased; however, the system follows SA if the fitness value is decreased.

We show pseudo code for WMN-PSOSA in Algorithm 9. The web-interface tool of WMN-PSOSA is shown in Figure 6.9.

Chapter 7

Evaluation of Implemented Systems

7.1 Evaluation and Comparison of Implemented Intelligent Systems

7.1.1 Evaluation and Comparison of WMN-HC, WMN-SA and WMN-GA Simulation Systems

Simulation Settings

We carried out many simulations to evaluate the performance of WMNs using WMN-HC, WMN-SA and WMN-GA simulation systems. In these simulation scenarios, we consider grids with 16×16, 32×32, 64×64 size. One grid unit is 20m $\times$ 20m (d=20m). In Figure 7.1, we show the coverage area of a mesh router, which has a radius of 50m. We consider the router to be positioned in the middle of a grid unit. In Table 7.1 to Table 7.4, we show the simulation parameters. The number of mesh routers are 4, 16, and 64 and the number of mesh clients are 12, 48, and 192, which are positioned in the simulation area by Weibull distribution. For each phase of calculations, SA and HC runs a number of 64 iterations. In GA, we consider the population size to be 64.

Results Discussion

The results for the size of GC for different area sizes and different algorithms are shown in Figure 7.2 to Figure 7.4. As the size of the area increases, the performance for each case decreases. For the area size 64×64, there are more routers than in previous cases and it takes more calculation phases to reach the maximum size of GC. HC and SA show more oscillations than GA, when the area size increases. However, GA is slower when converging to the maximum size of GC.

We show the results for the number of covered mesh clients, in Figure 7.5 to Figure 7.7.

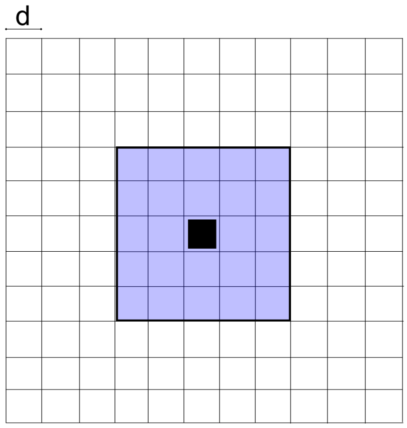


Figure 7.1: Mesh router coverage distance.

Table 7.1: Common parameters of simulations.

Parameters	Values
Client distribution	Weibull
Area size	$320[m] \times 320[m]$
	$640[m] \times 640[m]$
	$1280[m] \times 1280[m]$
Number of mesh router nodes	4, 16, 64
Number of mesh client nodes	12, 48, 192
Coverage of mesh router nodes	50[m]
Size of GC priority	0.7
Covered mesh clients priority	0.3

Table 7.2: Simulation settings for WMN-HC.

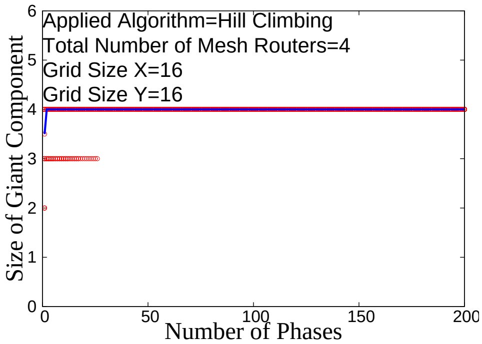
Parameters	Values
Iteration per phase	64
Applied method	Combination

Table 7.3: Simulation settings for WMN-SA.

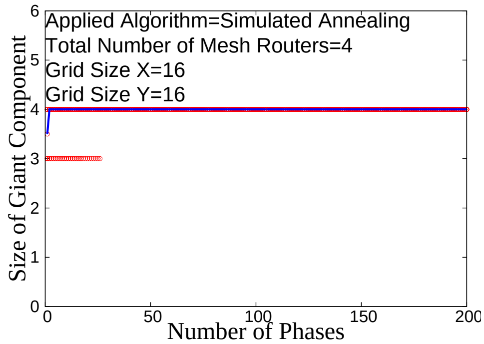
Parameters	Values
SA temperature	1
Iteration per phase	64
Applied method	Combination

Table 7.4: Simulation settings for WMN-GA.

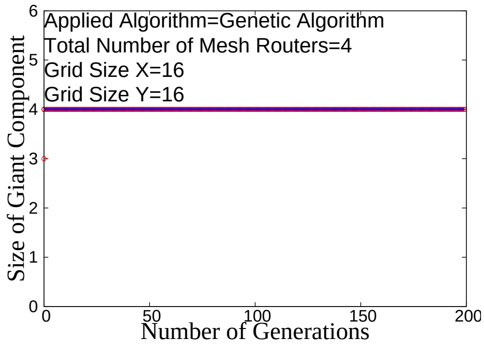
Parameters	Values
Selection method	Linear ranking
Mutation method	Single mutation
Crossover rate	0.8
Mutation rate	0.2



(a) Hill Climbing

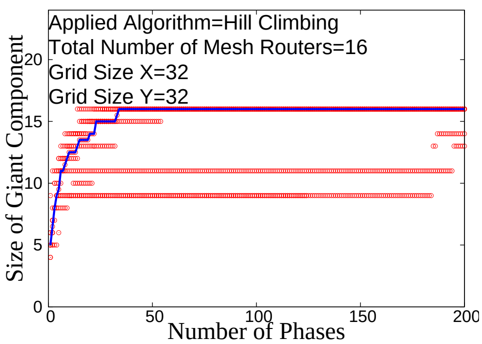


(b) Simulated Annealing

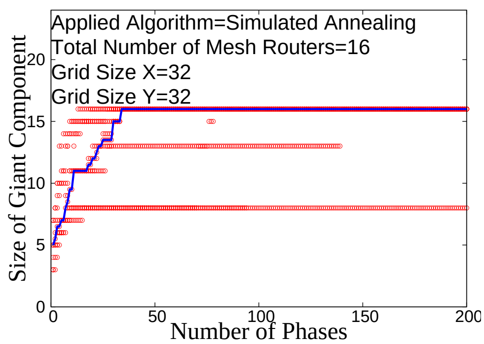


(c) Genetic Algorithm

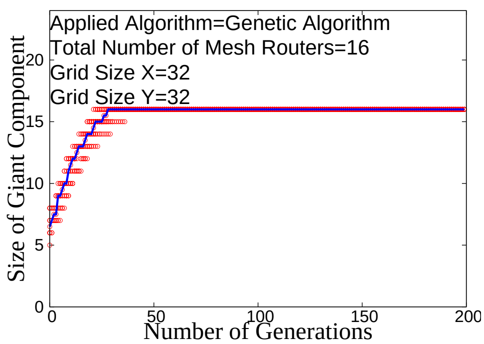
Figure 7.2: Size of GC for area size = 16×16.



(a) Hill Climbing

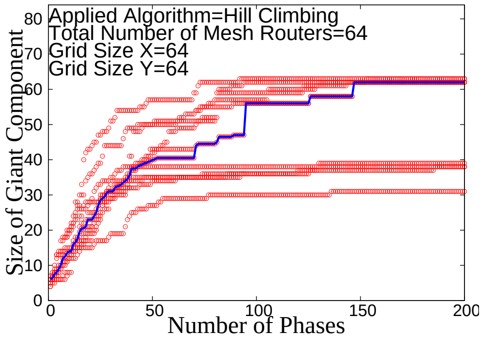


(b) Simulated Annealing

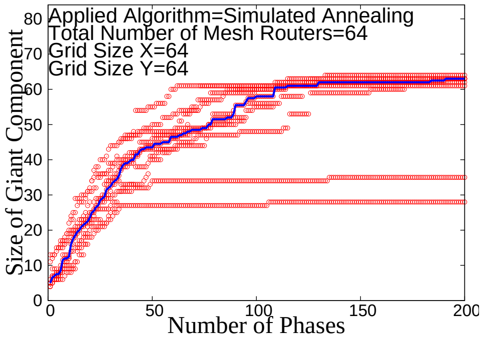


(c) Genetic Algorithm

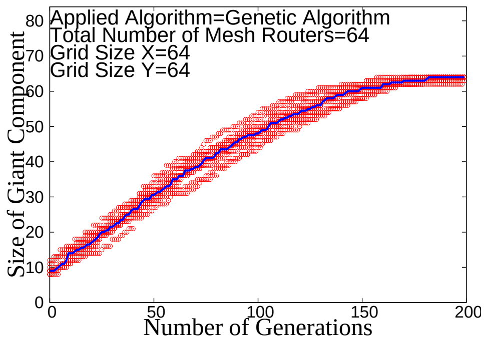
Figure 7.3: Size of GC for area size = 32×32.



