Realizing Adaptive Communication Mechanisms by Flexible Use of Multiple Media in Wireless Networks

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2. S. Kajioka, N. Wakamiya, H. Satoh, K. Monden, S. Matsui, and M. Murata, "Evaluation of a QoS-aware routing mechanism for multi-channel multi-interface ad-hoc networks," *Technical Report of IEICE (AN2008-1)*, vol. 108, no. 33, pp. 1–6, May 2008. (in Japanese).

3. S. Kajioka, N. Wakamiya, and M. Murata, "Proposal and evaluation of adaptive resource allocation among multiple nodes and applications in cognitive wireless networks," *Technical Report of IEICE (NS2009-197)*, vol. 109, no. 448, pp. 201–204, Mar. 2010. (in Japanese).

Preface

In recent years, we benefit from wireless networks anytime and anywhere, which makes our daily life convenient and comfortable. From the number of subscribers, the penetration rate of mobile telephone in Japan reaches 94 % and more than 90 million enjoy mobile access to the Internet [1, 2]. New wireless network technologies keep developing and getting common, such as HSPA (High Speed Packet Access) on 3G cellular networks, WiMAX (Worldwide Interoperability for Microwave Access), LTE (Long Term Evolution), and DSRC (Dedicated Short Range Communications). They have different characteristics in terms of the number of channels, the range of frequency, physical communication protocol, coverage area, speed of communication, delay in communication, and cost. For effective use of such various means of wireless communication in our living environment, a variety of mobile communication devices, equipment, and systems such as smartphone, laptop, and vehicle, are now equipped with the capability of access to two or more wireless networks by having multiple network interfaces or switching between networks. At the same time, many mobile applications emerge which rely very much on wireless networks in getting and emitting information. Each of mobile applications has different QoS (Quality of Service) requirements such as large bandwidth for remote monitoring or low delay for VoIP (Voice over IP) communication. Therefore, matching between applications and wireless networks is necessary to satisfy QoS requirements of applications by considering characteristics of wireless networks. Furthermore, because of the instability of wireless communication caused by interference and fading, we need an adaptive mechanism to handle dynamic changes in characteristics of wireless networks.

In this thesis, we investigate adaptive communication mechanisms for wireless networks, which consist of nodes having multiple interfaces and whose available bandwidth and connectivity dynamically change, to flexibly utilize multiple wireless media, i.e. channels and networks.

We begin this thesis by designing, implementing, and evaluating a QoS-aware routing mechanism for multi-channel and multi-interface wireless ad-hoc networks. Wireless ad-hoc networks do not require any fixed equipment such as routers, switches, access points, base stations, and cables in organizing a communication network. Because of such an infraless feature, wireless ad-hoc networks are considered the promising technology to establish a means of communication where installation of network equipments and cables is not allowed, difficult, or expensive as in a historic landmark or a festival site. A wireless ad-hoc network is also useful, when conventional communication infrastructures are destroyed such as in catastrophic disasters like earthquake. Despite the convenience, a wireless ad-hoc network suffers from the limitation on the wireless capacity, which makes it non-trivial to accommodate real-time multimedia traffic for remote monitoring, video conferencing, and VoIP communication transmitted on the above situations. So that a wireless ad-hoc network can provide real-time multimedia applications on connections with satisfactory QoS, we propose a new routing mechanism, which selects an appropriate path and effectively uses multiple channels available in the ad-hoc network. In our proposal, we consider bandwidth as a QoS metric and a source node determines a logical path with the maximum available bandwidth to avoid congested physical links and satisfy application QoS requirements. A logical path is constructed from physical paths, which are determined by a physical routing protocol, for which we use OLSRv2, as it is a proactive routing protocol having the capability of efficient control message propagation. For a source node to know the available bandwidth on physical links of the whole network, the information about channel usage is embedded in control messages of OLSRv2. In addition, to effectively utilize multiple channels on each hop, each node chooses a channel in a stochastic manner by the available bandwidth in sending a packet. In this way, our proposal can accomplish appropriate routing and effective use of multiple channels with consideration of application QoS requirements. Through simulation

experiments, we confirmed that our proposal can distribute the load over a network and achieves better performance than the existing QoS-aware routing protocol.

Next, to verify the practicality of the above routing mechanism in the real environment, we build a prototype and conduct practical experiments. This study stands on importance of verifying practicality of proposed method in the actual environment. The prototype has three available wireless network interfaces, which support IEEE 802.11b/11g MAC protocols in ad-hoc mode. Similarly to a regular embedded system, the node passes packets from IP to specific applications or from applications to IP via socket interface. To implement our proposal on a node, we modified the socket interface and encapsulate packets by additional header indicating addresses of intermediate nodes of the logical path. Through practical experiments, we confirm that our proposal can perform logical routing and effective channel selection in the actual environment.

The above study considers adaptive and flexible use of multiple channels available on physical links. We further extend our view to a case with multiple networks, which are heterogeneous in network characteristics. We propose an autonomous and adaptive mechanism to allocate wireless network resources among multiple nodes and among multiple applications taking into account required QoS of applications and network characteristics. Although such resource allocation can be formulated as an optimization problem to maximize a certain criterion, such as the total degree of satisfaction of nodes, it requires energy and bandwidth-expensive message exchanges to maintain the up-to-date state information. Therefore, our proposal adopts the *attractor composition model*, i.e. a mathematical model of autonomous and adaptive behavior of biological systems. In our proposal, each node tries to maximize the degree of satisfaction of itself. Through mutual but indirect interaction among nodes, limited network resources are fairly shared among nodes. Numerical analysis demonstrates that our mechanism can adaptively allocate wireless network resources to applications, while considering their QoS requirements and fairly sharing network resources among nodes.

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Chapter 1

Introduction

1.1 Background

In recent years, we benefit from wireless networks anytime and anywhere, which makes our daily life convenient and comfortable. From the number of subscribers and the population, the penetration rate of mobile telephone in Japan reaches 94 % and more than 90 million enjoy mobile access to the Internet [1, 2]. In addition to conventional wireless networks such as cellular and Wi-Fi, a variety of new wireless network technologies such as HSPA (High Speed Packet Access) on 3G cellular networks, WiMAX (Worldwide Interoperability for Microwave Access), LTE (Long Term Evolution), and DSRC (Dedicated Short Range Communications) keep developing and getting common. Thanks to the development of these wireless network technologies, future wireless networks will become larger in term of bandwidth, lower in terms of delay and delay jitter.

For effective use of such various means of wireless communication in our living environment, a variety of mobile communication devices, equipment, and systems such as smartphone, laptop, and vehicle, are now equipped with the capability of access to two or more wireless networks by, for example, having multiple network interfaces, switching between networks, or using several network interfaces simultaneously. At the same time, many mobile applications emerge on wireless networks such as remote monitoring, vehicle

navigation, video conferencing, VoIP (Voice over IP), web access, and e-mail. They rely very much on wireless networks in getting and emitting information.

On one hand, each of mobile applications has different QoS (Quality of Service) requirements. For example, remote monitoring and such video applications require large bandwidth, VoIP requires low delay and low delay jitter, and best-effort applications such as web access and e-mail require low-cost communication rather than large bandwidth, low delay, or low delay jitter. On the other hand, wireless networks have different characteristics in terms of the number of channels, the range of frequency, physical communication protocol, coverage area, speed of communication, modulation scheme, quality of backbone networks, delay in communication, and cost. Therefore matching between applications and wireless networks to satisfy QoS requirements of applications by characteristics of assigned wireless networks is indispensable to effectively use wireless network resources. Furthermore, because of the instability of wireless communication caused by interference and fading, we need an adaptive mechanism to handle dynamic changes in characteristics of wireless networks [3].

To adapt a change of the system, a node should be aware of the change from obtainable information and should do feasible control. However, the amount of control messages should be reduced as much as possible to prevent the performance deterioration in wireless networks. Especially, emitting broadcast messages, e.g. topology control messages, may cause hidden terminal problem since the RTS/CTS (Request To Send/Clear To Send) handshake cannot be activated when emitting them [4]. The RTS/CTS handshake is the optional mechanism of the IEEE 802.11 wireless networking protocol to reduce frame collisions introduced by the hidden terminal problem. The hidden terminal problem considerably deteriorates the performance of wireless networks [5]. For the reason, it is desirable for the node to reduce amount of transmitting broadcast messages, which is not negligible in wireless networks. Therefore, we introduce OLSRv2 (OLSR version 2), which is a proactive routing protocol for ad-hoc networks [6]. On OLSRv2 (and OLSR) protocol, nodes having a role in forwarding broadcast messages are limited so that avoiding the loss of bandwidth

for broadcast packets. Among nodes receiving a broadcast message, only elected nodes re-broadcast the message (RFC3626 1.4. [7] or [8]). Thus, OLSRv2 can mitigate performance deterioration of transmitting its control messages. This characteristic of OLSRv2 gives rise to the possibility of adaptive routing by embedding information in control messages of OLSRv2 with consideration of application QoS. Furthermore, we can utilize multiple channels effectively by defining and separating the role of each channel, i.e. some channels have a role in real-time applications while a channel has a role in other applications and routing.

In the former part of this thesis, we determine the possibility of adaptive routing in ad-hoc networks with consideration of application QoS. Then, in the latter part of this thesis, we extend our view to a case with heterogeneous applications and wireless networks and confirm the possibility of adaptive resource allocation using simple feedback of current system conditions.

Ad-Hoc Networks

Ad-hoc networks, which are a kind of wireless networks, do not require any fixed equipment or infrastructures such as routers, switches, access points, base stations, and cables. In ad-hoc networks, nodes communicate with each other through radio signals to organize a network and transmit data from one node to another. For its infra-less feature, ad-hoc networks are considered the promising technology to establish a means of communication where installation of network equipment and cables is not allowed, difficult, or expensive as in a historic landmark or a festival site or when conventional communication infrastructures are destroyed such as in catastrophic disasters like earthquake. In such situations, ad-hoc networks are expected to accommodate real-time multimedia traffic for remote monitoring, video conferencing, and VoIP communications.

In ad-hoc networks, a node creates a multi-hop path to communicate with another node autonomously. It has been recognized that the effective network capacity of a single-channel

and multi-hop wireless network using the typical IEEE 802.11 standard MAC is not $n \times$(*per-channel-throughput*), but $O(n/\sqrt{n}) \times$(*per-channel-throughput*) due to radio contention [9], where n is the number of nodes using the same channel in the wireless network. In [10], they further took into account that the wireless phenomena, such as medium contention, channel fading, and radio interference, causing the degradation of the effective bandwidth. Since the capacity of wireless link is limited and the effective bandwidth is much smaller for contention among nodes [9, 10], it is not trivial to accommodate real-time multimedia traffic in an ad-hoc network. Especially, it is a challenging problem by the fact that real-time applications may require certain level of QoS guarantee or control in terms of packet loss, delay, and delay jitter.

For this purpose, consideration of application QoS is necessary to accommodate real-time applications in ad-hoc networks. Network capacity or available bandwidth is the most important QoS metric for many real-time applications. By expansion or effectively use of network capacity, the ad-hoc network can accommodate larger number of real-time applications. In the former part of this thesis, we consider bandwidth as the QoS metric and we expand and effectively utilize the capacity of an ad-hoc network by collaboration of effective use of multiple channels and effective control message propagation on OLSRv2. Furthermore, by embedding QoS information about channel usage of nodes in control messages of OLSRv2, the QoS information is propagated effectively and a source node can do QoS-aware adaptive routing with the view of network topology and status of nodes in the ad-hoc network.

Extension to Heterogeneous Networks

The above-mentioned approach to mitigate the overhead in managing the up-to-date information about the state of network is helpful to some extent. However, when a variety of networks with different characteristics exist and multiple nodes and applications with heterogeneous requirements compete for the limited network resources, the state information, which each node or a centralized server should collect and maintain, amounts too much

to handle without introducing extra overhead. In addition, we cannot assure the integrity of connection in the case that the network condition dynamically changes by mobility of nodes. Therefore, we need a mechanism where each node autonomously behaves using local information in an adaptive manner for changing environment. To achieve this goal, our research group has adopted an approach to adopt adaptive behavior of biological systems to network management. For example, in [11], we propose a biologically inspired adaptive multi-path routing protocol for an overlay network to adaptively switch between paths whose performance dynamically changes. In this thesis, we adopt the *attractor composition model*, which imitates adaptive behavior of living organisms to unknown changes in their environment to live, grow, and reproduce, to adaptive network resource allocation among multiple nodes and multiple applications [12].

1.2 Outline of Thesis

In this thesis, we study an adaptive communication mechanisms by flexible use of multiple media in wireless networks where nodes are equipped with multiple wireless interfaces and each of which a different wireless channel or network can be assigned. The former part of this thesis describes design, implementation, and evaluation of a QoS-aware routing mechanism for ad-hoc networks. By considering bandwidth as the QoS metric and nodes emit available bandwidth of itself with control messages of OLSRv2, each node obtains information of available bandwidth with whole network topology and does QoS-aware routing by obtained information to adapt current communication environment. The latter part of this thesis describes proposal and evaluation of an adaptive resource allocation mechanism using biologically inspired model in heterogeneous wireless networks. By adopting the *attractor composition model* to the network resource allocation, we confirm that each node autonomously adapts to the current environment.

A QoS-aware Routing Mechanism for Multi-Channel Multi-Interface Ad-Hoc Networks [13, 14, 15, 16, 17]

We begin this work by designing, implementing, and evaluating a QoS-aware routing mechanism for multi-channel multi-interface wireless ad-hoc networks. To accommodate real-time multimedia applications, such as remote monitoring, video conferencing, and VoIP, while satisfying application QoS requirements in a wireless ad-hoc network, we need QoS control mechanisms. It is desirable for network operators, who establish wireless ad-hoc networks and provide services on the networks, to accommodate a larger number of real-time multimedia applications in a wireless ad-hoc network by adopting feasible QoS control mechanisms.

In Chapter 2, we study a routing mechanism to support real-time multimedia communication with QoS consideration by efficiently utilize the limited wireless network capacity. Our mechanism considers a wireless ad-hoc network composed of nodes equipped with multiple network interfaces to each of which a different wireless channel can be assigned. By embedding information about channel usage, i.e. bandwidth information, in control messages of OLSRv2, each node obtains a view of topology and bandwidth information of the whole network. Furthermore, by selecting one dedicated channel for OLSRv2, our mechanism prevents performance deterioration caused by emitting control messages on the other channels. Based on the obtained bandwidth information, a source node determines a path with the maximum available bandwidth to satisfy application QoS requirements. Packets are transmitted via one of available channels so that effectively use of multiple channels. We conducted simulation experiments and confirmed that our proposal effectively routed multimedia packets over selected path while avoiding congested links. As a result, the load on a network is well distributed and the network can accommodate much number of applications than QOLSR, which is a QoS-aware routing protocol that considering QoS on selecting a next-hop node. We also conduct practical experiments using wireless ad-hoc relay nodes with multiple network interfaces and verify the practicality of our proposal in the actual environment.