(a) Hill Climbing

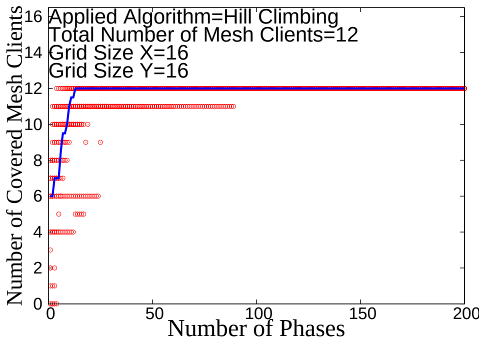


(b) Simulated Annealing

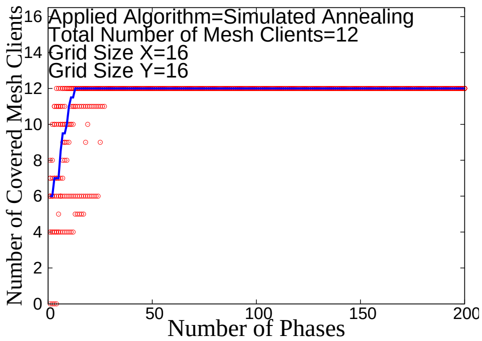


(c) Genetic Algorithm

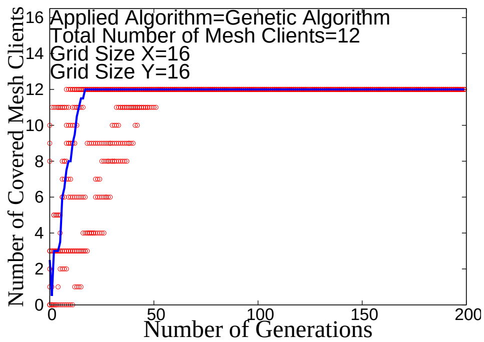
Figure 7.4: Size of GC for area size = 64×64.



(a) Hill Climbing

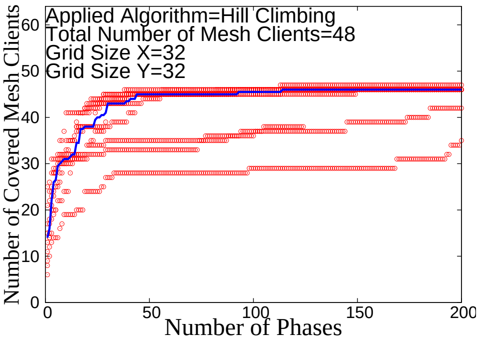


(b) Simulated Annealing

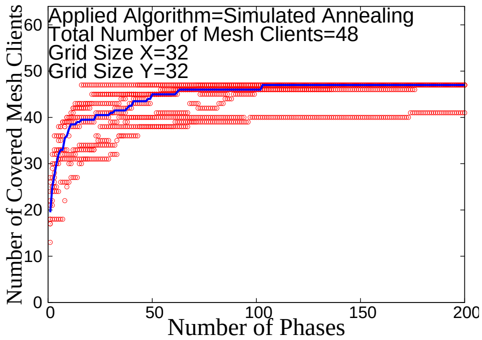


(c) Genetic Algorithm

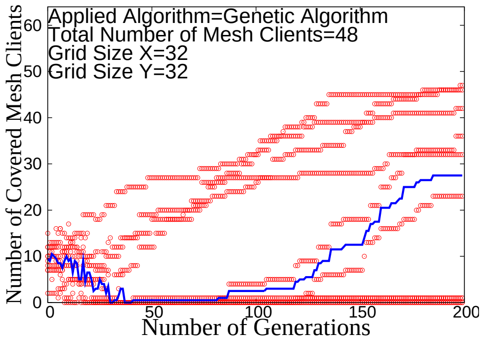
Figure 7.5: Number of covered mesh clients for area size = 16×16.



(a) Hill Climbing

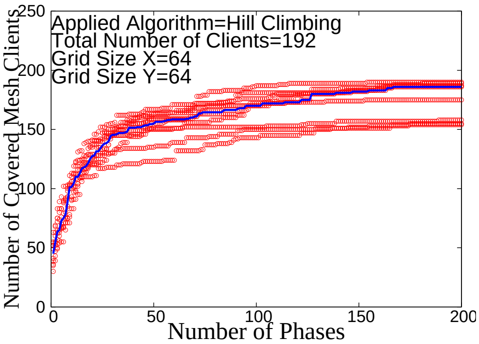


(b) Simulated Annealing

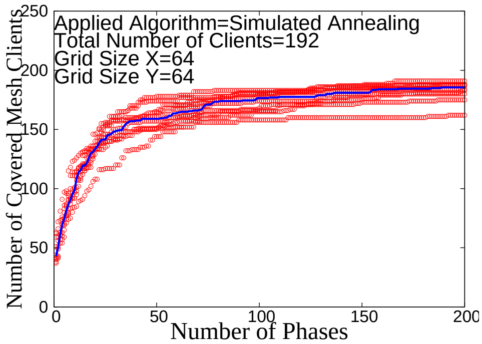


(c) Genetic Algorithm

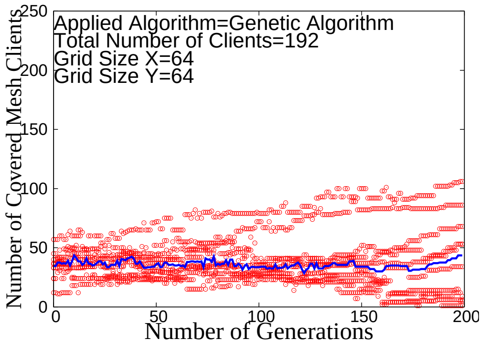
Figure 7.6: Number of covered mesh clients for area size = 32×32.



(a) Hill Climbing

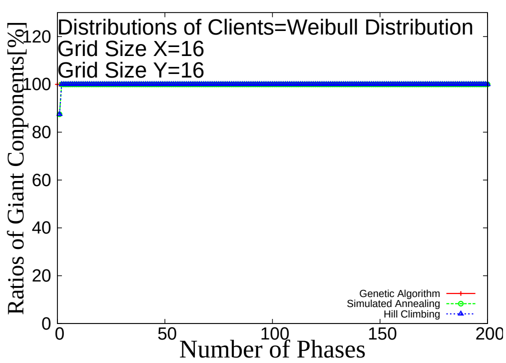


(b) Simulated Annealing

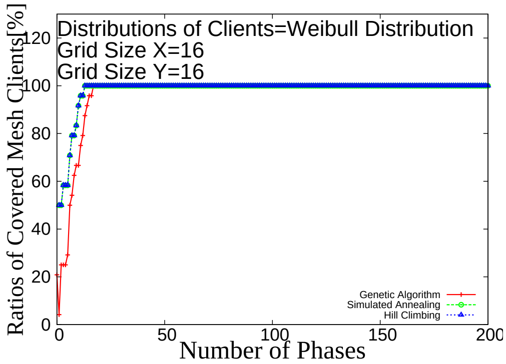


(c) Genetic Algorithm

Figure 7.7: Number of covered mesh clients for area size = 64×64.

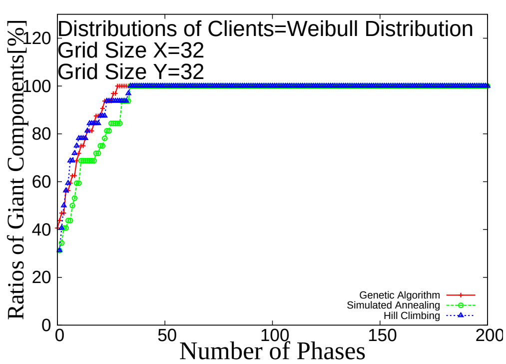


(a) Ratios of Giant Components

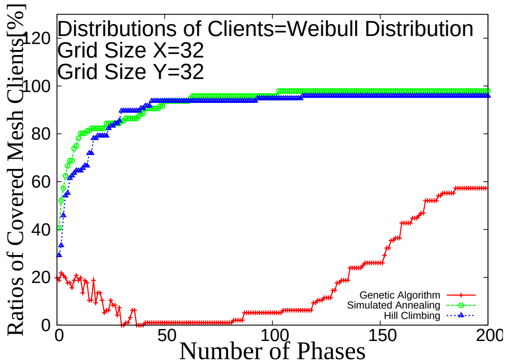


(b) Ratios of Covered mesh clients

Figure 7.8: Comparison among 3 algorithms for area size = 16×16.

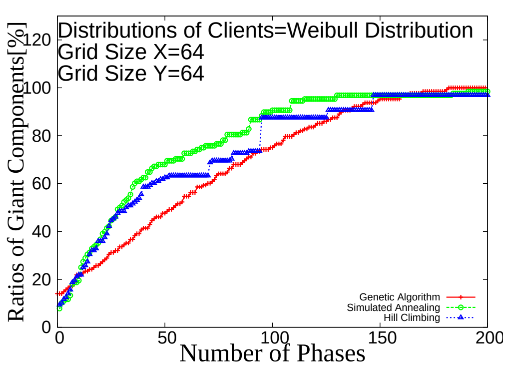


(a) Ratios of Giant Components

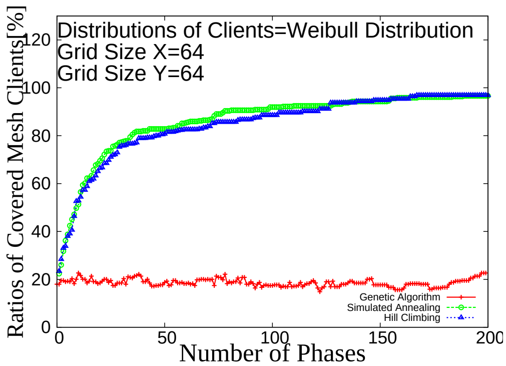


(b) Ratios of Covered mesh clients

Figure 7.9: Comparison among 3 algorithms for area size = 32×32.



(a) Ratios of Giant Components



(b) Ratios of Covered mesh clients

Figure 7.10: Comparison among 3 algorithms for area size = 64×64.

We also notice here that the best performance is for the smallest area size (Figure 7.5), where the number of mesh clients is also smaller. It is easier to cover 12 mesh clients and almost all algorithms have good performance, converging in less than 20 calculation phases. When the area size increases, HC, SA and GA need more calculations phases to reach 46, 47 and 28, respectively. On the other hand, using GA, the number of covered mesh clients is lower and it does not cover all clients.

7.1.2 Evaluation and Comparison of WMN-SA and WMN-TS

We use WMN-SA and WMN-TS systems for the node placement problem in WMNs. A bi-objective optimization is used to solve this problem by first maximizing the number of connected routers in the network and then the client coverage. The input parameters of WMN-SA and WMN-TS systems are shown in Table 7.5 and Table 7.6. In Figure 7.11, we show the location of mesh routers and clients for the optimized topologies generated by WMN-SA and WMN-TS systems for normal distribution.

Then, we optimize the position of routers in order to cover as many mesh clients as possible. We consider a normal distribution of mesh clients.

We used the throughput, delay, fairness index and remaining energy metrics to evaluate the performance of WMNs for two architectures by WMN-SA and WMN-TS simulation systems, considering normal distribution.

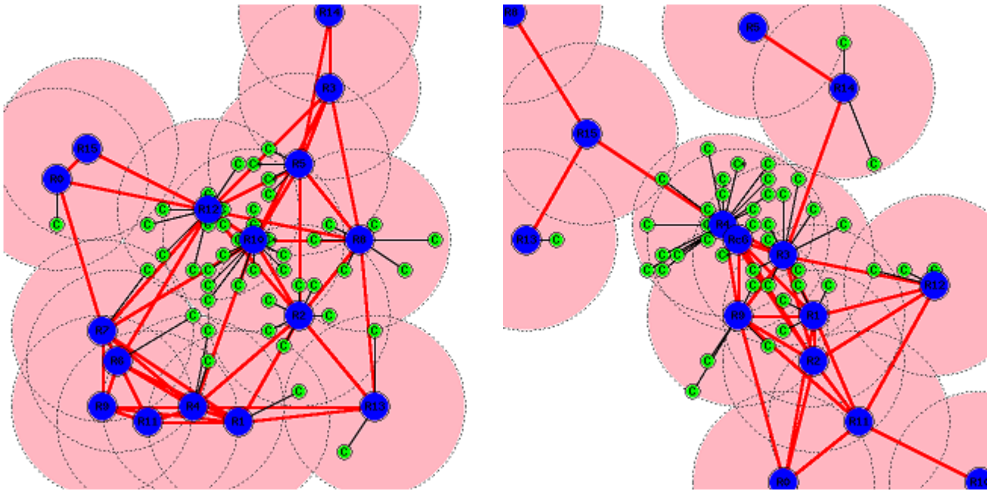
In Figure 7.12, we show the simulation results of the WMN-SA and WMN-TS simulation systems. For both simulation systems, the throughput of I/B WMN is a little bit higher than Hybrid WMN.

We compare the performance of WMN-SA and WMN-TS by using ns-3. We show the parameters for ns-3 in this scenario in Table 7.7. In Figure 7.13, we show the simulation result for the delay. For WMN-SA, the delay of I/B WMN is a little bit lower than Hybrid WMN. However, for WMN-TS the delay of Hybrid WMN is lower than I/B WMN.

In Figure 7.14, we show the fairness index of WMN-SA and WMN-TS simulation systems. For both simulation systems, the fairness index of I/B WMN is a little bit higher than Hybrid WMN.

In Figure 7.15, we show the remaining energy for both WMN architectures considering WMN-SA and WMN-TS simulation systems. For WMN-SA, the energy decreases sharply because of the high density of nodes and high throughput, thus the nodes spend more energy.

From the simulation results, we conclude that for WMN-TS the throughput, delay and remaining energy are better than WMN-SA. But, the fairness index is better for WMN-SA.

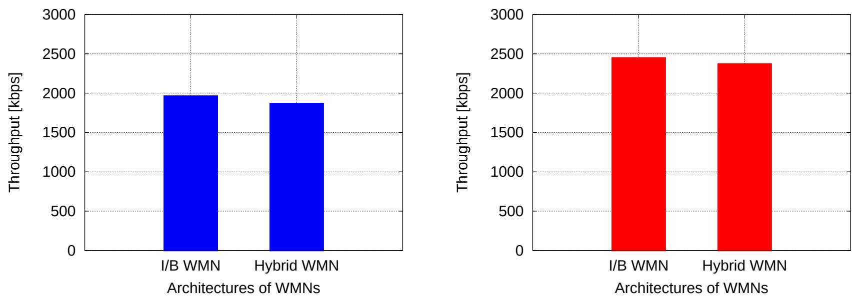


(a) WMN-SA (b) WMN-TS

Figure 7.11: Positions of mesh routers optimized by WMN-SA and WMN-TS systems.

Table 7.5: Input parameters of WMN-SA.

Parameters	Values
Number of clients	48
Number of routers	16
Grid width	32 [units]
Grid height	32 [units]
Communication Distance	2×2 [units]
Independent runs	10
Initial Router Placement Method	HotSpot
Iteration per Phases	9
Total Iterations	2000
Temperature	1
Replacement Method	Combination
Distribution of Clients	Normal



(a) WMN-SA (b) WMN-TS

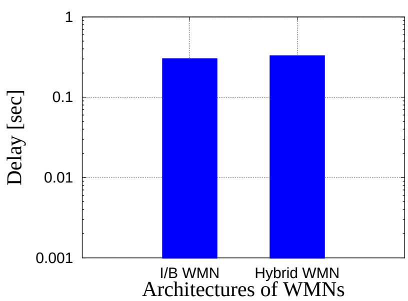
Figure 7.12: Results of average throughput.

Table 7.6: Input parameters of WMN-TS.

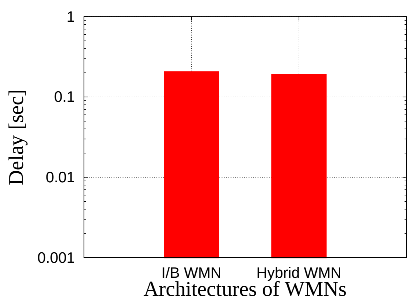
Parameters	Values
Number of clients	48
Number of routers	16
Grid width	32 [units]
Grid height	32 [units]
Communication Distance	2×2 [units]
Independent runs	10
Initial Router Placement Method	HotSpot
Max Iterations	2000
Max Tabu Status	9
Aspiration Value	15
Max Repetitions	15
Number of Intensifications	4
Number of Diversifications	4
Elite Size	10
Distribution of Clients	Normal

Table 7.7: Simulation parameters for ns-3.

Parameters	Values
Area Size	640[m]×640[m]
Distributions of mesh clients	Normal
Number of mesh routers	16
Number of mesh clients	48
PHY protocol	IEEE 802.11b
Propagation loss model	Log-distance Path Loss Model
Propagation delay model	Constant Speed Model
MAC protocols	DCF
Routing protocol	OLSR
Transport protocol	UDP
Application type	CBR
Packet size	1024 [Bytes]
Transmission rates	512 [kbps]
Number of source nodes	10
Number of destination node	1
Transmission current	17.4 [mA]
Receiving current	19.7 [mA]
Simulation time	600 [sec]

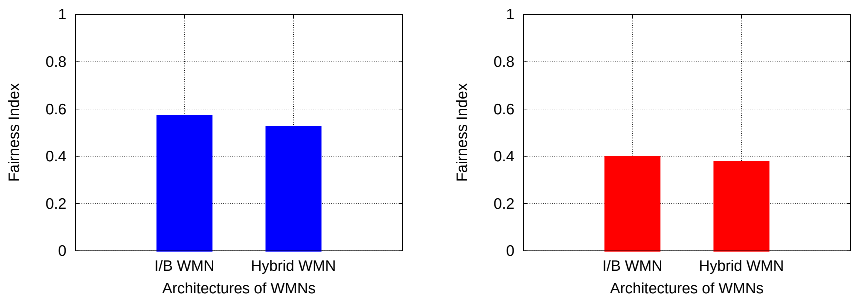


(a) WMN-SA



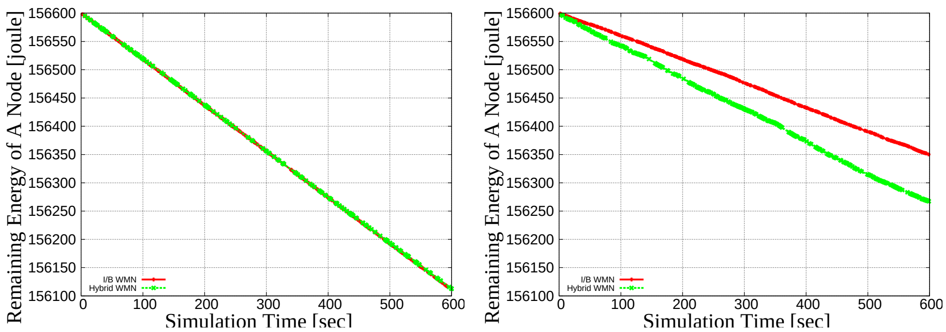
(b) WMN-TS

Figure 7.13: Results of average delay.



(a) WMN-SA (b) WMN-TS

Figure 7.14: Results of fairness index.



(a) WMN-SA (b) WMN-TS

Figure 7.15: Results of remaining energies.

7.1.3 Evaluation of WMN-PSO System

Evaluation of Fitness Function Weight-Coefficients in the WMN-PSO System

In this section, we show simulation results using the WMN-PSO system. In this work, the area size is considered to be 32×32. We use Normal distribution of mesh clients. The number of mesh routers is considered to be 16 and the number of mesh clients is 48. We evaluate weight-coefficients α and β for SGC and NCMC, respectively. The total number of iterations is considered to be 6400 and the iterations per phase is considered to be 32. We consider the number of particle-patterns to be 32. The simulation parameters and their values are shown in Table 7.8. We conducted simulations 30 times, in order to avoid the effect of randomness and create a general view of results. We used box-plots to analyze the range of data values. In Figure 7.16, we show an example of a box-plot in order to explain how to analyze the data. The bottom and top of the box (b and d) are the 75th and 25th percentile (the upper and lower quartiles, respectively), and the line of the box (c) is the 50th percentile (the median). The ends of the whiskers (a and e) represent the maximum and minimum of all solution data.