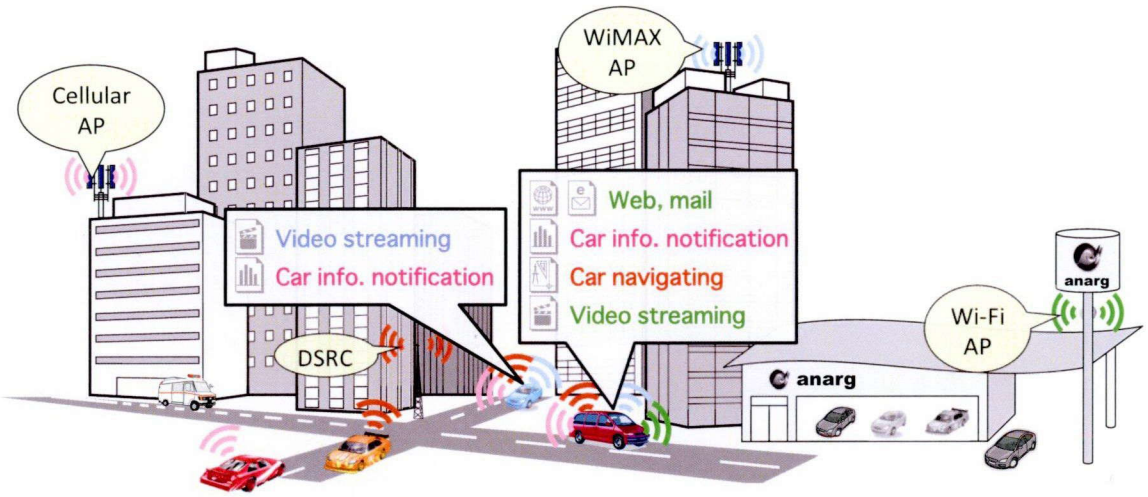


Figure 1.1: Example of resource allocation in heterogeneous wireless networks

Autonomous and Adaptive Resource Allocation of Heterogeneous Wireless Networks among Multiple Nodes and Multiple Applications [18, 19]

In Chapter 2, we consider adaptive routing and flexible use of multiple channels available on physical links. We assumed that a network operator deploys nodes in a certain area and provides services on the established wireless ad-hoc network. We further extend our view to a case with multiple networks, which are heterogeneous in network characteristics. In such an environment, there are two kinds of network operators, i.e. network provider and service provider. Each network provider establishes wireless networks such as DSRC, Wi-Fi, WiMAX, or cellular networks and provides wireless access on its networks while service providers utilize those wireless networks with consideration of characteristics of each wireless network. In Chapter 3, we focus on the service provider and study an autonomous and adaptive mechanism to allocate wireless network resources among multiple nodes and among multiple applications taking into account network characteristics and required QoS of application.

Figure 1.1 shows an example of resource allocation in heterogeneous wireless networks.

We assume that there are some wireless media, which are heterogeneous in network characteristics, available on the area. Each node, i.e. each car, is equipped with multiple wireless interfaces, which are capable of accessing to the dedicated wireless media. As shown in Figure 1.1, we assume that various kinds of applications, e.g. video streaming, car information notification, and car navigating, are running on a car, each of which requires different kinds of QoS. In such an environment, we need a mechanism for matching between applications and heterogeneous wireless networks to satisfy QoS requirements of each application. We also need a mechanism for changing media allocation dynamically to adapt the fluctuation of wireless communication environment caused by its mobility, change of application requirements, or instability of wireless networks. Furthermore, we expect to achieve the flexible resource allocation in the whole network by coordination of resource allocation by implicit cross-interaction among cars competing the same wireless media.

In Chapter 3, we introduce an adaptive resource allocation mechanism where each node autonomously determines wireless network resources to assign to each of networked applications running on it. For this purpose, we adopt an *attractor composition model*, which is based on an autonomous and adaptive behavior of biological systems. The *attractor composition model* is the expansion of *attractor selection model* [20]. It is known that biological systems have adaptability for changes in the environment [21]. Traditional adaptive mechanisms are designed and implemented assuming the certain range of conditions of operational environment. They can provide the best performance as far as environmental changes, including the quality of wireless communication, network topology, and traffic demand, are within the assumed range of conditions. However, once change goes beyond the assumption, the performance considerably deteriorates and the system easily collapses [22, 23]. While traditional approaches cannot handle such unpredictable changes, *attractor selection* has the capability of autonomously adapting to unpredictable changes by its stochastic behavior and simple feedback of current system conditions [20]. The *attractor composition model*, which is the expansion of the *attractor selection model*, is a noise-driven metaheuristic to find a stable solution of an optimization problem in an adaptive manner. When the current solution is appropriate in the *attractor composition model*, the state of the system

statically stays. Once the current solution becomes inappropriate for the new condition, the state begins to change randomly until a new good solution is found. By defining the degree of satisfaction of node as an indicator of goodness of resource allocation, a node can autonomously find a solution, i.e. resource allocation, which is appropriate for the current condition of wireless networks and QoS requirements of applications. Since the condition of wireless networks is influenced by resource allocation at other nodes, nodes indirectly interact with each other and they eventually share the available network resources in a fair manner.

Through numerical analysis, we confirmed that our mechanism could adaptively and stably allocate wireless network resources to applications, while considering their QoS requirements and flexibly sharing network resources with other nodes. It also is shown that our mechanism superiors to a mechanism where a node determines resource allocation by solving an optimization problem on the node using local information.

Finally, we conclude this thesis in Chapter 4.

Chapter 2

A QoS-aware Routing Mechanism for Multi-Channel Multi-Interface Ad-Hoc Networks

To accommodate real-time multimedia application while satisfying application QoS requirements in a wireless ad-hoc network, we propose a new routing mechanism that efficiently utilizes multiple channels and takes into account the bandwidth usage in determining a path. We consider a wireless ad-hoc network composed of nodes equipped with multiple network interfaces, to each of which a different wireless channel can be assigned. By embedding information about channel usage in control messages of OLSRv2, each node obtains a view of topology and bandwidth information of the whole network. Based on the obtained information, a source node determines a logical path with the maximum available bandwidth to satisfy application QoS requirements. Through simulation experiments, we confirmed that our proposal effectively routed multimedia packets over a logical path avoiding congested physical links. Consequently the load on a network is well distributed and the network can accommodate more sessions than QOLSR, i.e. an exiting QoS-aware routing protocol. We also conduct practical experiments using wireless ad-hoc relay nodes with multiple network interfaces and verify the practicality of our proposal in the actual

environment.

2.1 Introduction

Wireless ad-hoc networks do not require any fixed equipment or infrastructures such as routers, switches, access points, base stations, and cables. Nodes communicate with each other through radio signals to organize a network and transmit data from one node to another. For its infra-less feature, wireless ad-hoc networks are considered the promising technology to establish a means of communication where installation of network equipment and cables is not allowed, difficult, or expensive as in a historic landmark or a festival site or when conventional communication infrastructures are destroyed such as in catastrophic disasters like earthquake. In such situations, wireless ad-hoc networks are expected to accommodate real-time multimedia traffic for remote monitoring, video conferencing, and VoIP (Voice over IP) communications.

Packets which are transmitted over a wireless ad-hoc network may include both of best-effort traffic (file transfer, e-mail, and Web) and real-time traffic (remote monitoring, video conferencing, and VoIP). It has been recognized that the effective network capacity of a single-channel and multi-hop wireless network using the normal IEEE 802.11 standard MAC is not $n \times (\textit{per-channel-throughput})$, but $O(n/\sqrt{n}) \times (\textit{per-channel-throughput})$ [9], where n is the number of nodes using the same channel in the network. In [10], they further took into account that the wireless phenomena, such as medium contention, channel fading, and radio interference, causing the degradation of the effective bandwidth. Since the capacity of wireless link is limited and the effective bandwidth is much smaller for contention among nodes [9, 10], it is not trivial to accommodate real-time multimedia traffic in a wireless ad-hoc network. Especially, the fact that real-time applications require certain level of QoS guarantee or control in terms of packet loss, delay, and delay jitter makes it challenging.

Over the past several years, many studies have been devoted to QoS control in wireless ad-hoc networks [24, 25, 26, 27]. They summarized some of the QoS issues for ad-hoc

networks. There are several techniques or methods for controlling QoS in wireless ad-hoc networks, such as bandwidth reservation, channel switching, channel separation, and QoS-aware routing. At the MAC layer, some studies have been aimed to support frame transmission over a multi-channel and multi-interface wireless ad-hoc network by modification of IEEE 802.11 standard MAC protocol. A node switches wireless channels [28] or both of channels and interfaces [29, 30, 31, 32, 33, 34] in a hop-by-hop manner or a time-based manner, to reduce the number of packet losses and improve the network throughput. In [29], they proposed a kind of CSMA protocol for multihop multi-channel wireless networks. Their protocol selects channels dynamically like FDMA (frequency-division multiple access) scheme. In [30], they proposed a receiver-initiated collision-avoidance MAC protocol that does not require carrier sensing. In [31], they tackled a multi-user scheduling problem over multiple wireless channels to maximize total system throughput. In [33], they consider multi-channel multi-interface wireless network and proposed a distributed channel assignment and routing architecture. In [35], they consider multi-channel, multi-interface, and multi-rate wireless network, but they do not consider multi-hop scenario. Their idea is to assign physical links having same or similar data rates on the same channel to minimize the waste of channel resources due to inconsistency among high and low data rate links. According to this modification, they overcome the performance degradation caused by rate adaptation. Although multiple channels and interfaces contribute to avoidance of competition and collision for a wireless channel, P. Kyasanur et al. showed that channel switching in the same frequency band on an interface introduced non-negligible switching delay in [34]. To address the problem, they proposed to classify interfaces on a node into "fixed" and "switchable" interfaces so that neighboring nodes can communicate with each other on their fixed channels to avoid the interface switching delay. In their proposal, fixed interfaces stay on their channels for a longer period than switchable interfaces. As we described above, there are several proposals for efficient utilization of network capacity or controlling QoS at the MAC layer. However, we need to modify MAC to adapt these techniques.

ABC-MC [36] is a geographical routing scheme exploiting dynamic multi-channel switching for wireless sensor networks based on ABC [37]. In ABC-MC, each node has two transceivers, each of which is capable of switching channel dynamically. In negotiating a channel to use for communication, a receiver selects a channel with the least interference with other communication. Selection is done in accordance with a so-called Channel Risk factor List (CRL), i.e. a list of risk factor values of channels. A risk factor of a channel is derived based on the total channel influence distance and the hop distance where the channel is used. By choosing a channel with the smallest risk factor, which means that it is used farther from a receiver, the risk of interference can be avoided. Although ABC-MC is useful for flow-based interference control, it is designed for wireless sensor networks and as such it does not consider integration of multiple channels to accommodate the high-volume traffic of real-time multimedia applications.

Several papers on QoS routing have been proposed for wireless ad-hoc networks. QoS-AODV [38] is a per node available bandwidth estimation protocol based on AODV. It estimates the available bandwidth from the ratio between the numbers of transmitted and received packets. The original AODV is extended by adding new fields including `maximum delay extension` and `minimum bandwidth extension`. These extension fields are included on Route Request (RREQ) and Route Reply (RREP) messages during the phase of route discovery. A node becomes an intermediate node only if the node can meet the requirements specified in the RREQ. CEDAR [39] dynamically establishes the core of the network that is given the responsibility of managing the dissemination of control messages. A node incrementally propagates the link states to the core nodes and they perform on demand route computation using the propagated link states. In the CEDAR approach, the core provides an efficient low-overhead infrastructure to perform routing, while the link state propagation mechanism ensures availability of link state information at the core nodes without incurring high overheads. QOLSR [25, 40, 41] is a QoS-aware routing protocol based on the conventional OLSR (RFC3626 [7]). Differ from QoS-AODV and CEDAR, QOLSR is a table-driven (proactive) routing protocol. In selecting MPRs

(MultiPoint Relay), which are nodes designated to relay broadcast messages, QOLSR considers QoS-related metrics, i.e. bandwidth and delay, while OLSR considers hop distance. We will describe the details of QOLSR in Section 2.4.2. All of these QoS routing protocols are less concerned about multi-interface network, so we need routing at all channels to support multi-interface. Since any routing protocol must propagate control messages for route computation, the available bandwidth for user applications of wireless networks are decreased by the control messages.

In this chapter, we propose, design, implement, evaluate, and experiment a QoS-aware routing mechanism for wireless ad-hoc networks. We focus on a wireless ad-hoc network that serves as a communication infrastructure and is tentatively or even permanently deployed in the region where cabling for wired network is difficult, such as a historic landmark and disaster area. Although it is possible for mobile nodes to participate in organization of an infrastructure network, they are mainly used to patch an area where a node cannot be placed statically and stay there for a certain period of time, from our viewpoint of applications. One of interfaces of a node can be configured to operate in an infrastructure mode and a node can serve as an access point for mobile nodes to accommodate them. Our mechanism assumes a node equipped with multiple network interfaces and to each of which a different wireless channel can be assigned. More specifically, we consider that the number of available wireless channels is equal to or greater than the number of interfaces and channels are assigned statically to interfaces without overlap. Our mechanism consists of three cooperative techniques; bandwidth estimation, efficient message distribution, and logical routing. One of interfaces is assigned to best-effort traffic and OLSRv2 (OLSR version 2) [6]. The remaining interfaces are devoted to real-time multimedia traffic. A node estimates the usage of its wireless channels and disseminates the information about the available bandwidth on the node, called the bandwidth information, to the other nodes in the whole network. For this purpose, the bandwidth information is embedded in control messages of OLSRv2 and propagated in the whole network in an efficient and effective way. In transmitting real-time packets, a source node tries to estimate the optimal path to its destination node to satisfy application-level QoS requirements using the obtained topology

and bandwidth information. Since the derived path, called a logical path, is different from the physical path from the source to the destination established by the underlying OLSRv2, packets are encapsulated by destination addresses of logical next-hop nodes so that it traverses the logical path. Each intermediate node receiving an encapsulated real-time packet chooses the wireless channel in a stochastic manner based on available bandwidth on the node to transmit the packet for efficient use of wireless channels and collision avoidance. One of key advantages of our mechanism is that it can be implemented using off-the-shelf hardware.

In the rest of this chapter, we first describe our proposal in Section 2.2 and explain implementation in Section 2.3. Then, we perform simulation experiments to evaluate the effectiveness of our proposal from viewpoints of end-to-end packet delivery ratio, delay, delay jitter, and node utilization in Section 2.4. Next, we build a prototype and conduct practical experiments to verify the practicality in Section 2.5. Finally, we summarize the chapter and describe some future work in Section 2.6.

2.2 QoS-aware Routing Mechanism for Wireless Ad-Hoc Networks

In this section, we show an overview of our proposed mechanism and describe three key techniques in more details, i.e. estimation of available bandwidth, distribution of bandwidth information, and logical routing.

2.2.1 Overview of Our Proposed Mechanism

We consider a wireless ad-hoc network consisting of nodes equipped with K ($K \geq 2$) wireless network interfaces. The same number K of wireless channels out of more than or equal to K candidates is available for wireless communication. We assign wireless channels to interfaces with no overlap. Without loss of generality, we number channels and interfaces from 0 to $K-1$, while assigning the same number to the coupled channel and interface and numbering is the same among nodes. In our proposal, one channel numbered 0, called

Table 2.1: Example of wireless channel and IP address assignment

IF	ch	IP addr–node 1	IP addr–node 2	IP addr–node 3
wlan0	1	192.168.0.1/24	192.168.0.2/24	192.168.0.3/24
wlan1	6	192.168.1.1/24	192.168.1.2/24	192.168.1.3/24
wlan2	11	192.168.2.1/24	192.168.2.2/24	192.168.2.3/24

"best-effort channel", is reserved for best-effort traffic and the other $K-1$ channels, called "real-time channels", are used for real-time traffic such as voice or video data. On the best-effort channel, the OLSRv2 with extension for our proposed mechanism operates for proactive IP routing and bandwidth information dissemination. We refer to IP routing as physical routing in contrast to logical routing. It is known that broadcast messages, i.e. control messages of OLSRv2, may cause the hidden terminal problem because the RTS/CTS mechanism does not work when they are transmitted. So we classify channels into best-effort and real-time channels and define that no broadcast message can be transmitted on real-time channels. Since we focus on the infrastructure deployed in the region, we assume that the network is immobile and static. At least, the topology is stable and unchanged while a session is active. Nevertheless, condition of wireless communication can dynamically change by fading or some other environmental effects.