We show the simulation results in Figure 7.17. We evaluate the simulation results by using 2 metrics (SGC and NCMC). In Figure 7.17(a), with an increase of α, the SGC is increased. However, in Figure 7.17(b), with an increase of α, the NCMC is decreased. The reason is that α

Table 7.8: Simulation parameters for investigation of fitness function weight-coefficients in WMN-PSO system.

Parameters	Values
Clients distribution	Normal distribution
Grid size	32×32
Number of mesh routers	16
Number of mesh clients	48
Total iterations	6400
Iteration per phase	32
Number of particle-patterns	32
Radius of a mesh router	From 1.5×1.5 to 2.5×2.5
Weight-coefficients α and β	from 0.1 to 0.9
Movement method	LDVM

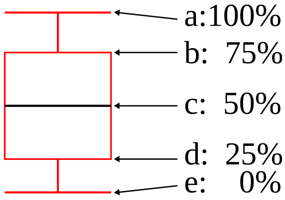
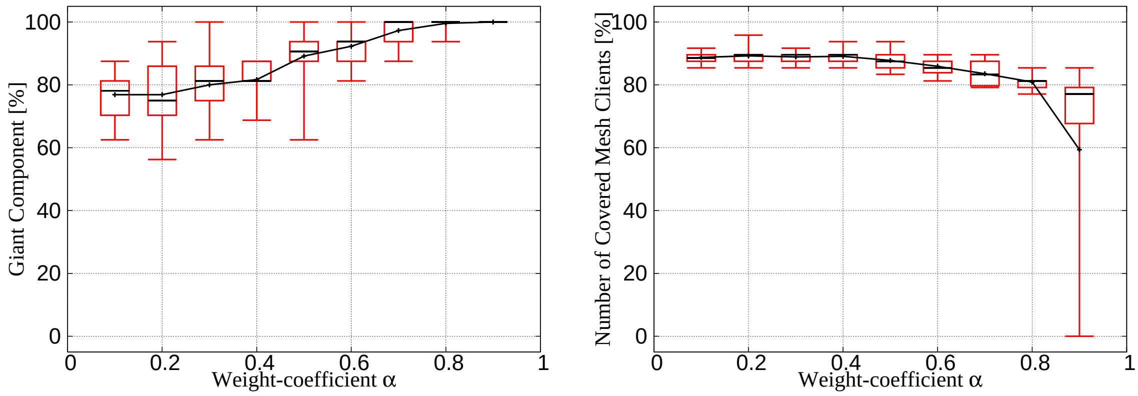


Figure 7.16: A model of boxplot that we use to analyze the simulation results.



(a) SGC (b) NCMC

Figure 7.17: Simulation results for investigation of fitness function weight-coefficients in WMN-PSO system.

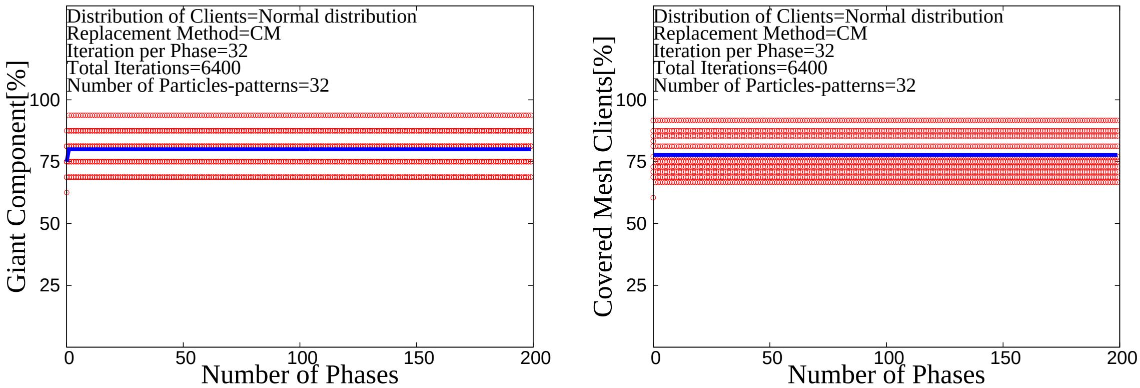
has higher priority for SGC and β can be decided by $\alpha + \beta = 1.0$. In other words, α and β are in a trade-off relation. The fitness function follows a hierarchical approach in which the main objective is to maximize the SGC in WMN. The median of SGC gets to 100% when $\alpha = 0.7$. Therefore, the best weight-coefficients of SGC and NCMC are 0.7 and 0.3, respectively.

Evaluation of Different Replacement Methods

This section is devoted to the performance evaluation of our proposed WMN-PSO system. In this work, a 32×32 area is considered, along with the normal distribution of mesh clients.

Table 7.9: Simulation parameters for investigation of different replacement methods.

Parameters	Values
Clients distribution	Normal distribution
Area size	32×32
Number of mesh routers	16
Number of mesh clients	48
Total iterations	6400
Iteration per phase	32
Number of particle-patterns	32
Radius of a mesh router	From 1.5×1.5 to 4.5×4.5
Initial router placement	Random
Replacement methods	CM, RIWM, LDVM, LDIWM



(a) Size of giant component.

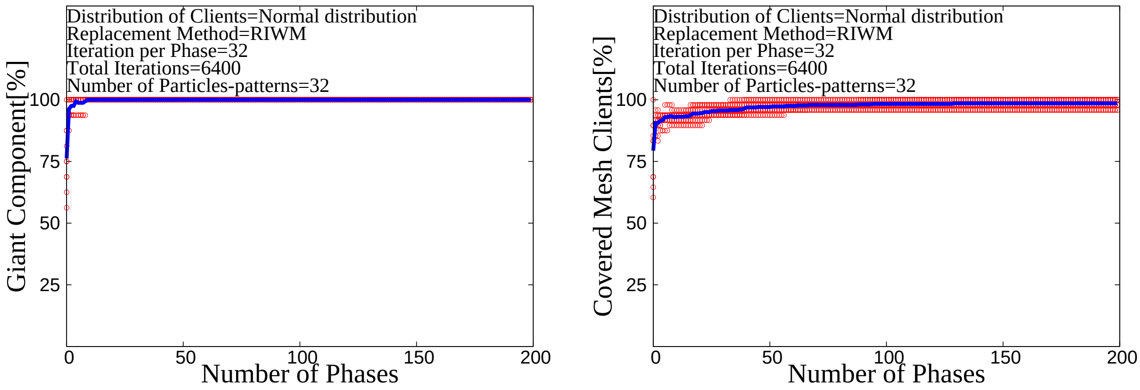
(b) Number of covered mesh clients.

Figure 7.18: Simulation results of CM for investigation of different replacement methods.

The number of mesh routers is set to 16 and the number of mesh clients is set to 48. We use four different replacement methods of routers: CM, RIWM, LDVM and LDIWM. The total number of iterations is set to 6400 and the iterations per phase is set to be 32. We consider that the number of particle-patterns is 32. The simulation parameters and their values are given in Table 7.9. The simulations have been conducted 10 times in order to avoid dealing with the effects of randomness and create a general view of the results.

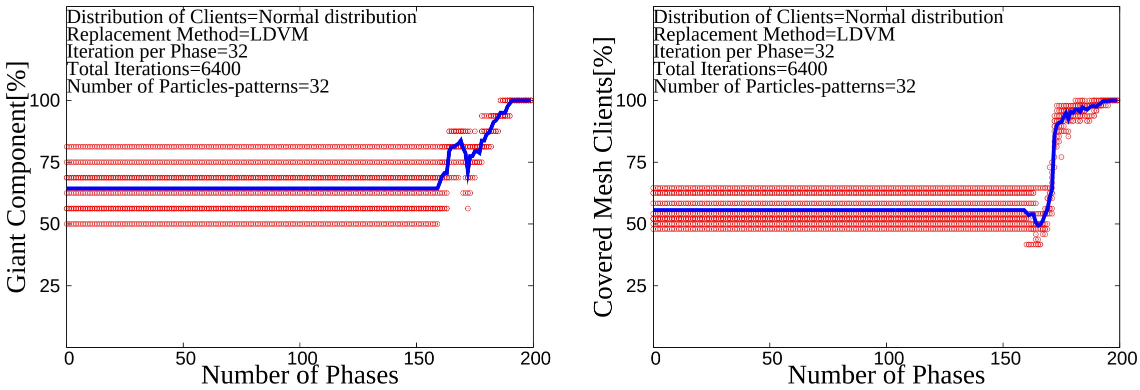
Simulation results are shown in Figure 7.18 to Figure 7.20. The results of CM are shown in Figure 7.18. For CM, the performance is almost constant. Its convergence is very fast, but the performance is not good. The results of RIWM are shown in Figure 7.19. In RIWM, the particle-patterns converge to a good solution fast and the performance is very good. The simulation results of LDVM are shown in Figure 7.20. In LDVM, the solutions converge after 170 phases. In Figure 7.21, we show the simulation results when the replacement method is LDIWM. The particle-patterns converge after 200 phases.

In Figure 7.22, the visualization results for the four replacement methods for mesh routers are shown. In Figure 7.22(a), for CM, it can be observed that some of mesh routers create an



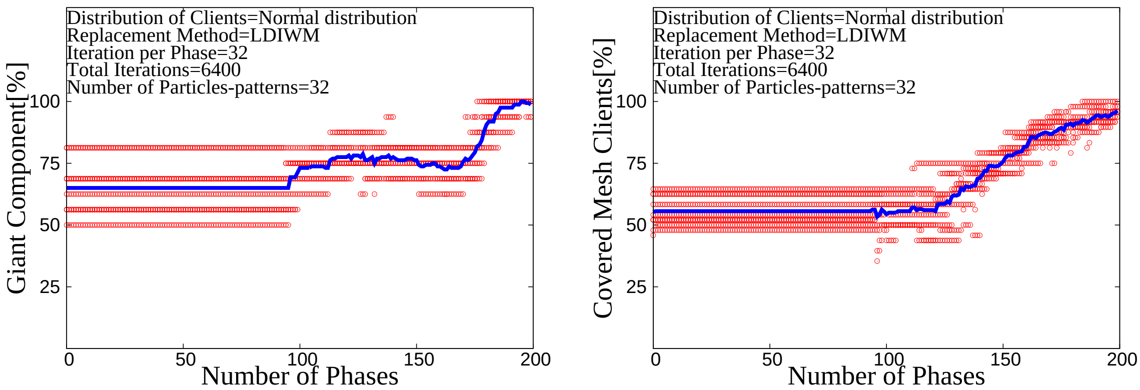
(a) Size of giant component. (b) Number of covered mesh clients.

Figure 7.19: Simulation results of RIWM for investigation of different replacement methods.



(a) Size of giant component. (b) Number of covered mesh clients.

Figure 7.20: Simulation results of LDVM for investigation of different replacement methods.



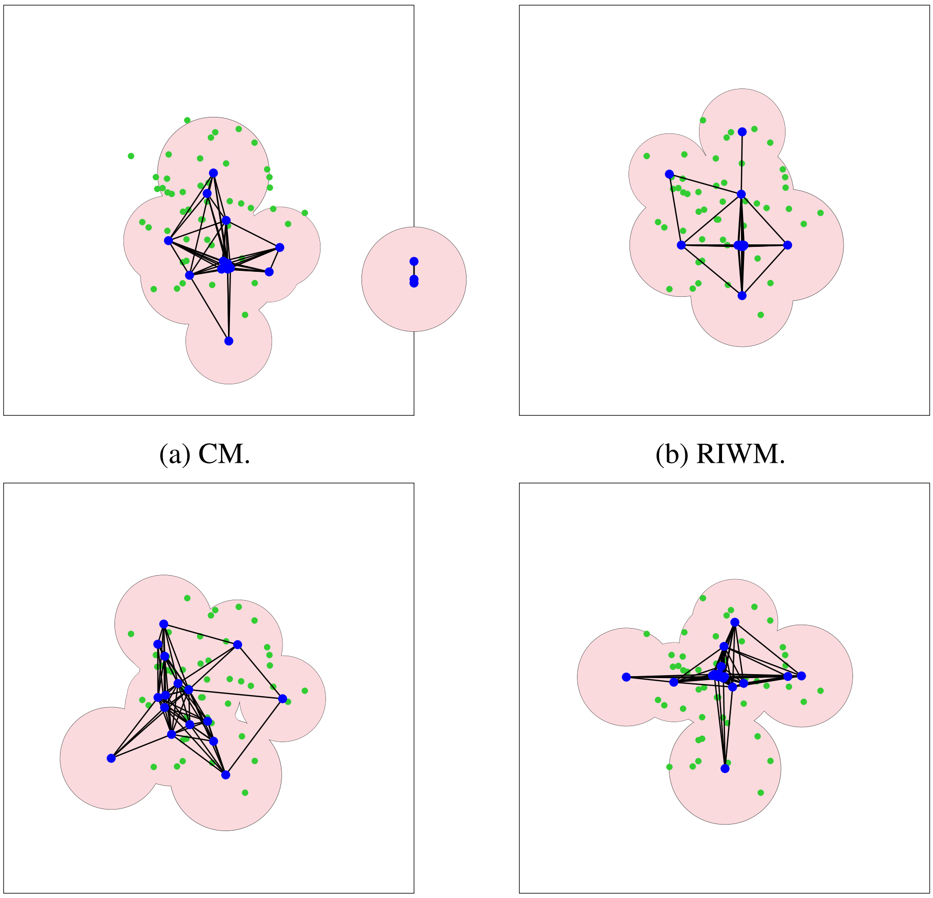
(a) Size of giant component. (b) Number of covered mesh clients.

Figure 7.21: Simulation results of LDIWM for investigation of different replacement methods.

island and do not cover any mesh client. The other three replacement methods, except CM, can find good solutions because all mesh routers connect to all mesh clients by using multi hops.

Comparing the four different replacement methods, it can be concluded that:

- CM converges very fast but it has the worst performance among the four replacement



(a) CM. (b) RIWM.

(c) LDVM. (d) LDIWM.

Figure 7.22: Visualization of results for investigation of different replacement methods.

methods.

- RIWM converges fast and has good performance.
- LDVM converges after 170 phases and has good performance.
- LDIWM converges after 200 phases.

7.1.4 Evaluation and Comparison of WMN-SA and WMN-PSO Simulation Systems

In this section, we show simulation results using WMN-SA and WMN-PSO systems. In this work, we consider the distribution of mesh clients as normal distribution. For comparisons of the calculation time, we consider the area size to be from 32×32 to 128×128. The number of mesh routers is considered to be 16 and the number of mesh clients is 48. The total number of iterations is considered to be 6400 and the iterations per phase is considered to be 32. In SA,

Table 7.10: Common simulation parameters.

Parameters	Values
Clients distribution	Normal distribution
Number of mesh routers	16
Number of mesh clients	48
Total iterations	6400
Iteration per phase	32
Area size	From 32×32 to 128×128
Radius of a mesh router	From 2.0 to 15.0

Table 7.11: Relationship of area size with radius of a mesh router parameters.

Area size	Radius of a mesh router
32×32	From 2.0 to 6.0
64×64	From 3.0 to 9.0
128×128	From 5.0 to 15.0

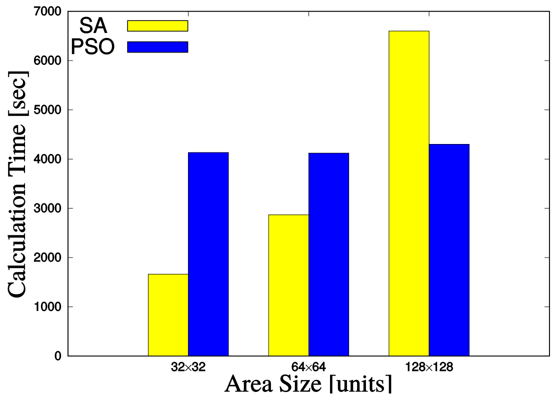


Figure 7.23: Comparison of WMN-SA and WMN-PSO calculation time for different area size.

we set the SA temperature to 1. In PSO, we consider the number of particle-patterns to be 32.

The simulation parameters and their values for both WMN-SA and WMN-PSO are shown in Table 7.10. We show the relationship of the area size and radius of a mesh router in Table 7.11. The radius of a mesh router is decided randomly. The WMN-SA parameters and WMN-PSO parameters are shown in Table 7.12 and Table 7.13, respectively. We conducted simulations 30 times, in order to avoid the effects of randomness and created a general view of the results.

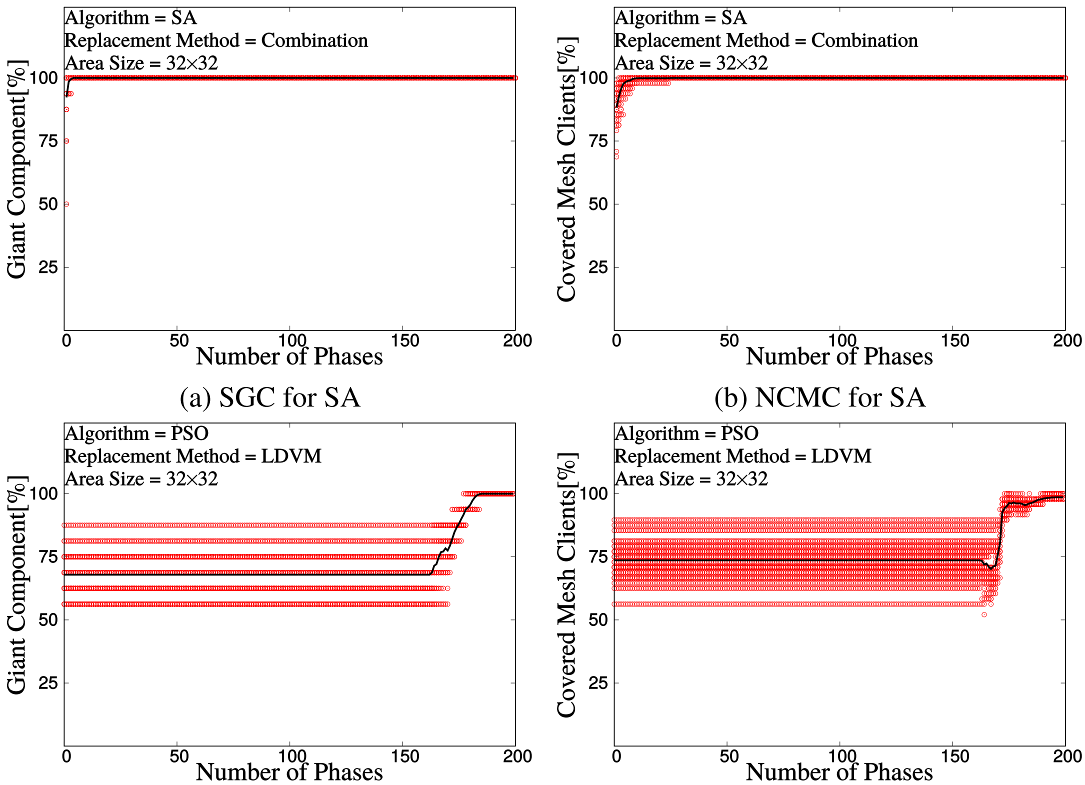
We show the simulation results from Figure 7.23 to Figure 7.26. In Figure 7.23, we show the calculation time of WMN-SA and WMN-PSO systems. We can see that WMN-PSO needs more calculation time than WMN-SA when the area size is small. However, the calculation time of WMN-SA is exponentially increased with an increase of area size. On the other hand, WMN-PSO calculation time is almost constant. In Figure 7.24, Figure 7.25 and Figure 7.26, we evaluate the simulation results by using 2 metrics (SGC and NCMC). In Figure 7.24, we consider the area size to be 32×32. The WMN-SA converges very fast and its performance is very good. It should be noted that WMN-PSO also has archived maximal values of SGC and

Table 7.12: WMN-SA parameters.