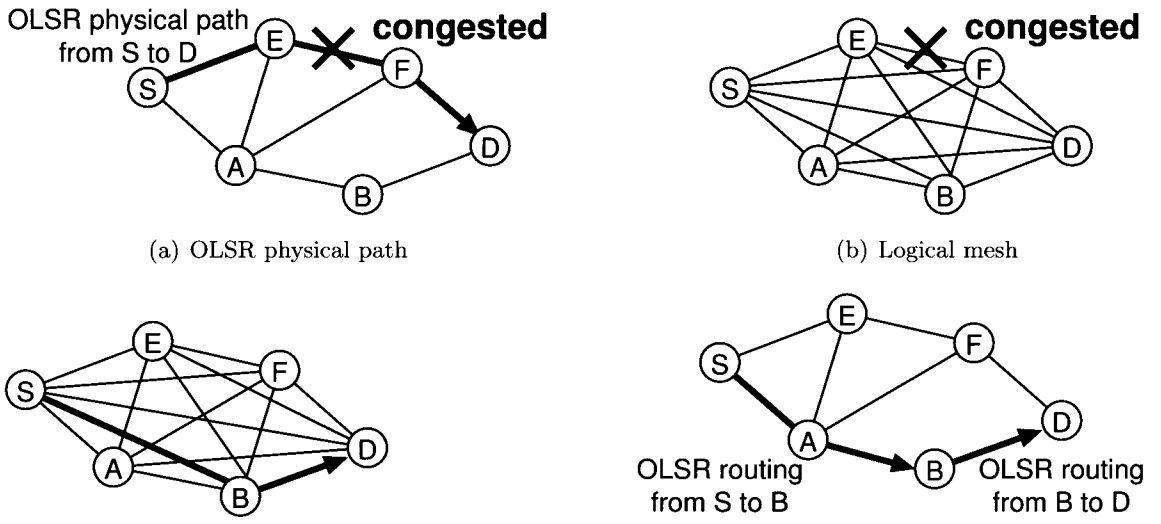
Table 2.1 shows an example of wireless channel and IP address assignment on our proposed mechanism. In this example, each of nodes 1, 2, and 3 has three wireless network interfaces named wlan0, wlan1, and wlan2. There are three available channels without interference, 1, 6, and 11. As seen, we assigned the interface wlan0 to channel 1, wlan1 to channel 6, and wlan2 to channel 11 on all of the three nodes, respectively. Interfaces are configured to belong to different networks, i.e. 192.168.0.0/24 on wlan0, 192.168.1.0/24 on wlan1, and 192.168.2.0/24 on wlan2. Furthermore, each node is assigned a unique host address, 1, 2, and 3, respectively. Therefore, node 1 for example has three IP addresses, 192.168.0.1, 192.168.1.1, and 192.168.2.1, on three network interfaces, wlan0, wlan1, and wlan2. By such channel and address assignment, channel switching can be easily done by changing network address of a packet at each node.

In the above example, assume that node 1 receives a real-time packet destined to neighboring node 2 with the destination IP address of 192.168.0.2. If node 1 selects the interface wlan1 to transmit the packet for its availability, the destination IP address in the packet is changed to 192.168.1.2 accordingly. Then the packet is sent from node 1 to node 2 on channel 6.

Each node always evaluates the usage of real-time channels and estimates the available bandwidth. The estimated available bandwidth is disseminated over the whole network by being embedded on control messages, i.e. HELLO messages and TC (Topology Control) messages of OLSRv2, which is a proactive routing protocol, operating on the best-effort channel. In our mechanism, with a help of OLSRv2, all nodes obtain and maintain the complete information about the available bandwidth on all nodes in the network.

Packets belonging to best-effort traffic are transmitted to a destination node on the best-effort channel. Intermediate nodes choose a next-hop node for the destination node of a received packet in accordance with the routing table maintained by OLSRv2. On the other hand, packets belonging to real-time traffic are transmitted to a destination on the real-time channels traversing a so-called logical path. A logical path consists of one or more contiguous logical links. A logical link consists of one or more physical links from one end to the other. A logical path is determined taking into account the topology of a wireless ad-hoc network, the available bandwidth on all physical links, and application-level QoS requirements.

Figure 2.1(a) illustrates an example of a physical path from node S to node D by OLSRv2 and an example of logical path construction and packet forwarding is illustrated in Figure 2.1(b), 2.1(c), and 2.1(d). Figure 2.2 shows the way that a packet is processed in our system. We refer to a flow of traffic generated by a real-time application as a session. The purpose of the logical routing is to avoid traversing a physical path containing any congested links, e.g. path E–F, which deteriorate QoS provided to an application. In our proposal, when a packet to a new destination is generated by a real-time application, a source node determines a logical path to its destination for the session. To determine a logical path, source node S first considers a logical mesh topology on a physical network (Figure 2.1(b)).



(a) OLSR physical path

(b) Logical mesh

(c) Logical routing

(d) OLSR routing on the logical path S-B-D

Figure 2.1: OLSR routing and QoS-aware routing by proposed mechanism

Each of logical links in the logical mesh topology is related to a physical path connecting the two ends of the logical link. Then, source node S tries to find an optimal path with respect to application QoS requirements and some other metric if needed, to destination node D. In this example, logical path S-B-D is chosen (Figure 2.1(c)). The purpose of the logical routing is to avoid traversing a physical path containing any congested links, which deteriorate the QoS provided to an application. So that packets travel the logical path, all packets belonging to the session are encapsulated by a logical routing header, which indicates the first destination node B and the last destination node D, as shown in Figure 2.2. Encapsulated packets are sent to the first destination node B through the physical path from source node S to node B, and then sent to the final destination node D from node B (Figure 2.1(d)). In this case, the logical next-hop node at node S is node B while the physical next-hop node at node S is node A, based on OLSRv2 physical routing. Therefore, node S sends a packet to node A, then the node A forwards the packet to node B. The intermediate node A only relays a received packet to node B, which is regarded as the destination of the packet from the physical routing view point. For efficient use of wireless bandwidth, each node chooses one real-time channel in a stochastic manner based

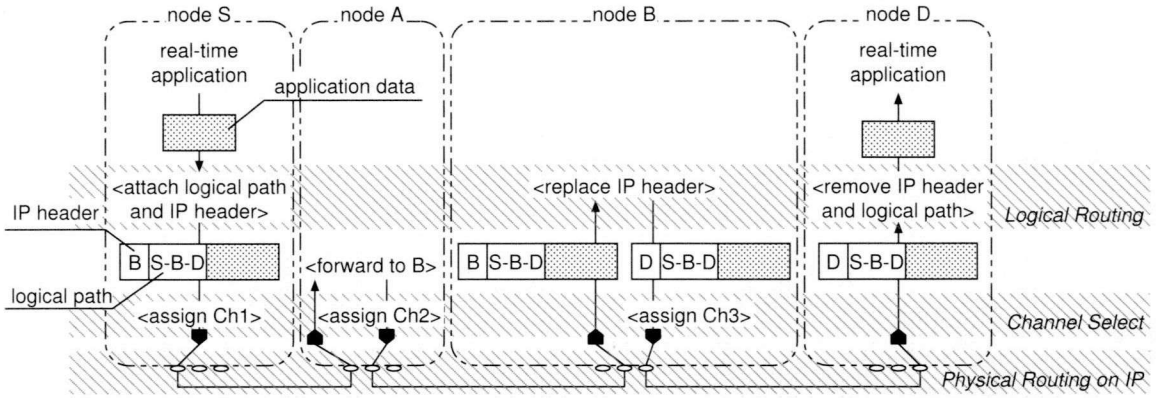


Figure 2.2: Packet processing in proposed mechanism

on available bandwidth among real-time channels in forwarding a packet to a physical next-hop node. If a node has two wireless network interfaces named wlan1 and wlan2, and their available bandwidths are 1 Mb/s and 2 Mb/s, respectively, then one of three real-time packets may be transmitted via wlan1 and the other two real-time packets may be transmitted via wlan2. When a packet arrives at a logical intermediate node, it is encapsulated with a new IP header indicating the next logical hop node (Figure 2.2, node B). Then the packet is forwarded to the logical next-hop node. In this way, real-time packets traverse a logical path over a network maintained by a physical routing protocol, i.e. OLSRv2.

2.2.2 Estimation of Available Bandwidth at Node

There have been some studies on estimation of the available bandwidth in a wireless network [10, 42, 43]. It is still a challenging problem, because the bandwidth is shared among neighboring nodes and the radio context varies momentarily. In [10], Shah et al. proposed an available bandwidth estimation scheme using a data packet size and the channel's bit-rate. They have shown that the measured throughput highly depends on transmitted packets sizes. However, a network manager can enable Auto Rate Fallback mechanism to achieve faster transmission at higher data rates and more stable transmission at lower data rates. The IEEE 802.11-based interfaces have the ability to transmit frames at different

data rates. Higher data rates use more complex modulations to achieve higher throughput and lower data rates use more resistant modulations to reach farther nodes or to operate in a noisier environment. In such a situation, the evaluation of available bandwidth using a data packet size and the channel's bit-rate is not feasible, because the channel bit-rate may vary among next hop nodes or packets.

Instead of using such variable values to estimate the available bandwidth, we rather consider the radio conditions. In [42], the channel utilization ratio is calculated from radio states. They assumed that the IEEE 802.11 wireless radio states are classified into busy state (transmitting, receiving, or carrier sensing) and idle state. Then the ratio of busy state during a time period is defined as the channel utilization ratio. In [44], Saghir et al. also derived the available bandwidth based on the radio states. Their method computes the idle periods of the shared wireless media. In their method, each node adds up all the idle periods T_{idle} during an observation interval T and then divides it by the observation interval T to derive the idle ratio R_{idle}. The available bandwidth B is derived by multiplying the idle ratio R_{idle} with the raw channel bandwidth C_{max}, e.g. 2 Mb/s for standard IEEE 802.11 radio. Although these radio state based estimation leads higher accuracy, Sarr et al. pointed out in [43] that the channel bandwidth C_{max} should not be the raw medium capacity, since we must take into account the overheads, i.e. frame headers, acknowledgments, and so on, introduced by the IEEE 802.11 MAC protocol.

Taking these into consideration, our available bandwidth estimation method uses the idle ratio R_{idle}, which is derived by the following equation using the idle periods T_{idle} during the observation interval T.

$$R_{idle} = \frac{T_{idle}}{T} \tag{2.1}$$

We set the observation interval T to 2 s, which is the interval of HELLO message of the OLSR. To abandon the overheads introduced by the MAC protocol, we define C_{max} as the maximum effective medium capacity. We assume that C_{max} is a half of the raw medium capacity since a node cannot measure the effective medium capacity of real-time channels from a packet (like QOLSR [40]) when no real-time traffic exists. The available bandwidth

$B_k(c)$ of channel c ($1 \leq c \leq K-1$) on node k is estimated by Equation (2.2), where $R_{k\_idle}(c)$ corresponds to the idle ratio of channel c on node k and $C_{k\_max}(c)$ corresponds to the maximum effective medium capacity of channel c on node k.

$$B_k(c) = R_{k\_idle}(c) \times C_{k\_max}(c). \tag{2.2}$$

The available bandwidth $B_k(c)$ is used in selecting one real-time channel among $K-1$ real-time channels to transmit a packet. The probability that channel c is chosen is given as $B_k(c)/\sum_{c=1}^{K-1} B_k(c)$. Since the channel selection is performed at each node stochastically among $K-1$ real-time interfaces in transmitting a packet, we can treat the sum of available bandwidth $B_k(c)$ as the available bandwidth of node k. The total available bandwidth B_k for real-time traffic on node k is derived by the following equation.

$$B_k = \sum_{c=1}^{K-1} B_k(c). \tag{2.3}$$

B_k is used to estimate the available bandwidth of a logical path in the logical routing (see Section 2.2.4).

2.2.3 Distribution of Bandwidth Information on OLSRv2

On OLSRv2 (and OLSR) protocol, nodes to forward TC messages are limited to avoid the loss of bandwidth for control packets. They are called MPRs (MultiPoint Relay). Among nodes receiving TC message, only MPRs rebroadcast the message. MPRs are chosen in a distributed manner to keep the connectivity with the smallest number of MPRs. Nodes which select other nodes as MPR are called MPR selectors. Please refer to the standard for selection of MPR (RFC3626 1.4. [7] or [8]).

Nodes exchange HELLO messages with neighboring nodes in the range of radio signals at regular HELLO intervals, e.g. 2 seconds. A HELLO message consists of validity time, originator address of the message, neighbor list of the originator, and some optional information. In addition to HELLO messages, an MPR generates and disseminates TC messages

at regular intervals, e.g. 5 seconds. A TC message contains validity time, originator address of the message, and addresses of its MPR selectors. On receiving a TC message, a node builds or updates a table called Topology Set consisting of MPRs, their MPR selectors, sequence number, and validity time. A node also builds or updates another table called Attached Network Set consisting of OLSRv2 gateway address, network address which may be reachable via the gateway, prefix length of the network address, sequence number, and validity time. A routing table, called Routing Set, is built and maintained when any of Link Set, Neighbor Address Association Set, 2-hop Neighbor Set, or Topology Set changes. The Routing Set consists of destination address, next-hop address to the destination, number of hops to the destination, and interface address. Entries of the Routing Set are copied to the IP routing table in the system.

In our proposal, the bandwidth information, i.e. B_k derived by Equation (2.3), is entrained in HELLO and TC messages by adding the extended field in the form of TLV (Type Length Value) block. On receiving them, a node builds or updates the Extended Topology Set, newly introduced for our proposal, to maintain the bandwidth information.

2.2.4 Logical Routing based on Bandwidth Information

A node generates a logical full-mesh topology when the node receives a first packet to a new destination to determine the maximum available bandwidth path. The current physical network topology and bandwidth information of each node are obtained from OLSRv2 with our extension to make a logical full-mesh topology. Logical link (i, j) between node i and node j in the logical full-mesh topology is associated with the available bandwidth $B(i, j)$. The available bandwidth $B(i, j)$ is given as the minimum among the available bandwidth of all physical links on the widest shortest path (WSP [45]) between node i and node j. The available bandwidth of physical link is defined as the minimum of the available bandwidth on nodes at the both edges. For example, the available bandwidth $B(S, B)$ in Figure 2.1 is given as $B(S, B) = \min(\min(B_S, B_A), \min(B_A, B_B))$, where B_S, B_A, and B_B are the total available bandwidth for real-time traffic on each node derived by Equation (2.3). When

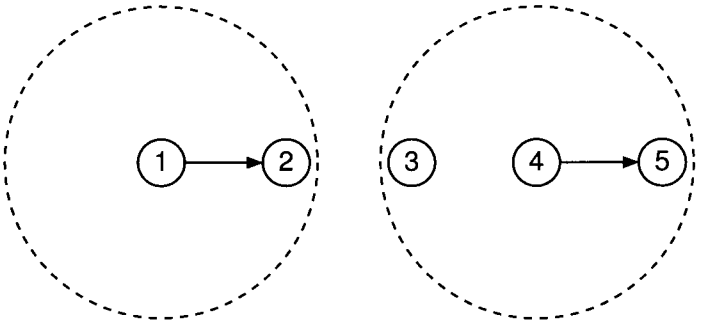


Figure 2.3: Chain topology

there are two or more shortest paths for a logical link, one with the minimum available bandwidth is chosen.

Once a logical mesh network is constructed, a source node begins to find the optimal path which has the maximum available bandwidth. First, a set of logical paths with a logical hop count of less than H_l and a physical hop count of less than $H_p\times$ (*minimum-physical-hop-count*) are obtained from the logical mesh network. The upper bounds H_l and H_p are introduced to avoid generating an unnecessarily long path and shorten the calculation time. We set 3 as the upper bound H_l and 1.3 as the upper bound H_p.

Finally, the logical path with the largest available bandwidth in the set is chosen for the session. Since there is interference between adjacent links, we derive the available bandwidth of a logical path taking into account the number of physical hops of the logical path. In general, communication over two-hop path obtains half the throughput of communication over one-hop path [9]. Furthermore, for communication over a path of more than two hops, the throughput decreases to one third, where links apart by two links or more do not interfere each other as illustrated in Figure 2.3, which denotes dashed line circles as nodes' transmission range. Then, the following equation gives the available bandwidth W_p of logical path p, where p is a set of logical links constituting the path and $l(p)$ is the number of physical hops of the path.

$$W_p = \frac{\min_{(i,j)\in p} B(i,j)}{\min(l(p),3)}. \tag{2.4}$$

When there are two or more logical paths with the same largest available bandwidth, the

logical path that has the smallest physical hop count is chosen for the session to minimize end-to-end delay. When there are two or more logical paths with the same largest available bandwidth and the smallest physical hop count, the logical path found the earliest is chosen for avoidance of overhead in memory copy.

It is a fact that route fluctuation may occur when the interval of refreshing bandwidth information is longer than the interval of new session appearance. We set the interval of refreshing bandwidth information to 2 seconds, i.e. HELLO messages interval, and 5 seconds, i.e. TC messages interval. If a number of new sessions appear within the interval of refreshing bandwidth information at a node, the node may select the same logical route for all the new sessions. In addition, if the new sessions end their communication within the interval of refreshing bandwidth information, the logical route derived at the node may fluctuate. However, applications such as remote monitoring and VoIP appear discretely and rarely end within 2 or 5 seconds, i.e. the interval of refreshing bandwidth information. Thus, we expect that our proposal uses multiple routes appropriately. Since the selected logical path for a session is active while the end of the session, route fluctuation does not occur among communicating sessions.

2.3 Implementation of QoS-aware Routing Mechanism

In this section, we describe how our QoS-aware routing mechanism is implemented on a wireless ad-hoc network system. We adopt the same implementation methodology for programming simulation codes and building prototypes. Figure 2.4 shows module components of our proposed mechanism. In the figure, a node has four network interfaces and four wireless channels. We assign channel 0 for best-effort traffic and channels 1, 2, and 3 for real-time traffic.

Packets generated by a best-effort application are transmitted through channel 0. They are sent to a destination following physical routing maintained by the OLSR module, which implements standard OLSR with our extension.

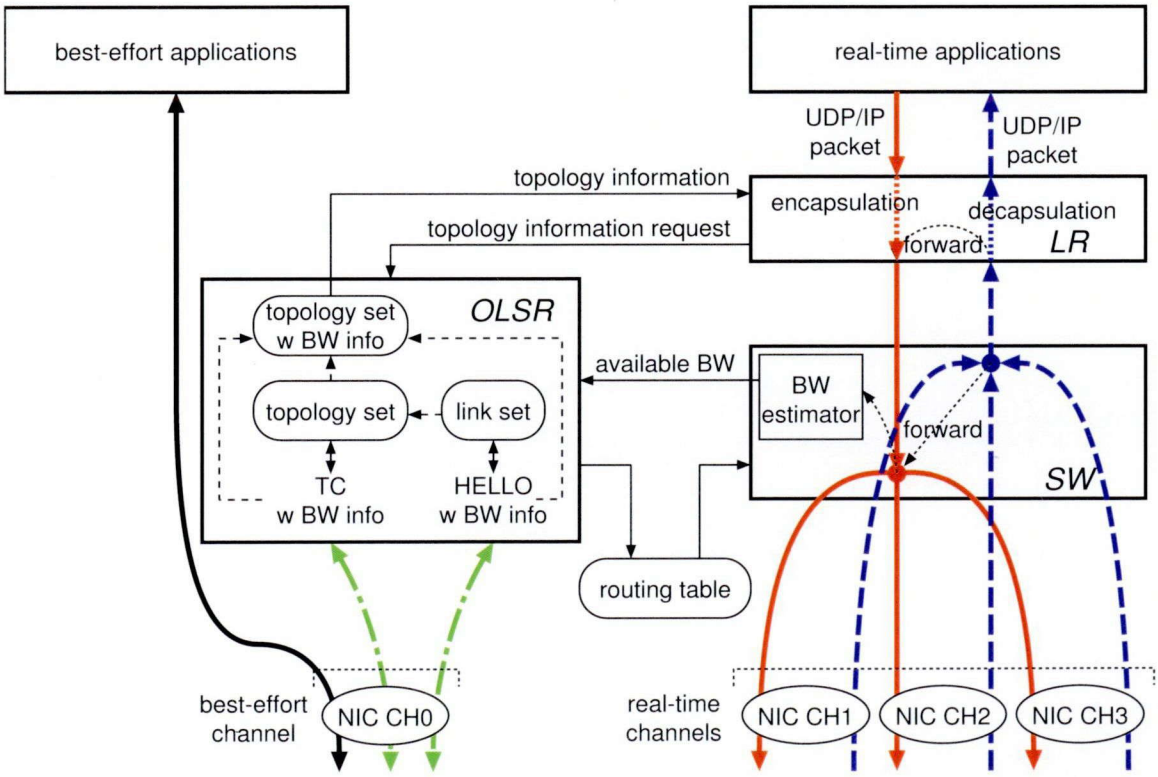


Figure 2.4: Module components of proposed mechanism

2.3.1 LR Module

Packets generated by a real-time application are first processed by the logical routing module (LR). On receiving the first packet of a new session, the LR determines a logical path based on topology and bandwidth information maintained by the OLSR module (OLSR). Packets are encapsulated by LR header indicating addresses of intermediate nodes of the logical path as shown in Figure 2.5, so that it traverses the logical path on the physical network maintained by the OLSR. Encapsulated packets are passed to the switching module (SW). The LR header consists of two parts, i.e. the header information part and the logical path information part. The header information part consists of header identifier, message type, number of addresses in the logical path information part, message length, source port number, and destination port number. The logical path information part consists of pairs of flags (IP version, source, destination, and visited bit) and an IP address, from the source node to the destination node on the logical path. The LR maintains a table of existing sessions, called the session management table, consisting of destination IP address, source port number, destination port number, timestamp, and the corresponding LR header information. Timestamp in the table is updated when the entry is made or referred to. The structure of the session management table, written in C language, is shown below.

```
struct session_management_table {
  InetAddr  dstAddr;   /* destination IP address */
  uint16_t  srcPort,   /* source port number */
            dstPort;   /* destination port number */
  clocktype lastTime;  /* made/referred timestamp */
  void      *lr_info;  /* LR header information */
}
```

Constructed LR headers are stored in a memory, and the LR header information in the table is a pointer to the corresponding one of them prepared to avoid reconstruction overhead. If the session management table already has an entry for the session and less than 30 seconds

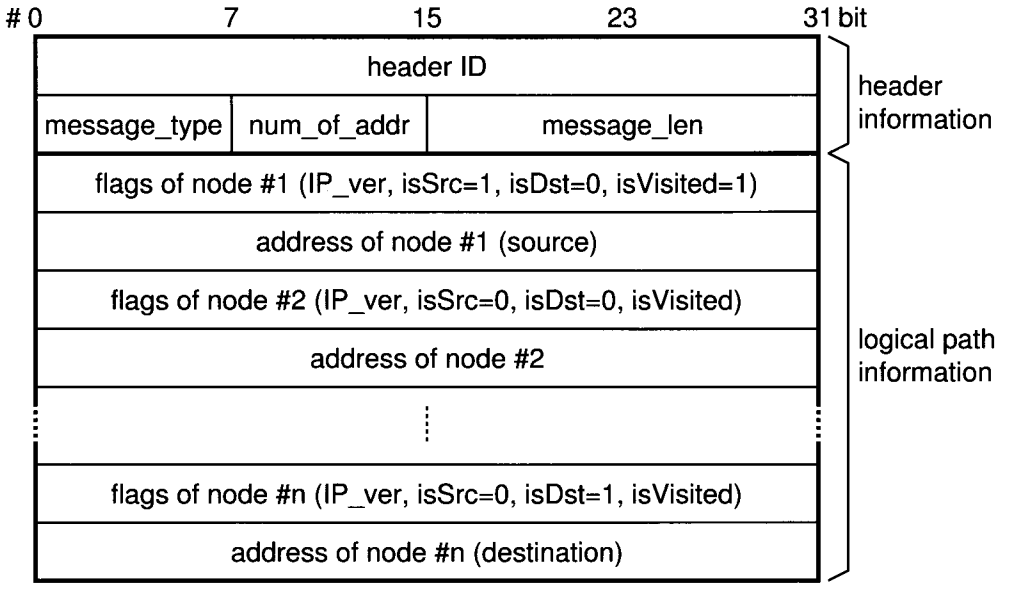


Figure 2.5: LR header format

have passed since the entry was made or referred to, the LR header is obtained from the LR header information of the entry.

2.3.2 SW Module

On receiving a real-time packet from the LR, the SW looks up the logical next-hop node written on the LR header of the packet. Next, the SW determines a physical next-hop node for the logical next-hop node based on the routing table. The routing table is maintained by the OLSR, which works on the best-effort channel. Then, the SW selects one real-time interface in a stochastic manner based on available bandwidth, which corresponds to the evaluation per interface. We assume that each interface is assigned to specific channel respectively and a pair of nodes can communicate on each interface each other if the nodes are connected by a bi-directional link on the best-effort channel. Finally, the SW emits the real-time packet destined to the logical next-hop node though the network interface. It means that the packets of a flow may be routed on different real-time interfaces at a node.

On the contrary, when the SW receives a packet from a network, it searches the logical

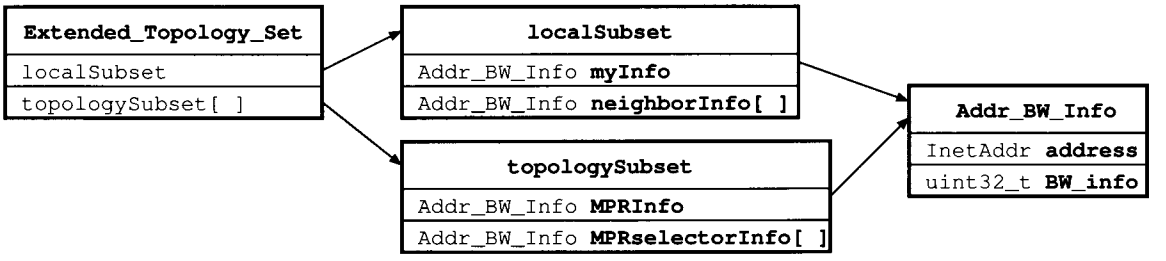


Figure 2.6: Structure of Extended Topology Set

path information part in the LR header. The topmost node with unset 'visited flag' is the logical next-hop node. If the logical next-hop node is not node itself, the SW selects one real-time interface in a stochastic manner based on available bandwidth and sends the packet to the physical next-hop node on the physical path toward the logical next-hop node. Otherwise, the SW forwards the packet to its own LR. On receiving a real-time packet from the SW, the LR investigates the LR header to check whether it is the final destination or not. If the node is the final destination, the LR removes the LR header from the packet and passes it to the corresponding real-time application.

The SW is also responsible for estimation of the available bandwidth. The BW estimator module in the SW estimates the available bandwidth by Equation (2.2), derives the available bandwidth of node by Equation (2.3), and reports the result to the OLSR.

2.3.3 OLSR Module

The OLSR manages a physical network by exchanging HELLO and TC messages on a best-effort channel. The OLSR obtains information about the available bandwidth of node from the SW. The obtained information is stored in the `myInfo` field of the `localSubset` in the Extended Topology Set, which deposits the original topology information of OLSRv2 and additionally the bandwidth information (Figure 2.6). `Addr_BW_Info` consists of IP address

and bandwidth information as shown below.

```
struct addr_bw_info {
  InetAddr address;          /* IP address */
  uint32_t bandwidth_info;   /* bandwidth information */
}
```

The OLSR embeds the information about its available bandwidth in HELLO messages and sends them to neighboring nodes. Once the OLSR receives a HELLO message from a neighboring node, it also embeds the information about the neighboring node's available bandwidth in HELLO messages. In addition to HELLO messages, the OLSR of an MPR generates and disseminates TC messages embedded with the information about its available bandwidth and the available bandwidth of its MPR selectors. On receiving HELLO or TC message, the OLSR builds or updates the Extended Topology Set. The structure of the Extended Topology Set is shown below.

```
struct extended_topology_set {
 struct localSubset {
  struct addr_bw_info myInfo;     /* obtained from the SW */
  struct addr_bw_info neighborInfo[]; /* obtained from HELLO messages */
 }
 struct topologySubset[] {
  struct addr_bw_info MPRInfo;  /* obtained from TC messages */
  struct addr_bw_info MPRselectorInfo[]; /* obtained from TC messages */
 }
}
```

On receiving a request from the LR, the OLSR provides the LR with the Extended Topology Set.

2.4 Simulation Experiments and Discussions

In this section, we evaluate the performance of our proposal through simulation experiments by comparing with QOLSR. We used QualNet 4.0 simulator [46]. We based our OLSR module on the nOLSRv2 [47] with some modifications for supporting our proposed mechanism. Although the normal nOLSRv2 supports multiple interfaces, we modified the nOLSRv2 to operate on the best-effort channel only, thus, no routing protocol operated on the real-time channels.

2.4.1 Fundamental Settings

We built a network consisting of 100 nodes in the 6000×6000 m^2 region. We chose IEEE 802.11g PHY model for physical layer. Each node has four wireless network interfaces with omni-directional antenna, to each of which ch1 (2.412 GHz), ch6 (2.437 GHz), and ch11 (2.462 GHz) for real-time channels and ch14 (2.484 GHz) for best-effort channel are assigned respectively. Since it is hard to imitate the real wireless environment, many researches of ad-hoc or mesh networks consider a simple connection model, where a node can communicate with other nodes in the diameter of 125 m at the rate of 54 Mb/s and radio signals can cause interference in the diameter from 126 m to 250 m. In our simulation, different from these researches, a node can communicate with other nodes in the diameter of up to 1218 m at the rate ranging from 6 to 54 Mb/s depending on the distance shown in Table 2.2. However, the actual distance that two nodes can communicate would be smaller than the maximum due to interference. Broadcasting data rate was set to 6.0 Mb/s, which is the lowest rate of IEEE 802.11g with OFDM, to keep network connectivity. Radio signals transmitted by a node can cause SINR (Signal to Interference and Noise Ratio) deterioration of other nodes in the diameter of 2237 m (-111.0 dBm). When wireless connection speed slows down caused by interference or node mobility at actual equipments, transmitter boosts transmission power and receiver can be more sensitive. We set transmission power at 16.0 mW for 54 Mb/s of link speed and 20.0 mW for 6 Mb/s, and the minimum receivable SINR at -69.0 dBm for 54 Mb/s and -85.0 dBm for 6 Mb/s for achieving closer assumption to actual equipments

Table 2.2: Transmitting data rates, maximum communication range, and transmission power

transmitting data rate	maximum communication range	transmission power
6.0 – 9.0 Mb/s	1218 m	20.0 mW
12.0 – 18.0 Mb/s	862 m	19.0 mW
24.0 – 36.0 Mb/s	427 m	18.0 mW
48.0 – 54.0 Mb/s	121 m	16.0 mW

Table 2.3: Transmitting data rates and receiver sensitivity

transmitting data rate	receiver sensitivity
6.0 – 9.0 Mb/s	−85.0 dBm
12.0 – 18.0 Mb/s	−83.0 dBm
24.0 – 36.0 Mb/s	−78.0 dBm
48.0 – 54.0 Mb/s	−69.0 dBm

as shown in Tables 2.2 and 2.3. We used the free space path-loss model with no shadowing and no fading. Using the free space path-loss model, the loss L_r in dB at a receiver r is described by the following equation,

$$L_r = 10\log_{10}\left(\left(\frac{4\pi d}{\lambda_r}\right)^2\right) \tag{2.5}$$

$$= 20\log_{10}\left(\frac{4\pi d f_r}{c}\right) \tag{2.6}$$

where d is the distance between the transmitter and the receiver of the signal, λ_r is the signal wavelength, f_r is the signal frequency, and c is the speed of light. We chose IEEE 802.11 DCF protocol for MAC layer, which is a standard function in IEEE 802.11 wireless networks, and we enabled RTS/CTS flow control for unicast communication to avoid the hidden terminal problem. A FIFO buffer at IP layer has the capacity of 50000 bytes. For OLSRv2, we set intervals of HELLO and TC messages at 2 seconds and 6 seconds, respectively.