Parameters	Values
SA temperature	1
Replacement method	Combination

Table 7.13: WMN-PSO parameters.

Parameters	Values
Number of particle-patterns	32
Replacement method	LDVM



(a) SGC for SA (b) NCMC for SA

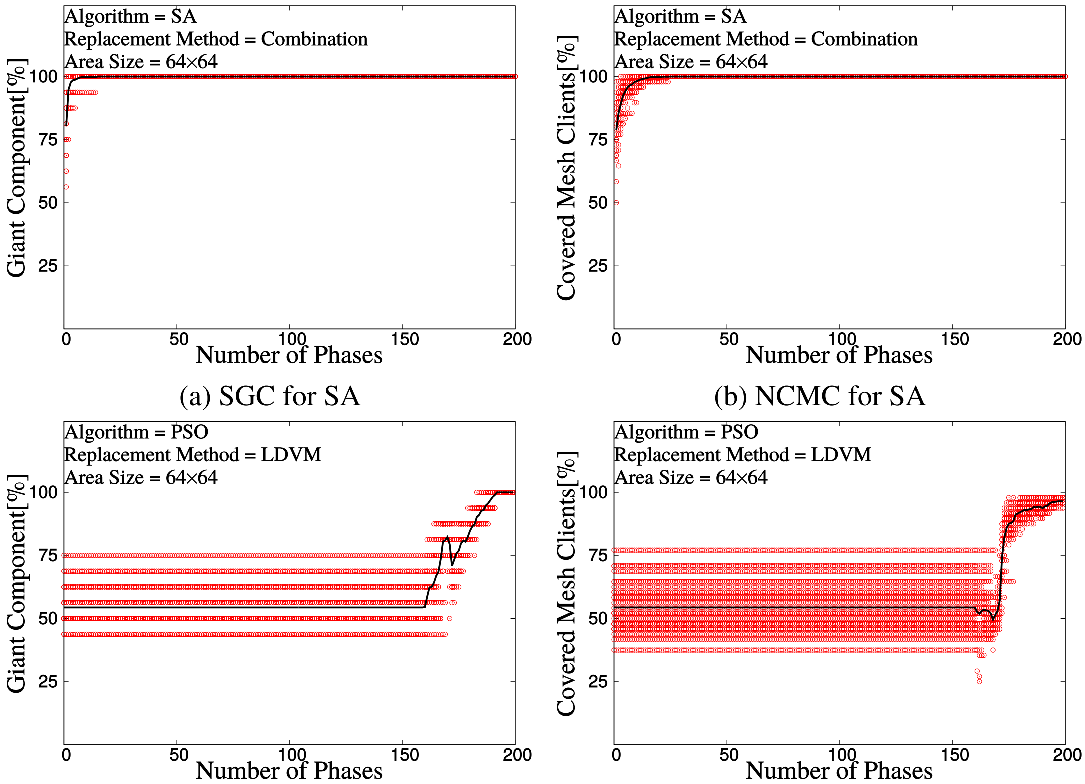
(c) SGC for PSO (d) NCMC for PSO

Figure 7.24: Simulation results for different algorithms when the area size is 32×32.

NCMC.

In Figure 7.25, we consider the area size of 64×64. Comparing the performance with Figure 7.24, WMN-SA converges slower than the area size 32×32, but still has good performance. However, WMN-PSO has almost the same performance as in Figure 7.24.

In Figure 7.26, we can see that with increasing of the area size to 128×128, the performance of WMN-SA is decreased, but the system still has good behavior. On the other hand, the performance of WMN-PSO decreased much more. However, the WMN-PSO calculation time is better than WMN-SA.



(a) SGC for SA (b) NCMC for SA

(c) SGC for PSO (d) NCMC for PSO

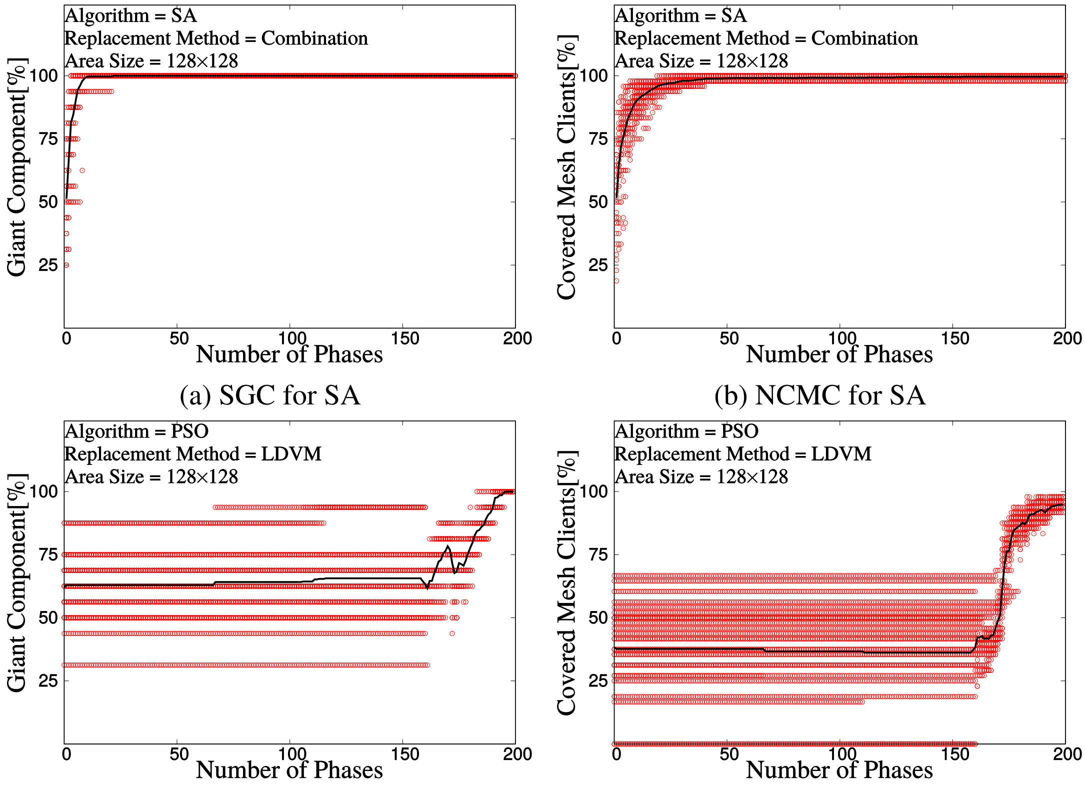
Figure 7.25: Simulation results for different algorithms when the area size is 64×64.

7.2 Comparison of WMN-PSO, WMN-PSOHC and WMN-PSOSA Systems

In this section, we show simulation results using WMN-PSO, WMN-PSOHC and WMN-PSOSA systems. In this simulation, we set the same parameters in order to compare two simulation systems. We consider there to be a normal distribution of mesh clients. The number of mesh routers is considered to be 16 and the number of mesh clients is 48. The total number of iterations is considered to be 800 and the iterations per phase is considered to be 4. We consider the number of particle-patterns to be 9. We conducted the simulation 10 times, in order to avoid the effect of randomness and create a general view of the results. For WMN-PSOSA, the temperature value was set to 10. The temperature value decreases by multiplying by 0.99426 per iteration. At the end of simulation, the temperature value will be 0.1.

We show the parameter setting for WMN-PSO and WMN-PSOHC in Table 7.14. The parameter setting for WMN-PSOSA is shown in Table 7.15.

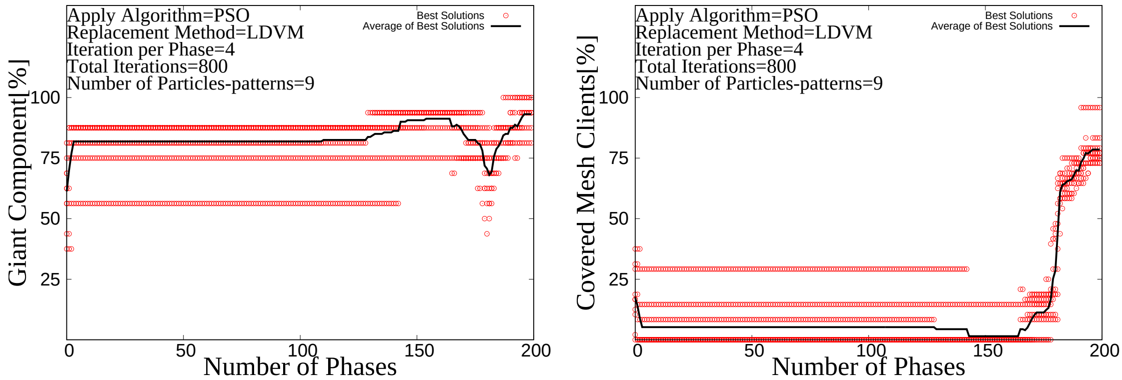
We show the simulation results from Figure 7.27 to Figure 7.30. In Figure 7.27, we see that solutions converge after 170 phases and NCMC does not reach the maximum (100%). In Figure 7.28, we show simulations results for WMN-PSOHC. We see that solutions converge very fast. The NCMC also converges soon and all solutions reach the maximum value. Figure 7.29



(a) SGC for SA (b) NCMC for SA

(c) SGC for PSO (d) NCMC for PSO

Figure 7.26: Simulation results for different algorithms when the area size is 128×128.