As a real-time application, we assumed video streaming traffic. A pair of source and

destination nodes was chosen at random without overlapping between two nodes. A source node generated UDP packets of 1292 bytes every 20 ms, i.e. 512 kb/s CBR traffic. We measured the packet delivery ratio, the delay, and the delay jitter averaged over all packets of all sessions. After first 60 s for initialization of network, we started sessions one by one from 60 to 120 s in simulation time. Each session kept sending packets for 60 s. To keep the number of active sessions from 120 to 540 s in the experiments, we initiated a new session between a newly selected node pair as soon as any of existing session was finished. A simulation run was terminated at 606 s in simulation time after all packets had reached to destination nodes.

2.4.2 Comparison with QOLSR

To evaluate the effectiveness of our proposal, we consider QOLSR [41], one of the QoS-aware routing protocol based on the OLSR, for comparison. The key difference between our proposal and QOLSR is how to use the bandwidth information. In our proposal, the bandwidth information is used not for physical routing but for logical routing. In contrast, it is used for physical routing in QOLSR. More specifically, QOLSR uses the bandwidth information for MPR selection, i.e. a node that has larger bandwidth tends to be selected as MPR. MPRs tend to relay packets from one to another node. In [40], they consider bandwidth and delay as routing criteria. Since the best path with all parameters at their optimal values may not exists, i.e. a path with both maximum bandwidth and minimum delay may not necessarily exists, they decided the precedence among bandwidth and delay. They pointed out that the delay has two basic components; queuing delay and propagation delay. The queuing delay varies more dynamic according to traffic, thus bandwidth is often more important for most real-time multimedia applications. If there is no sufficient bandwidth, queuing delay will be very high. So, they define the precedence as bandwidth and then the propagation delay. By their strategy, a node finds a path with maximum bandwidth (a widest path), and when there is more than one widest path, it chooses the one with shortest delay (a shortest-widest path). In our proposal, it is quite rare that

the available bandwidth is the same among links, so we modified the original QOLSR to consider only bandwidth which can be measured by our SW. We also extended QOLSR to handle multiple interfaces and channels. From now on, we refer to the modified QOLSR simply as QOLSR. In the QOLSR evaluation, each node operating on QOLSR also has four channels. Ch1 (2.412 GHz), ch6 (2.437 GHz), and ch11 (2.462 GHz) are assigned to real-time channels and ch14 (2.484 GHz) to best-effort channel. Real-time channels accommodate real-time traffic and best-effort channel carries best-effort traffic and control messages. Each node operating on QOLSR measures available bandwidth on each link to its neighboring nodes. On the original QOLSR, the available bandwidth on a link is derived from multiplying link utilization by link throughput. The link utilization is the same as the idle ratio R_{idle} of our proposal, i.e. Equation (2.1). The link throughput is measured using existing traffic on the original QOLSR. However, in our proposal, QOLSR propagates control messages only on best-effort channel, thus the link throughput of real-time channels cannot be measured if no real-time traffic exists. Therefore, the link throughput between node i and j is derived from the following equation

$$\text{Throughput}_{(i,j)} = \min(B_i, B_j) \tag{2.7}$$

where B_i and B_j are derived from Equation (2.3). We would like to note that the wireless channel contention problem is considered in the link utilization and the overhead of MAC protocol is considered in the link throughput. Each node operating on QOLSR selects MPRs in the descending order of available bandwidth. In case of a tie, a node with maximum number of uncovered 2-hop neighbors is chosen as an MPR. Each node propagates control messages via the selected MPRs on the best-effort channel to manage network topology. As in our proposal, the physical topology for routing real-time traffic in QOLSR is the same as that constructed based on control messages exchanged on the best-effort channel. A real-time packet is sent to one of neighboring MPRs on a real-time channel with the largest available bandwidth. We had disabled our LR (QoS-aware logical routing) when QOLSR (QoS-aware physical routing) was running while our SW was kept active to obtain

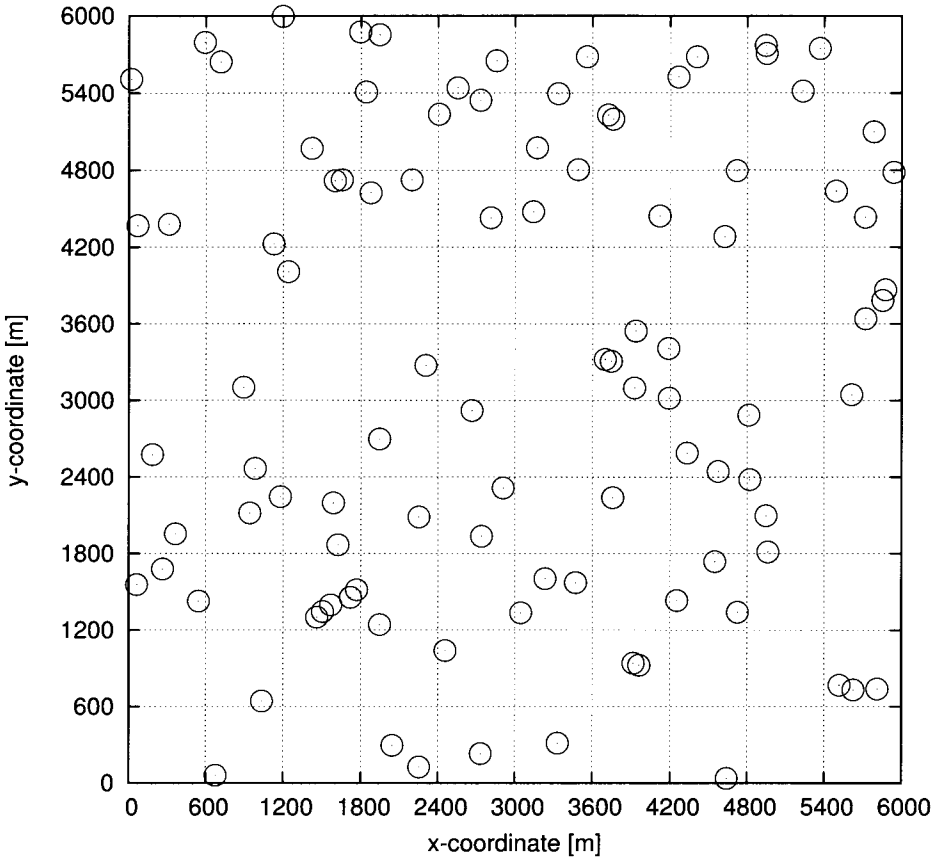
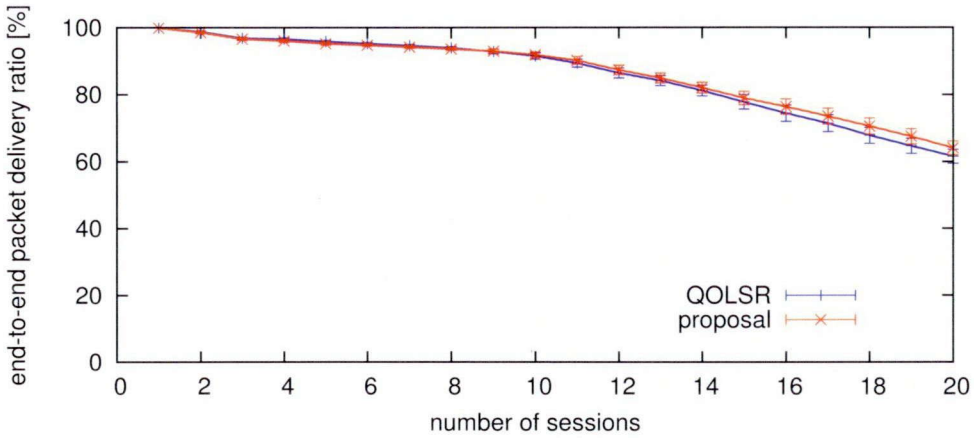


Figure 2.7: Node placement of one case of simulation I

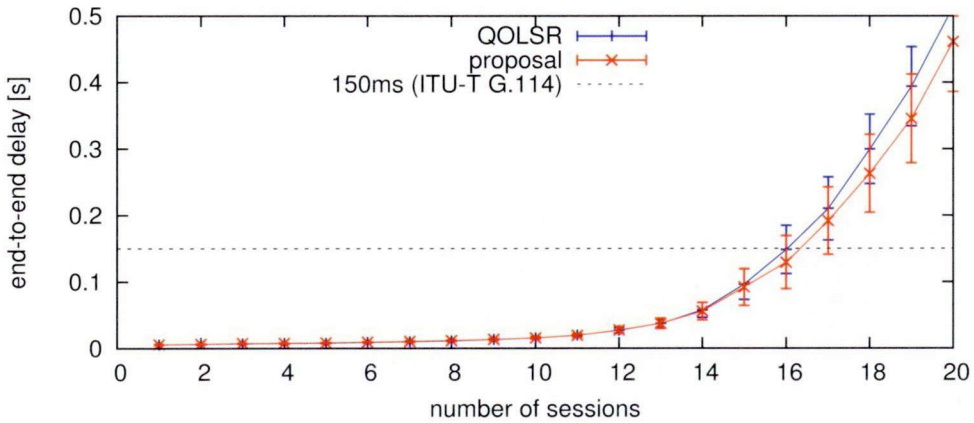
bandwidth information used for MPR and channel selection. As a physical routing protocol, QOLSR was running instead of our OLSR in the QOLSR evaluation.

2.4.3 Simulation I—General Topology

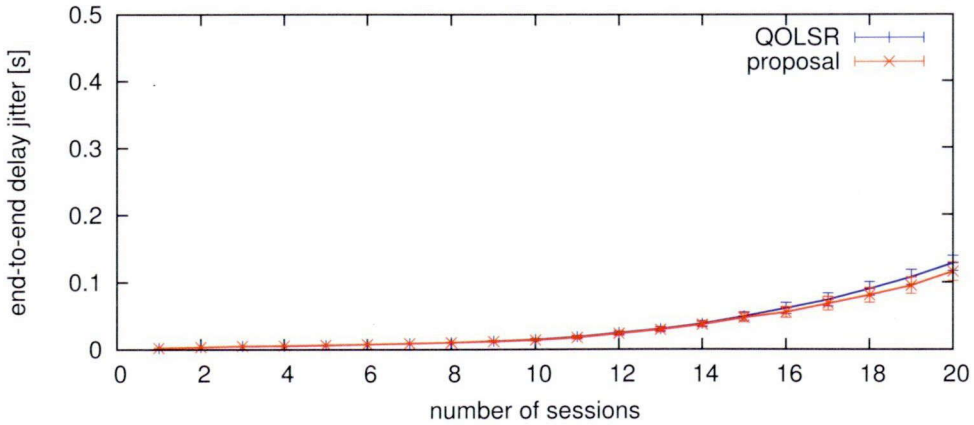
We evaluated the performance of our proposal on a general topology. We accommodated 20 random seeds. 100 nodes were randomly distributed in the 6000×6000 m^2 region. An example of node placement is shown in Figure 2.7. Because of the density, all nodes have at least one node in the range of radio signals and a constructed network is connected. Results on the average end-to-end packet delivery ratio, the average end-to-end delay, and the average delay jitter are shown in Figure 2.8 with 95% confidence interval. We can see



(a) Comparison of average packet delivery ratio

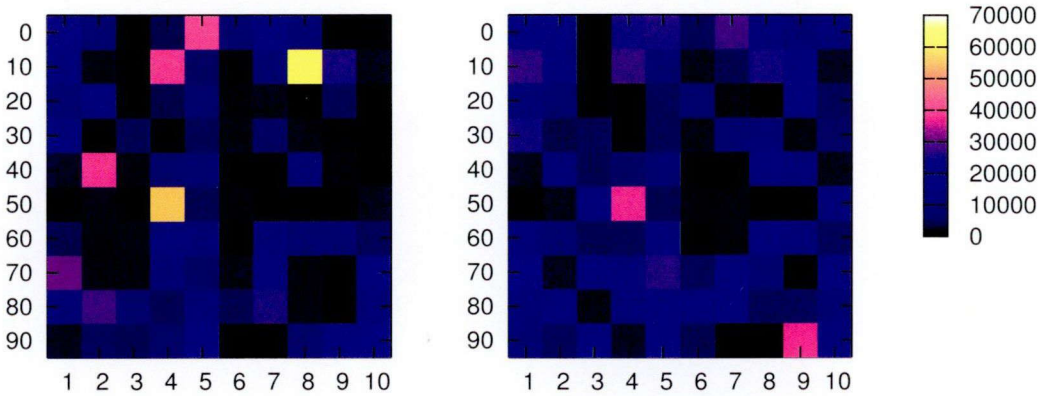


(b) Comparison of average delay



(c) Comparison of average delay jitter

Figure 2.8: Results of simulation I



(a) QOLSR (b) Our proposal

Figure 2.9: Comparison of total number of transmitted MAC frames

from Figure 2.8(a) that the average end-to-end packet delivery ratio is similar between our proposal and QOLSR, e.g. 93.0% with our proposal and 92.9% with QOLSR for 9 sessions, or little lower in QOLSR for more than 10 sessions. From Figures 2.8(b) and 2.8(c), our proposal is also slightly inferior to QOLSR in terms of the average delay and the average delay jitter. A reason for these slight performance degradations are for establishing about 1.3 times as long path in the number of physical hops as the shortest path established by QOLSR in order to detour congested links. Although our proposal not only needs additional LR header for logical routing but establishes about 1.3 times as long path in the number of physical hops, we conclude that our proposal performs as well as QOLSR.

While the performance in terms of packet delivery ratio, delay, and delay jitter is almost identical among the proposal and QOLSR, the proposal has an advantage in load distribution. In Figure 2.9, the total numbers of transmitted MAC frames at nodes on a random seed are illustrated. We refer to the same color bar. Each of cells corresponds to a node. The sum of values on the x and y axes indicates the node identifier, i.e. node number. We should note that nodes are arranged following their identifiers, not the location. It is noticed that nodes 18 and 54 are heavily loaded with QOLSR (Figure 2.9(a)),

whereas the load is relatively distributed over the whole network with our proposal (Figure 2.9(b)). From quantitative viewpoints, the variance of transmitted MAC frames per node is 141×10^6 in Figure 2.9(a) while it is 83.2×10^6 in Figure 2.9(b). The fairness index is 0.40 in Figure 2.9(a) and it is 0.60 in Figure 2.9(b). The fairness index f of 100 nodes is derived by the following equation [48].

$$f = \frac{\left(\sum_{i=1}^{100} x_i\right)^2}{100 \sum_{i=1}^{100} x_i^2} \tag{2.8}$$

where x_i is the value of transmitted MAC frames at node i. The fairness index 1 means that nodes are used equally. From these results, we can say that our proposal compensates the performance degradation caused by taking a longer physical path with avoiding congested links and balancing the load over the whole network.