(a) SGC (b) NCMC

Figure 7.27: Simulation results for WMN-PSO for comparing implemented systems.

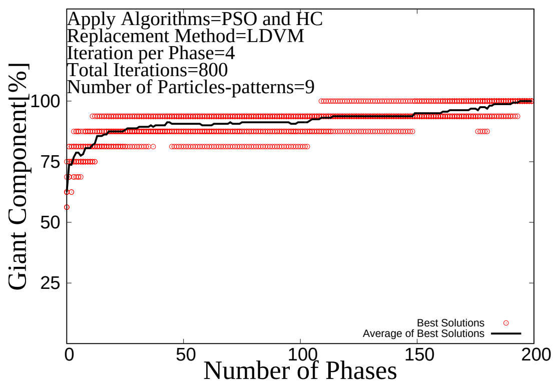
shows that the SGC and NCMC of WMN-PSOSA increases gradually and all solutions reach the maximum value. We show the visualized results in Figure 7.30. We see that all mesh routers are connected for all systems. However, some mesh clients are not covered in WMN-PSO. On the other hand, all mesh clients are covered by mesh routers in WMN-PSOHC and WMN-PSOSA. Comparing intelligent hybrid systems, WMN-PSOHC converges faster than WMN-PSOSA.

Table 7.14: WMN-PSO and WMN-PSOHC parameters for comparing implemented systems.

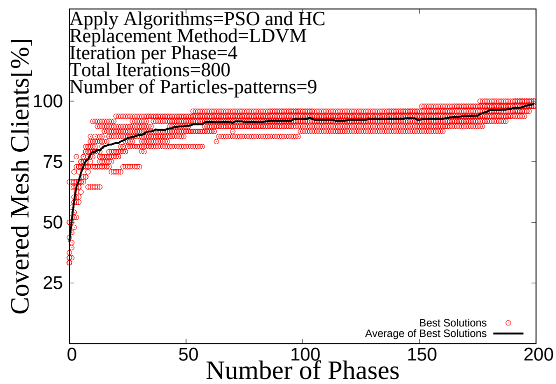
Parameters	Values
Clients distribution	Normal distribution
Grid size	32×32
Number of mesh routers	16
Number of mesh clients	48
Total iterations	800
Iteration per phase	4
Number of particle-patterns	9
Radius of a mesh router	2.0
Replacement method	LDVM

Table 7.15: WMN-PSOSA parameters for comparing implemented systems.

Parameters	Values
Clients distribution	Normal distribution
Grid size	32×32
Number of mesh routers	16
Number of mesh clients	48
Total iterations	800
Iteration per phase	4
SA Starting temperature	10
SA Ending temperature	0.1
Decreasing speed of SA temperature (α)	0.994260
Number of particle-patterns	9
Radius of a mesh router	2.0
Replacement method	LDVM

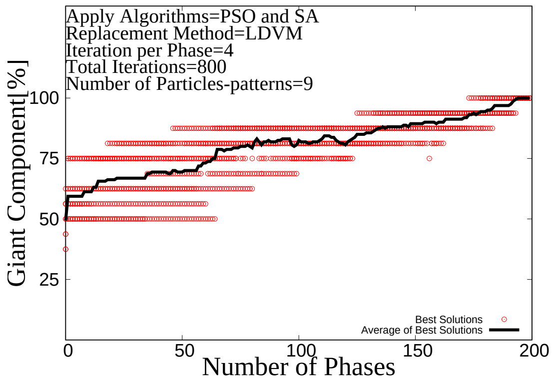


(a) SGC

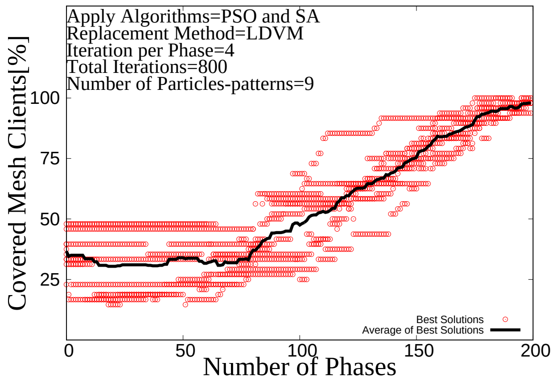


(b) NCMC

Figure 7.28: Simulation results for WMN-PSOHC for comparing implemented systems.

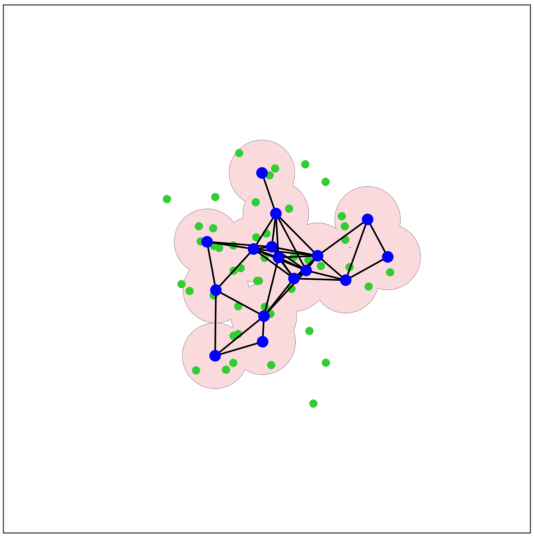


(a) SGC

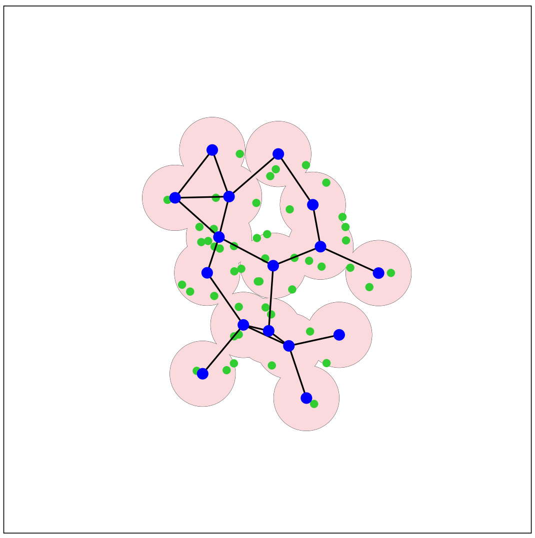


(b) NCMC

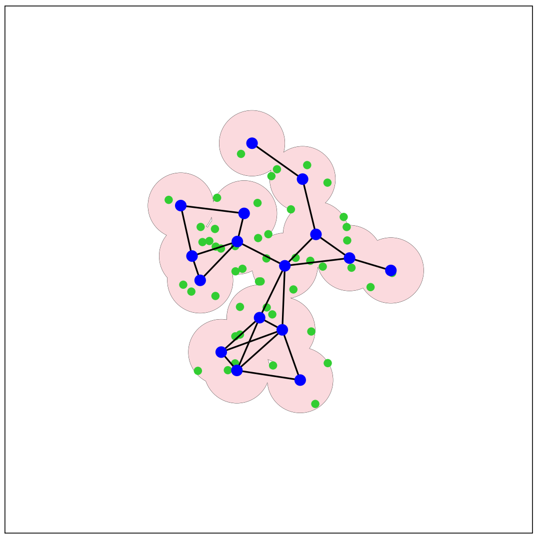
Figure 7.29: Simulation results for WMN-PSOSA for comparing implemented systems.



(a) WMN-PSO



(b) WMN-PSOHC



(c) WMN-PSOSA

Figure 7.30: Visualized image of simulation results for comparing implemented systems.