2.4.4 Simulation II—Uniform Topology

We accommodated other 20 random seeds. In the second simulation scenario, considering rather regular placement of nodes as in the actual environment where nodes are placed keeping a certain distance, we first divided the region into 100 cells and placed nodes at random location one per cell. Furthermore, taking into account the fact that video sessions are not established among arbitrary pairs of nodes, but between a specific pair of nodes, we fixed source and destination nodes during a simulation run. An example of node placement is shown in Figure 2.10, where filled circle at lower left cell indicates the source node and one at upper right cell indicates the destination node. Because of the regularity of node placement, a node has at least one neighbor within the distance of 863 m and thus we set the broadcasting data rate at 12.0 Mb/s. Results are shown in Figure 2.11.

We can see that the proposal can accommodate more sessions than QOLSR keeping the high packet delivery ratio in Figure 2.11(a). Up to 4 sessions, both of the proposal and QOLSR could achieve the packet delivery ratio of about 97.7%. However, when the amount

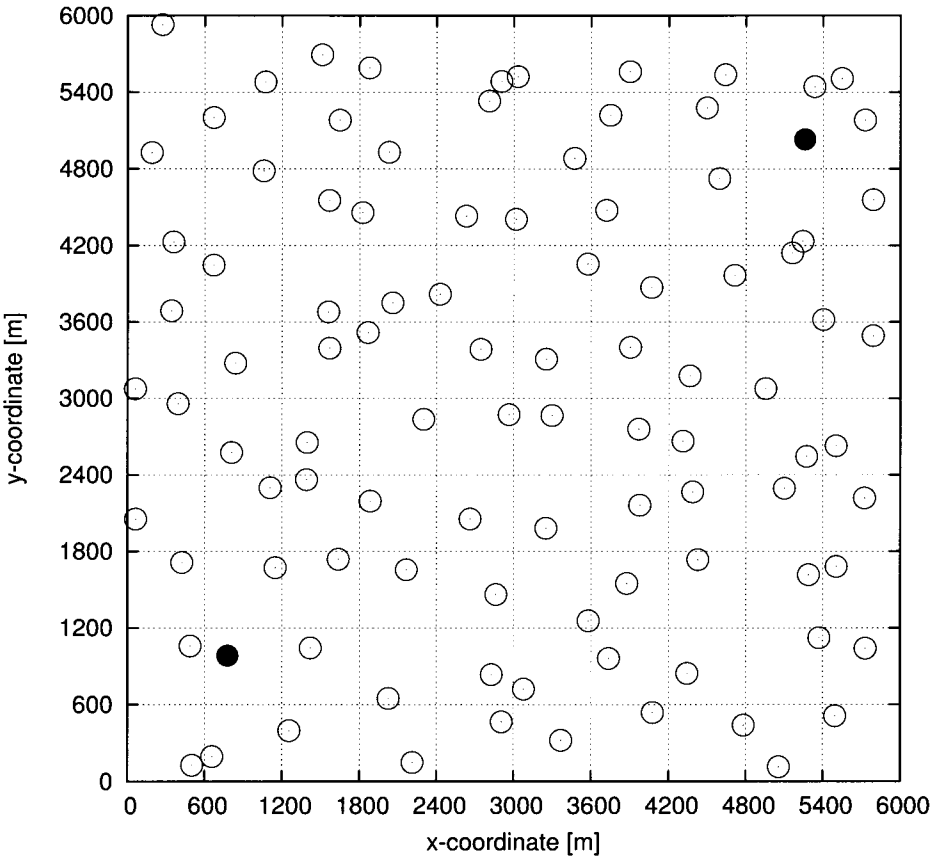
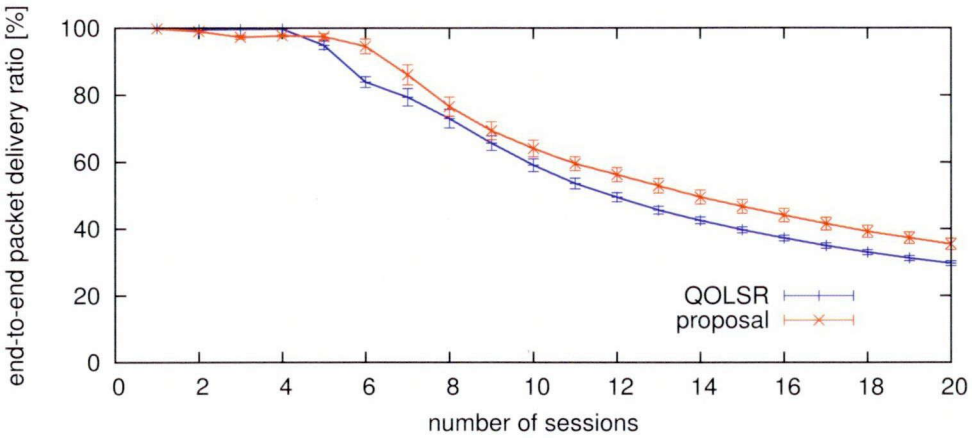
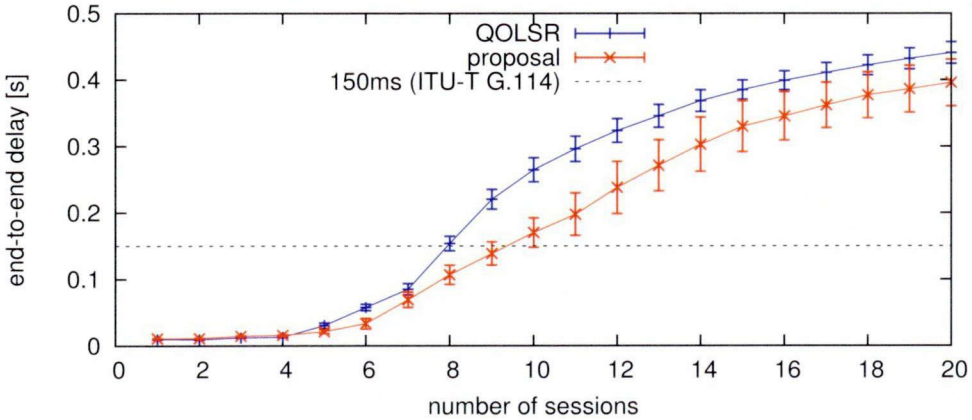


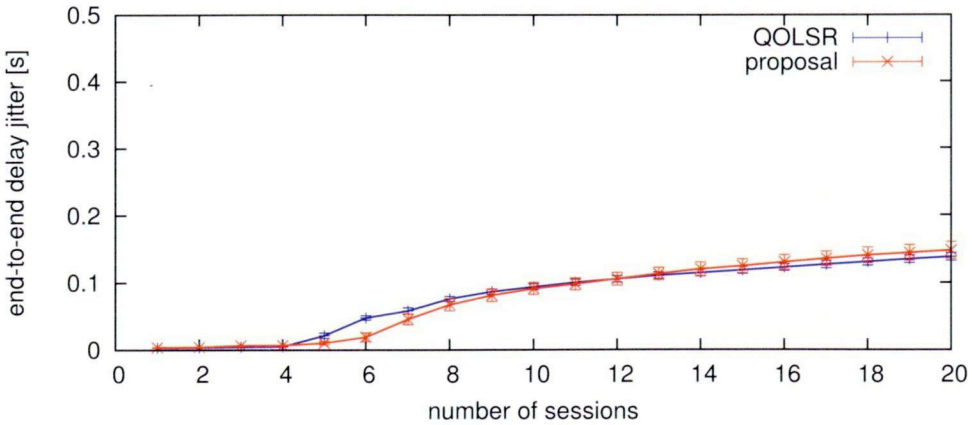
Figure 2.10: Node placement of one case of simulation II



(a) Comparison of average packet delivery ratio



(b) Comparison of average delay



(c) Comparison of average delay jitter

Figure 2.11: Results of simulation II

of traffic further increases, the performance of QOLSR deteriorates more rapidly than the proposal for the concentration of traffic. For example, with 6 sessions, the packet delivery ratio is about 94.6% with the proposal and about 83.9% with QOLSR. The difference is more remarkably in the delay in Figure 2.11(b). The delay jitter is similar between our proposal and QOLSR (Figure 2.11(c)). In a heavily loaded network, i.e. more than 6 sessions, the proposal outperforms QOLSR by distributing traffic over the whole network by the logical routing. The number of sessions satisfying the delay requirement for interactive voice communication, i.e. 150 ms (ITU-T G.114 about one-way transmission time [49]) increases from 7 with QOLSR to 9 with the proposal. From these results, we consider that our proposal is effective especially for real-time multimedia applications which may exhaust the capacity of particular wireless links, such as high-quality P2P video conferencing and remote monitoring with multiple cameras and single monitoring point.

2.5 Practical Experiments and Discussions

We implemented the proposal on a real wireless ad-hoc network and conducted practical experiments to verify the practicality and applicability of the proposal. In this section, we describe the experimental system and the obtained results.

2.5.1 Experimental System

We used the ad-hoc wireless relay nodes made by Hitachi Information & Communication Engineering shown in Figure 2.12, to implement our proposed mechanism. The main part of specifications of the ad-hoc wireless relay node is shown in Table 2.4. A node has four wireless network interfaces which support IEEE 802.11b/11g MAC protocols. We set three interfaces to the ad-hoc mode and configured one interface among them as best-effort channel and the other two as real-time channels. Since IEEE 802.11g has three orthogonal channels by being separated by at least 25 MHz to avoid inter-channel interference, we assigned 2.412 GHz (numbered as channel 0) to best-effort channel and 2.442 GHz (channel 1) and 2.472 GHz (channel 2) to real-time channels.

Table 2.4: Specifications of ad-hoc wireless relay node

Wireless interfaces	4 × IEEE 802.11b/11g
Ethernet interfaces	1 × 10Base-T/100Base-TX
MPU	SH7780 (SH-4A) 32 bit RISC
OS	Linux Kernel 2.6
RAM	DDR-SDRAM (64 MB)
Serial ports	2 ports
Chassis and Size	Aluminum case, Not waterproof, 230 × 210 × 60 mm
Manufacturer	Hitachi Information & Communication Engineering

A node is equipped with SH7780 (SH-4A) 32 bit RISC MPU and 64 MB flash memory. On the node, Linux OS version 2.6.10 is running with GNU C library version glibc-2.3.3. Due to low capacity of flash memory, BusyBox, i.e. single small executable file supporting many common UNIX utilities, is installed. So that several modules running on a node could share the information on an embedded system with very limited memory space, we developed a semaphore module and realize a shared memory mechanism. Similarly to a regular embedded system, a node supports only minimum modules or APIs by default. Therefore, we rebuilt the kernel so that it supports a semaphore module and rewrote the start-up section of the flash memory. We also developed the LR, SW, and OLSRv2 modules. These modules were cross-compiled, installed, and set to run automatically on boot. To avoid the performance degradation for exclusive memory access, we should have carefully determined the locking duration of each access.

To assist smooth experimentation, we developed additional applications for logging experimental data. It is necessary for performance evaluation to record system and communication statuses, i.e. when and what kind of message was transmitted on what node, and when the message was received on what node. Because of the low MPU performance, it has been hard to adjust the system clocks for all the nodes, i.e. the system clock gains according to the system load. To deal with this problem, our developed applications recorded these statuses per node every second with minimum interruption to the system. After the end of an experiment, we gathered the recorded log files to our computation server via an

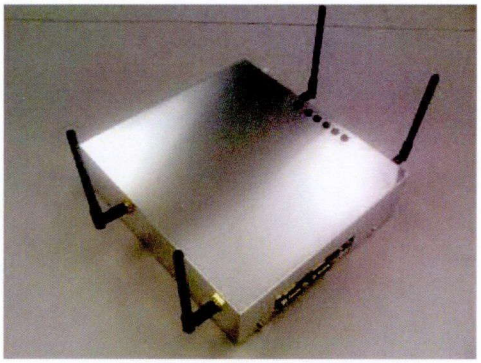


Figure 2.12: Ad-hoc wireless relay node

ethernet connection.

Because of these severe limitations on the architecture and the device, the obtained performance was not as high as expected as will be shown later. However, we could successfully confirm the behavior of our proposal in an actual operating environment, i.e. logical routing and efficient use of multiple channels.

2.5.2 Experimental Environment and Discussions

Since we had only four available nodes, we organized a simple square topology as illustrated in Figure 2.13. On this topology, we could confirm multiple paths between diagonal nodes. Nodes are placed at corners of a building (Figure 2.14). Although each channel was separated by 30 MHz to avoid inter-channel interference, a channel might be affected by other channels. In our preliminary experiments, we found that there was radio interference between electromagnetic waves emitted from antennas, but electromagnetic waves also emitted from antenna cables. Since the interference from antennas and antenna cables could be mitigated by separating them by more than 20 cm, we built an antenna tower by cardboard boxes as shown in Figures 2.15 and 2.16 to achieve the separation. The cardboard boxes are suitable for using in such practical experiments since they are almost transparent from the point of view of radio. A node was put in the second lowest box as shown in Figure 2.15 and antennas were fixed on the side at the different height as shown

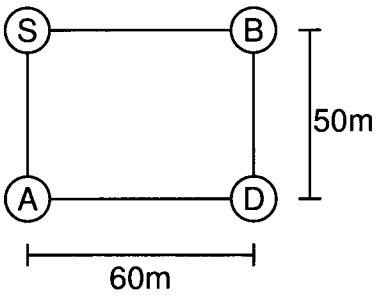


Figure 2.13: Experimental topology

in Figure 2.16.

Nodes S and D are source and destination node, respectively. The distance between two neighboring nodes were about 50–60 m, i.e. S-A and B-D were 50 m and S-B and A-D were 60 m, respectively. Solid lines indicate physical links constructed by OLSRv2. The nodes had possibilities to connect direct links between S-D or A-B at the good condition of best-effort channel, but the nodes might not construct a link between S-D or A-B on our experiments. Assuming VoIP traffic, we configured the source node to generate 64 kb/s CBR traffic per session. In practical experiments, source node S generated a new session every 5 s and the generated sessions kept alive until the end of each experiment. At the beginning of measurement, all network interfaces were operating and OLSRv2 was fully functional on the best-effort channel.

Figure 2.17 shows the data reception rate and the expected data reception rate, which is equal to 8600 bytes per second (64 kb *data traffic* + *IP header*). Until about 35 s, the data reception rate per session was as high as the expected data reception rate and the packet delivery ratio was higher than 98%. Figure 2.18 shows the delay jitter per session. Figures 2.19, 2.20, and 2.21 show channel usage in terms of the transmission data rate at source node S, intermediate nodes A and B, respectively. In Figure 2.19, lines for the data transmission rate on channels 1 and 2 overlap with each other. This implies that the node S, i.e. source node, evenly distributed real-time packets among these two real-time channels by observing the channel usage. The nodes A and B, i.e. intermediate nodes, also

Figure 2.14: Node placement on practical experiments

Figure 2.15: Front view of antenna tower

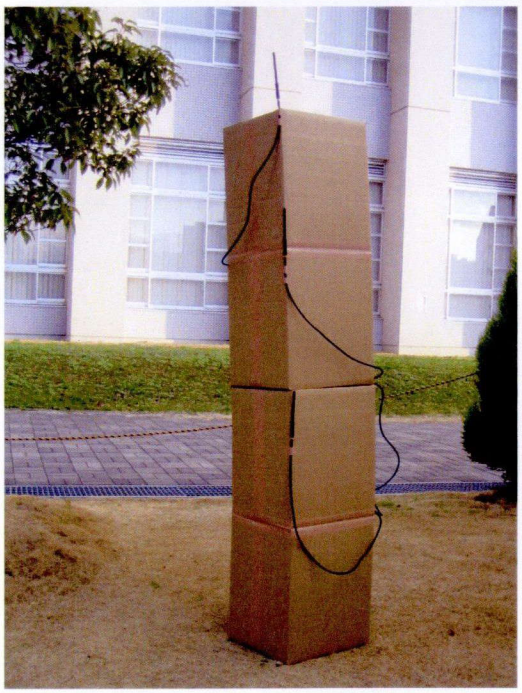


Figure 2.16: Rear view of antenna tower

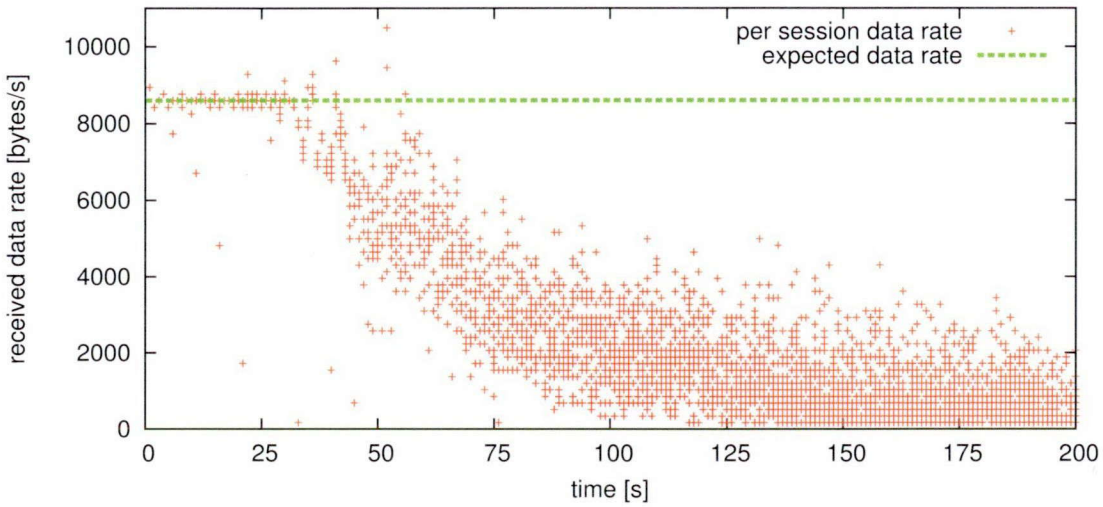


Figure 2.17: Data reception rate per session at node D

used real-time channels in a balanced manner as shown in Figures 2.20 and 2.21. Since the node S started a new session every 5 seconds, we can see the stepwise increase in the data transmission rate (Figure 2.19).

For the first 7 sessions, we can see in Figure 2.18 that the delay jitter was as small as 20 ms. A physical path from node S to D established by OLSRv2 was S-A-D. However, as can be seen in Figures 2.20 and 2.21, nodes A and B were almost equally used by load balancing of logical routing. From the timing of increase in the transmission data rate in Figures 2.20 and 2.21, it can be said that the LR on node S chose the path S-A-D for the first two sessions and then moved to the path S-B-D for the following four sessions. Since the advertising period of estimated channel information is 2 seconds and the propagation period of TC message is 5 seconds, there are few seconds of time lag for updated the Extended Topology Set that is used for logical routing.

As the number of sessions increased over 8 at 35 s, the data reception rate per session suddenly deteriorated (Figure 2.17) and the delay jitter exponentially increased (Figure 2.18). The reason for this can be explained by Figure 2.22, where the transition of CPU usage on node S is depicted. The ratio of idle CPU dropped to zero at 35 s and was kept

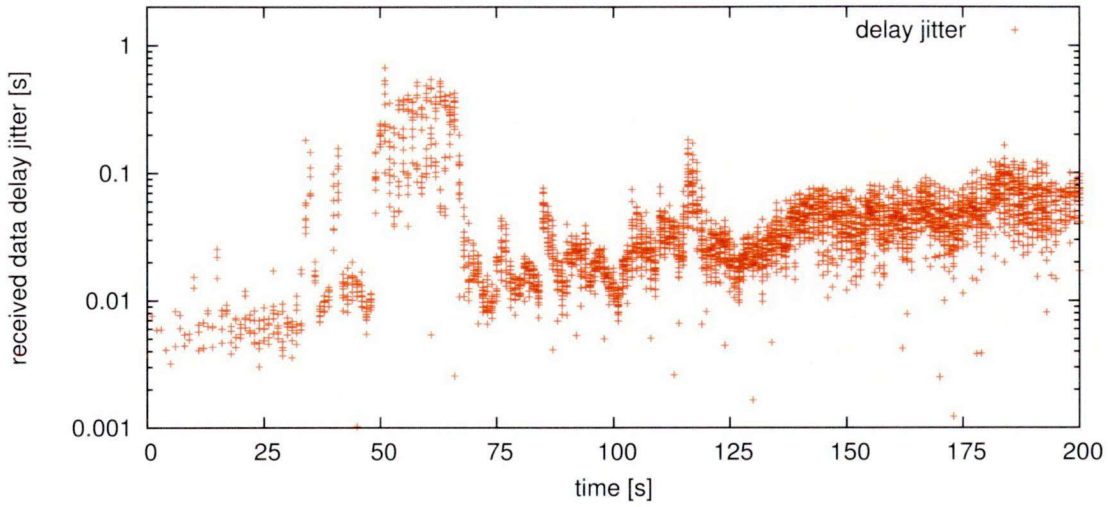


Figure 2.18: Delay jitter per session at node D

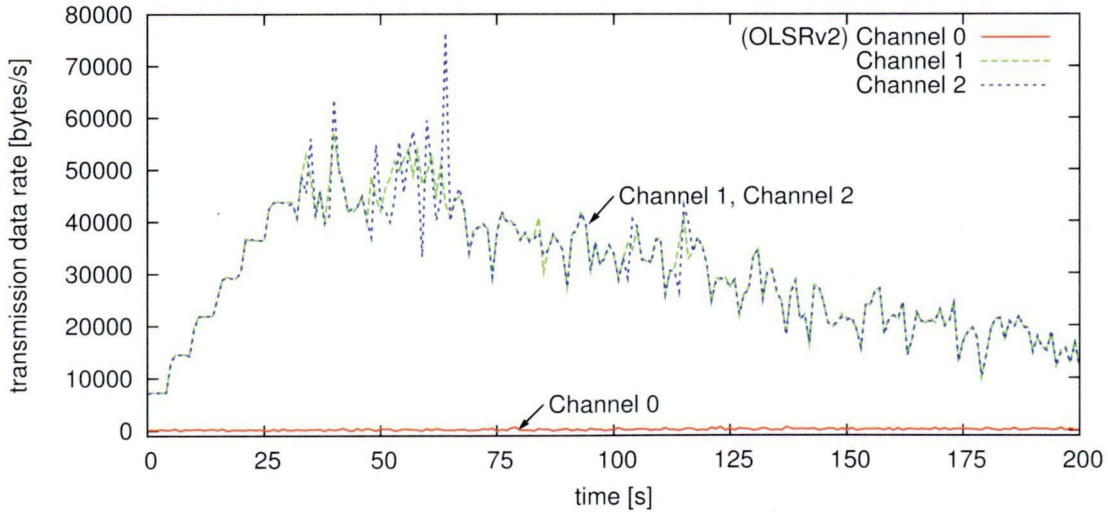


Figure 2.19: Transmission data rate per channel at node S

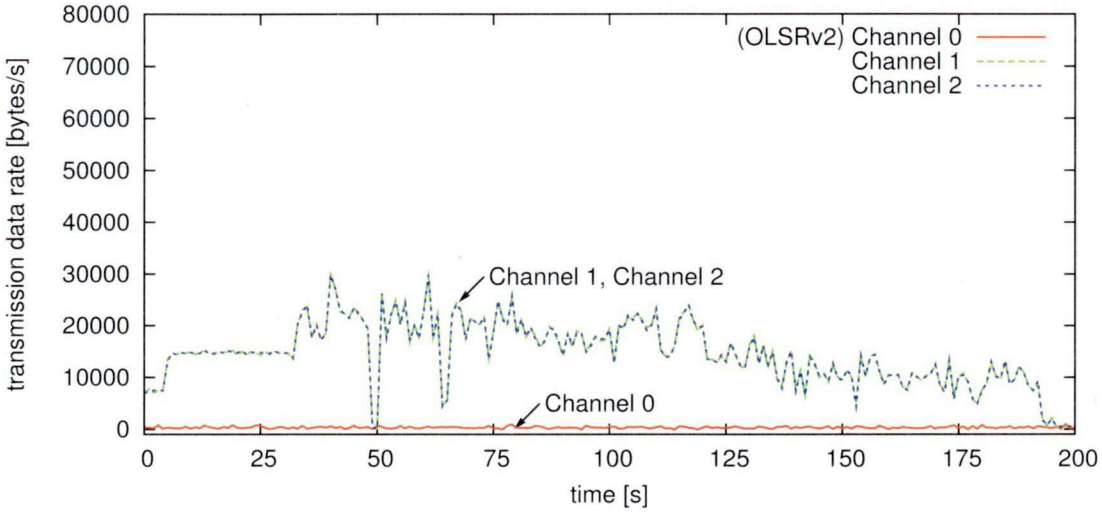


Figure 2.20: Transmission data rate per channel at node A

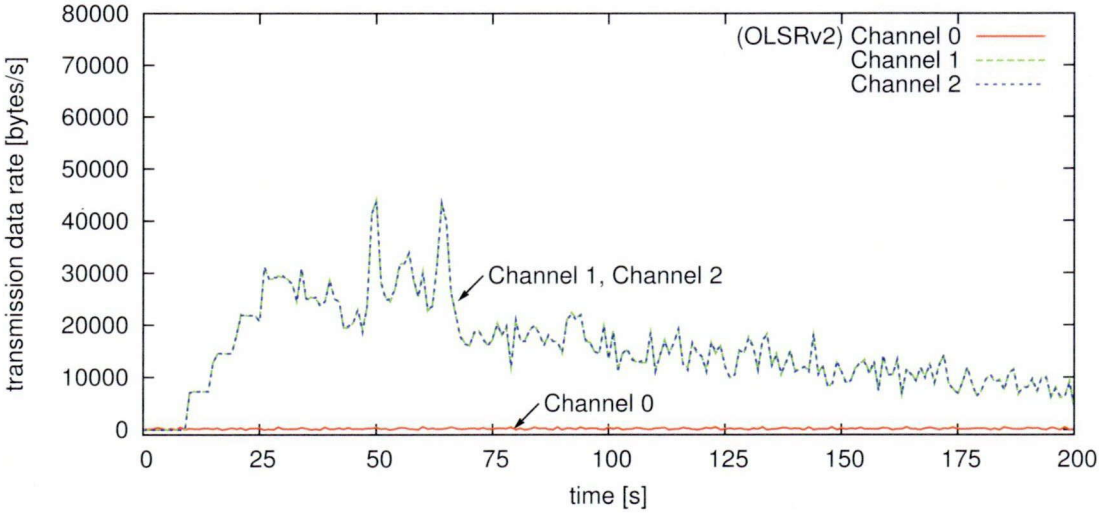


Figure 2.21: Transmission data rate per channel at node B

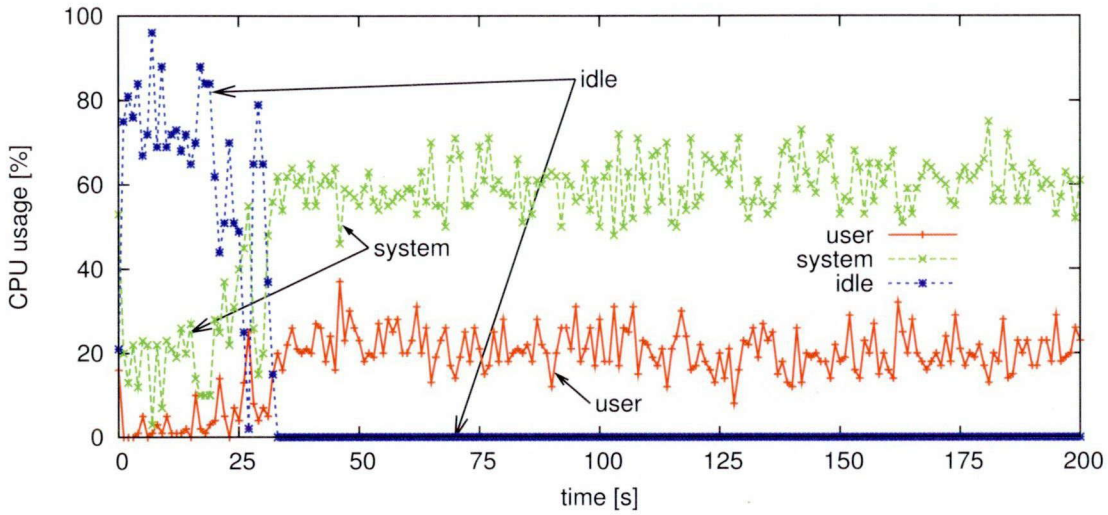


Figure 2.22: Transition of CPU usage at node S

zero since then. It implies that the drop of data reception rate was caused by full utilization of poor CPU resource of node S.

2.6 Summary

In this chapter, we proposed a QoS-aware routing mechanism for real-time applications. By embedding bandwidth information in control messages of OLSRv2, a source node establishes the logical path with the maximum available bandwidth. Since the bandwidth information is updated and emitted periodically, a source node can obtain the latest bandwidth information of the whole network and find the appropriate logical path adaptively. In addition, our proposal utilizes multiple channels adaptively. Through experiments on a simulator, we confirmed that our proposal could achieve almost the same packet delivery ratio, the end-to-end delay, and the delay jitter as QOLSR in general topology. In addition, our proposal more evenly distributed traffic over the whole network than QOLSR. When we considered more regular node placement, our proposal could achieve better performance than QOLSR. Since the logical routing is done at a source, the proposal can be extended to deal with other QoS measurements than the available bandwidth as far as the required

information is locally obtained by the SW module.

We further implemented our proposal to the experimental system and confirmed that our proposal worked on the practical testbed, although we recognized that it was hard to accommodate heavy traffic at ad-hoc wireless relay node due to low MPU performance. This problem can be solved by improving the structure and program to reduce the load on node or using future equipments that have a more powerful MPU.

In our proposal, we basically tried to protect real-time traffic from best-effort traffic and statically assigned channels to real-time traffic. Because of the volume and QoS requirement of real-time traffic, we believe that it is reasonable to give more channels to real-time traffic as in other QoS mechanisms such as ATM, IntServ, and DiffServ. However, depending on the balance between traffic volumes, it is also possible to assign more channels to best-effort traffic. Our proposal can be easily extended to the case with multiple channels for best-effort traffic, while limiting OLSR traffic on one best-effort channel.

As future research work, we are going to conduct large-scale experiments and for this purpose we need to improve the structure and program to reduce the load on node.