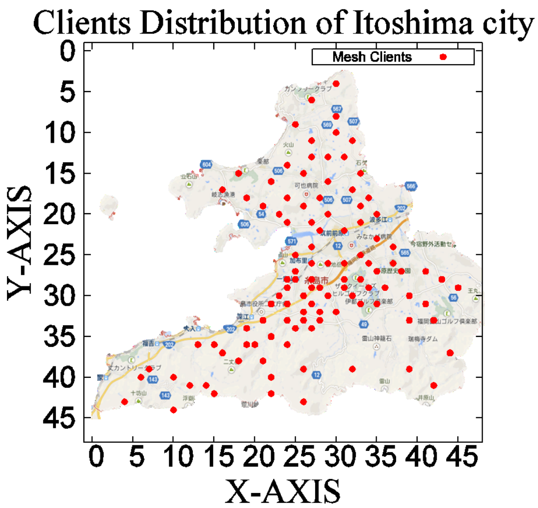
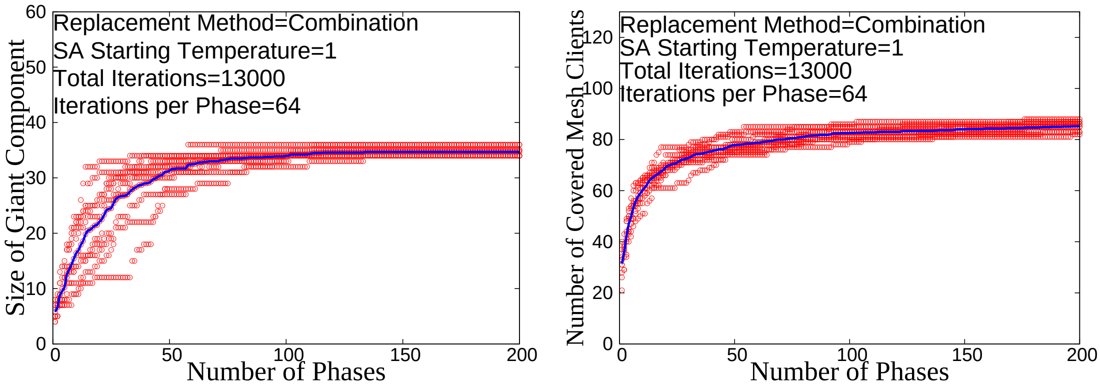


Figure 7.31: Clients distribution of Itoshima city.



(a) Giant component

(b) Covered mesh clients

Figure 7.32: Evaluation of WMNs for 36 mesh routers.

7.3 Application of Simulation System for WMN Node Placement in a Realistic Scenario

7.3.1 Client Distribution

As for the distribution of mesh clients, we considered a realistic scenario in Itoshima City, Fukuoka Prefecture, Japan and applied our WMN-SA simulation system. Itoshima City is located in the western part of Fukuoka Prefecture. The mesh client distribution of Itoshima City is shown in Figure 7.31. We deployed 108 mesh clients in the city.

7.3.2 Simulation Results

In this section, we present the simulation results of applying the implemented WMN-SA simulation system in a realistic scenario in Itoshima City.

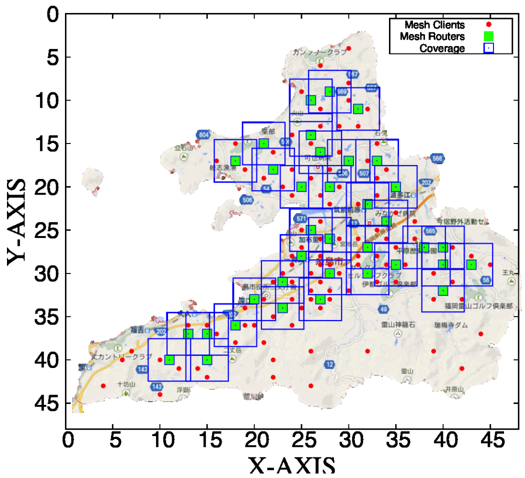


Figure 7.33: Visualization of simulation result.

Table 7.16: Simulation settings.

Parameters	Values
Area size	48×48
Number of mesh routers	36
Number of mesh clients area	108
Client distribution	Itoshima city model
Communication distance	2
SA temperature	1
Iteration per phase	64
Total Iteration	13000
Apply method	Combination

For simulations, we considered a grid size is 48×48, 108 mesh clients and 36 mesh routers. We show the simulation parameters in Table 7.16.

The replacement method of mesh routers is Combination. The radius of mesh router nodes in the WMN-SA system is set to 2 as shown in Figure 7.1. One grid unit is considered to be 400m $\times$ 400m (d=400m). We keep both the number of iterations per phase and the SA temperature fixed to 64 and 1, respectively.

For each phase, WMN-SA runs 64 iterations. Because of the presence of random processes in our simulation system, we conduct the simulations 10 times, in order to avoid the effects of randomness and create a general view of the results.

Simulation results are shown in Figure 7.32 and the visualization of the simulation results are shown in Figure 7.33. From the simulation results, we see that the size of GC is at maximum for 138 phases (see Figure 7.32(a)), while, the NCMC is 88 (See Figure 7.32(b)). In order to cover all the mesh clients, we need to deploy more mesh routers. However, the cost of the implementation for WMNs will be increased. Also, some of mesh clients are scattered in remote areas and they have low density, so it is difficult to cover all of them. For this reason, we will carry out other simulations to improve the coverage of mesh clients.

Chapter 8

Conclusions and Future Work

In this thesis, we implemented various intelligent and hybrid systems for solving the node placement problem in WMNs. In order to analyze the performance of the implemented systems, we evaluated and compared the implemented systems.

This thesis consists of eight chapters. Chapter 1 presented the background information and our motivation for writing this thesis. Chapter 2 introduced general aspects of wireless networks. Also, WSANs and MANET were explained as a related work to this thesis. We presented WMNs in Chapter 3. We explained the node classification in WMNs and routing protocols for WMNs. In addition, we defined the Node Placement Problem in WMNs. In Chapter 4, Intelligent Algorithms are discussed such as Hill Climbing (HC), Simulated Annealing (SA), Tabu Search (TS), Genetic Algorithm (GA), Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO). We presented in detail about PSO and its process and stability in Chapter 5. The implemented intelligent systems and intelligent hybrid systems were presented in Chapter 6. Chapter 7 showed the evaluation and comparison of implemented systems by conducting simulations and an application system for a realistic scenario. In Chapter 8, we presented some concluding remarks and future work.

8.1 Conclusions from Simulation Results

8.1.1 Evaluation and Comparison of WMN-HC, WMN-SA and WMN-GA Simulation Systems

We conducted simulations for 3 cases when the grid size is 16×16, 32×32 and 64×64, when we deployed 12, 48 and 192 mesh clients and 4, 16 and 64 mesh routers. From the simulation results we conclude as follows.

- The size of GC, in most cases, reaches around 100%.

- For covered mesh clients, SA and HC have a better performance than GA.
- The performance of SA and HC is almost the same.

8.1.2 Evaluation and Comparison of WMN-SA and WMN-TS

We evaluated the performance of WMN-SA and WMN-TS simulation systems for a normal distribution of mesh clients considering OLSR protocol. From the simulations, we found the following results.

- For both simulation systems, the throughput of I/B WMN is a little bit higher than Hybrid WMN.
- For WMN-SA, the delay of I/B WMN is a little bit lower than Hybrid WMN. However, for WMN-TS the delay of Hybrid WMN is lower than I/B WMN.
- For both simulation systems, the fairness index of I/B WMN is a little bit higher than Hybrid WMN.
- For WMN-SA, the energy decreases sharply because of the high density of nodes and high throughput, and thus the nodes spend more energy.

8.1.3 Evaluation of the WMN-PSO System

Evaluation of Fitness Function Weight-Coefficients in the WMN-PSO System

We investigated fitness function weight-coefficients for optimization in the WMN-PSO simulation system. From the simulation results, we found that as α increases, the SGC is increased, but the NCMC is decreased. In other words, α and β are in a trade-off relation. The fitness function follows a hierarchical approach in which the main objective is to maximize the SGC in WMN. The median of SGC got to 100% when $\alpha = 0.7$. Therefore, the best weight-coefficients of SGC and NCMC were 0.7 and 0.3, respectively.

Evaluation of Different Replacement Methods

We considered four replacement methods for mesh routers. Using the Size of Giant Component (SGC) and the Number of Covered Mesh Clients (NCMC) as performance metrics, our simulation has revealed that:

- CM converges very fast but it has the worst performance among 4 replacement methods.
- RIWM converges fast and has good performance.

- LDVM converges after 170 phases and has good performance.
- LDIWM converges after 200 phases.

8.1.4 Evaluation and Comparison of WMN-SA and WMN-PSO Simulation Systems

We compared the performance of WMN-SA and WMN-PSO systems by simulations.

From the simulation results, we conclude as follows.

- When the area size is 32×32 and 64×64, WMN-SA has better performance than WMN-PSO.
- When the area size is 128×128, WMN-SA performs better than WMN-PSO. However, WMN-SA needs more calculation time than WMN-PSO.

8.1.5 Comparison of WMN-PSO, WMN-PSOHC and WMN-PSOSA Systems

From the simulation results, we conclude that all mesh routers are connected and all mesh clients are covered for both intelligent hybrid systems. Comparing intelligent hybrid systems, WMN-PSOHC converges faster than WMN-PSOSA.

8.1.6 Application of a Simulation System for WMN Node Placement in a Realistic Scenario

We applied our proposed WMN-SA simulation system in a realistic scenario of the distribution of mesh clients in Itoshima City, Fukuoka Prefecture, Japan. From the simulation results, we conclude as follows.

- The size of GC is maximal for 138 phases, so the convergence of the WMN-SA system is very good.
- Only 88 mesh clients were covered by 36 routers, so we need to add more mesh routers to improve the coverage.
- However, by increasing the number of mesh routers, the cost of the deployment for WMNs will be increased.

From the simulation results, we found many insights that could be very important for the actual deployment of WMNs.

8.2 Future Works

In future work, we will deal with the following issues.

Simulation models:

The node movement is a key factor of the simulation. Thus, we would like to consider node mobility. Also, we would like to propose and implement a new model which considers walls or obstacles.

Resource management of WMNs:

This work also can be seen as resource management of WMNs. In the future, every resource will be more important as the human population increases. Thus, we would like to make considerations in terms of energy consumption. Also, reducing the number of mesh routers is also good for cutting off energy consumption. Therefore, we would like to find good solutions with regards to the number of mesh routers and the spent energy.

Proposal of a killer application for WMNs:

As WMN's cost-effectiveness cannot be expected, the popularization of WMNs to end-users has almost stopped. Therefore, we need to propose and implement a killer application for WMNs.

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