Chapter 3

Autonomous and Adaptive Resource Allocation of Heterogeneous Wireless Networks among Multiple Nodes and Multiple Applications

In the forthcoming future, various means of wireless communication, such as cellular, Wi-Fi, WiMAX, and DSRC, will be available to mobile users and applications. Since they compete for the limited wireless resources whose communication quality dynamically change, we need an adaptive mechanism for them to share the available network resources while satisfying their QoS requirements. In this chapter, we propose an adaptive resource allocation mechanism where each node autonomously determines wireless network resources to assign to each of networked applications running on it. For this purpose, we adopt an attractor composition model, which is based on an autonomous and adaptive behavior of biological systems. Through numerical analysis, we confirmed that our mechanism could adaptively

and stably allocate wireless network resources to applications, while considering their QoS requirements and fairly sharing network resources with other nodes. It also is shown that our mechanism superiors to a mechanism where a node determines resource allocation by solving an optimization problem.

3.1 Introduction

With the proliferation of wireless network technology, various means of wireless communication will be available to mobile users and applications to support our daily life everywhere in the forthcoming future. Wireless networks, such as cellular, Wi-Fi, WiMAX, and DSRC (Dedicated Short Range Communication) have heterogeneous characteristics in terms of the availability, capacity, delay, connectivity, and cost. Furthermore, most characteristics dynamically change due to instability of wireless communication and competition among users and applications for wireless network resources. Therefore, it is necessary for a node, that is, equipment where networked applications are running, to choose a wireless network resource dynamically to use for each of applications taking into account the condition of wireless networks and QoS requirements of applications. For example, a VoIP application running on a smartphone requires one-way end-to-end delay of lower than 150 ms for interactive communication [49]. Therefore, it is better to assign a cellular or DSRC network, which provides an application with a connection with small delay and delay jitter, to a VoIP application. On the other hand, an e-mail application can tolerate delay, while the volume of traffic is large. Therefore, a Wi-Fi or WiMAX network is appropriate for an e-mail application, because those networks can provide an application with high-speed connection for lower cost than a cellular network.

For effective and efficient use of available wireless networks, in recent years, cognitive networking has been attracting attention of researchers and developers. Cognitive network is, in one definition, the technology that cognizes the condition of wireless networks and selects an appropriate network to efficiently utilize the available network resources [50, 51, 52, 53, 54]. The network selection is done on each node. In the context

of cognitive network, a wireless network resource corresponds to a network, channel, or spectrum distinguished by wireless network technology, MAC protocol, coding algorithm, or frequency. Although existing proposals are useful in adaptive resource allocation in heterogeneous wireless network environment, most of them only deal with either of resource allocation among multiple nodes or resource allocation among multiple applications running on a node.

In the environment where a variety of heterogeneous networks are available and there exist multiple nodes having a variety of applications running, we need a mechanism to allocate an appropriate wireless network to each application on each node taking into account characteristics of wireless networks and QoS requirements of the application. Such resource allocation can be done on each node and formulated as an optimization problem to maximize the degree of satisfaction per node and per application, once information about the current condition of available wireless networks and QoS requirements of all applications is given. However, such optimization requires for a central node, e.g. an access point, to maintain the up-to-date information by frequent and aggressive message exchanges with nodes in the area. Even if the task of derivation of optimal resource allocation is distributed among nodes, nodes need to frequently exchange messages with other nodes to obtain latest information about the current status of applications running on the other nodes. From a viewpoint of dynamic features of wireless networks and cost, e.g. bandwidth and energy, spent in message exchanges, such mechanisms are not feasible at all in the new generation network environment, where various wireless networks are available to a large number of networked applications.

In this chapter, we propose an autonomous, fully distributed, and adaptive mechanism of network resource allocation among multiple nodes and multiple applications. In our mechanism, each node decides wireless networks to use for its applications. A node first recognizes the condition of wireless networks available to the node. Next, it evaluates the degree that applications are satisfied with the allocated networks. Then, it determines a wireless network to allocate to each application. To accomplish stable and adaptive resource allocation in the dynamically changing environment, we adopt a nonlinear mathematical

model of dynamical and adaptive behavior of biological systems, which is called an attractor composition model [12]. The attractor composition model is a noise-driven metaheuristic to find a stable solution of an optimization problem in an adaptive manner. Possible solutions are defined as attractors of a dynamical system and the potential of solution space is affected by the goodness of the current solution. When the current solution is appropriate, a basin of attractor corresponding to the solution in the solution space becomes deep and the state of the system statically stays there. Once the current solution becomes inappropriate for the new condition, the basin of attractor becomes shallow and the state begins to change randomly until a new good attractor is found. By defining the degree of satisfaction of node as an indicator of goodness of resource allocation, a node can autonomously find a solution, i.e. resource allocation, which is appropriate for the current condition of wireless networks and QoS requirements of applications. Since the condition of wireless networks is influenced by resource allocation at other nodes, nodes indirectly interact with each other and they eventually share the available network resources in a fair manner.

The rest of the chapter is organized as follows. We first introduce the attractor composition model in Section 3.2. Next in Section 3.3, we propose a novel resource allocation mechanism for multiple nodes and multiple applications in heterogeneous wireless network environment. Then we show results of numerical evaluation and comparison with a mechanism adopting per-node optimization in Section 3.4. Finally, we conclude the chapter and describe future directions in Section 3.5.

3.2 Attractor Composition Model and Its Application to Resource Allocation

Since the attractor composition model is an extension of the attractor selection model, we first briefly introduce the attractor selection model and then explain the attractor composition model in this section.

3.2.1 Attractor Selection Model

The attractor selection model is a metaheuristic of optimization problems that given condition dynamically changes [20]. The model is developed from an adaptive behavior of biological systems leading to symbiotic condition. In biological experiments, mutant *E. coli* cells are manipulated to synthesize two nutrients A and B, which are indispensable for them to grow. Nutrient synthesis is in a mutually inhibiting relation, where synthesis of one nutrient disturbs synthesis of the other nutrient. Nutrient synthesis is governed by the gene expression level of corresponding mRNA.

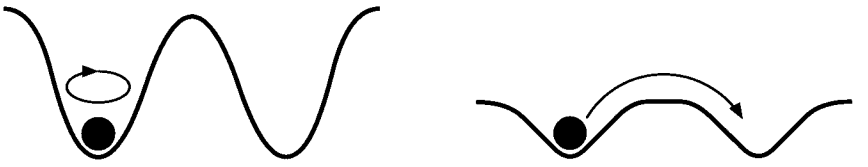
Temporal differential equations defining the dynamics of mRNA concentrations are given as follows.

$$\frac{dm_1}{dt} = \frac{s(\alpha)}{1+m_2^2} - d(\alpha) \times m_1 + \eta_1 \tag{3.1}$$

$$\frac{dm_2}{dt} = \frac{s(\alpha)}{1+m_1^2} - d(\alpha) \times m_2 + \eta_2. \tag{3.2}$$

m_1 and m_2 are mRNA concentrations corresponding to nutrient A and B, respectively. A pair of m_1 and m_2, i.e. (m_1, m_2), determines the state of cell. α $(0 \leq \alpha \leq 1)$ is a parameter called *activity* reflecting the current condition of a cell, e.g. the growth rate, which is a function of the state of cell and the environmental nutrient condition. $s(\alpha)$ and $d(\alpha)$ are functions for synthesis and decomposition of nutrients, respectively. For example, $s(\alpha) = \frac{6\alpha}{2+\alpha}$ and $d(\alpha) = \alpha$ in [20]. η_1 and η_2 correspond to the white Gaussian noise, which implement internal and external noise inherent in biological systems. A dynamical system defined by the above equations has two stable states, called *attractors*, where $m_1 \gg m_2$ or $m_1 \ll m_2$. In other words, the potential space of the dynamical system has two basins of attractors as shown in Figure 3.1(a).

Let us assume that a cell stays one of attractors and synthesizes nutrient A, i.e. $m_1 \gg m_2$. When the environment, i.e. the culture medium, contains both nutrients sufficiently, the cell can grow well and the activity is high. Therefore, basins of attractors are deep and the force of entrainment of attractors is strong. As a result, although the mRNA



(a) High activity (b) Low activity

Figure 3.1: Potential space with two attractors

concentrations are affected by the noise terms, the cell statically stays at the attractor. Now, assume that the nutrient condition occasionally changes and the environment lacks nutrient B. Since the cell synthesizes nutrient A, it does not have nutrient B sufficient to grow. Consequently, the activity of the cell decreases. Basins of attractors become shallow accordingly. At the same time, the noise terms begin to dominate the state (m_1, m_2). By being driven by the noise, the cell happens to synthesize more nutrient B than nutrient A, i.e. $m_1 < m_2$, and moves toward the attractor as shown in Figure 3.1(b). Since such nutrient synthesis is preferable in the current nutrient condition, the cell begins to grow and the activity increases. The increased activity makes basins of attractors deeper and the state is entrained to a new attractor, where $m_1 \ll m_2$. Eventually, the cell begins to synthesize nutrient B statically. In this way, the cell can successfully adapt its nutrient synthesis to dynamic change in the environmental nutrient condition.

In [55], we extended the model to M dimension as,

$$\frac{dm_i}{dt} = \frac{s(\alpha)}{1 + (\max_{1 \le j \le M} m_j)^2 - m_i^2} - d(\alpha) \times m_i + \eta_i \tag{3.3}$$

where $1 \le i \le M$ and

$$s(\alpha) = \alpha(\beta \times \alpha^\gamma) + \frac{1}{\sqrt{2}} \tag{3.4}$$

$$d(\alpha) = \alpha. \tag{3.5}$$

m_i-s are called state values. The model has M attractors where $m_i \gg m_j$ $(1 \le j \le M, j \ne i)$. β and γ are parameters having positive real numbers. With large β, basins of attractors

become deep leading to the higher stability of attractors. With large γ, the rate of increase in state value becomes smaller. As a result, the strength of entrainment becomes weaker and the speed of convergence gets slower.

By defining the activity as the goodness of control, e.g. performance, and attractors as alternatives of control, the attractor selection model enables adaptive control to maximize the performance in the dynamically changing environment. For example, the model has been applied to overlay multipath routing [11] and MANET routing [56]. In the case of MANET routing, the activity is determined based on the path length and attractors correspond to selection of neighbor nodes, where M is equal to the number of neighbors. Each node on a path evaluates the attractor selection model and it chooses a neighbor node leading to the shorter path in forwarding a packet. It was shown that the attractor selection-based routing achieves the higher performance than conventional routing in the dynamically changing environment.

3.2.2 Attractor Composition Model

Now consider the general model of attractor selection, which is formulated as,

$$\frac{d\vec{m}_i}{dt} = f(\vec{m}_i) \times \alpha_i + \vec{\eta}_i, \quad 1 \leq i \leq N. \tag{3.6}$$

$\vec{m}_i$ is a vector $\vec{m}_i = (m_{i,1}, \ldots, m_{i,j}, \ldots, m_{i,M})$ of state values of entity i, e.g. a cell and a node, and α_i is the activity of entity i. $f()$ is a function defining attractors. $\vec{\eta}_i$ is a vector of white Gaussian noise to introduce the effect of noise to each of state values. N is the number of entities. As explained in the previous section, the attractor selection model enables each entity i constituting the system to autonomously and adaptively determine its behavior $\vec{m}_i$ leading to the high activity α_i. Although their decision is independent from each other, through mutual interactions among them by sharing the same environment, the system eventually reaches the globally good condition where all entities have high activity and they comfortably coexist. For example, nutrients synthesized by a cell change the concentrations of nutrients in the culture media by membrane permeation. Therefore,

adaptive behavior of a cell influences other cells.

In the attractor composition model, interaction among entities is explicitly formulated and the global optimization is accelerated [12]. The attractor composition model is formulated as,

$$\frac{d\vec{m}_i}{dt} = f(\vec{m}_i) \times \alpha + \vec{\eta}_i, \quad 1 \leq i \leq N. \tag{3.7}$$

Note here that the activity is now a global parameter reflecting the goodness of the whole system. Therefore, each entity constituting the system autonomously and adaptively determines its behavior to maximize the global activity with this model.

In [12], the attractor composition model is applied to the cross-layer optimization in a wireless sensor network where an overlay network for periodic data gathering is organized over a physical sensor network. Based on Equation (3.7), each of sensor nodes adaptively changes the operational frequency, while an overlay network adaptively changes the overlay topology. By sharing the same activity, which is defined as the data gathering delay, between layers, autonomous and adaptive control in different layers accomplishes the global goal to minimize the data gathering delay.

3.2.3 Application of Attractor Composition Model to Resource Allocation

In applying the attractor composition model to resource allocation among nodes and among applications, there are two alternatives different in interpretation of the global activity shared among entities. When we define the activity α as the goodness of resource allocation in a certain region where multiple nodes exist, entity i corresponds to a node. Such a mechanism requires all nodes or a central node to know the degree of satisfaction of all nodes to derive the activity. It apparently is bandwidth and energy expensive and not feasible.

On the other hand, to define the activity α per node is more practical and feasible. In this case, entities competing for resources correspond to applications. Application i running on a node autonomously decides a wireless network to use by using Equation (3.7),

where N is the number of applications and M is the number of available network resources. Since the activity α shared among applications is derived from the degree of satisfaction of all applications running on a node, applications behave in a cooperative manner to maximize the degree of satisfaction of the node. Nodes further behave in a cooperative manner through indirect interaction among nodes by sharing network resources. In the next section, we provide details of our proposal based on this interpretation.

3.3 Autonomous and Adaptive Resource Allocation Mechanism

As explained in the previous section, we adopt the attractor composition model to achieve autonomous and adaptive resource allocation among multiple nodes and multiple applications in the environment where heterogeneous wireless networks are available to nodes. In this section, we explain a scenario considered in the chapter and then describe our resource allocation mechanism.

3.3.1 Target Network and Application

In this chapter, we assume that various wireless networks are available to nodes. In numerical experiments, we consider that cellular, Wi-Fi, WiMAX, and DSRC networks are available and a node allocates one of those networks to each of applications. However, our proposal does not limit target networks to them. Furthermore, resource allocation can be in the arbitrary granularity, from a network distinguished by their technologies, channel, spectrum, and waveform, as far as their characteristics are obtained at that granularity. Those networks have different characteristics in terms of the size of access area, the wireless capacity, the delay in communication and connection establishment, the reliability of connection, the stability of communication, and the cost to use. For example, a cellular network is mostly available except for underground in the urban area. However, the capacity is only about 7.2 or 14.4 Mb/s and the effective bandwidth is much smaller than the capacity. Furthermore, there is restriction on the number of simultaneous connections in a

cell and communication costs much. On the other hand, a Wi-Fi network provides nodes with the high-speed connection with the capacity of up to 54 Mb/s and it is less expensive than a cellular network. However, a Wi-Fi network has the very limited accessibility, whose access area is as long as tens meters in radius from an access point.

A node corresponds to a mobile device such as a smartphone, laptop, and vehicle. On each node, multiple applications are running and they require access to wireless networks. In the case of a car, a variety of applications such as road navigation, automobile condition reporting, video streaming, VoIP, e-mail, and web browsing are operating and each of which has different QoS requirements [57, 58]. For example, a video streaming application requires the large bandwidth while a VoIP application requires a connection with low delay jitter. We further assume that there exists a module or a program, which is responsible for allocation of resources to applications. In the case of a car, an OBU (On Board Unit) is equipped with multiple wireless network interfaces to provide applications with access to wireless networks. A node in this case corresponds to a car or more specifically an OBU of a car.

3.3.2 Overview of Our Mechanism

In our proposal, a resource allocation is done on each node autonomously. At regular control intervals, each application running on a node declares its QoS requirements in terms of the required bandwidth, tolerable delay jitter, and affordable transmission cost, for example, to the node. At the same time, a node obtains the information about the current status of available wireless networks, e.g. the available bandwidth, delay jitter, and transmission cost by using a cognitive radio technology [59, 60, 61]. Next, the node evaluates the degree that QoS requirements of each application are satisfied with an allocated network. Then, from the degree of satisfaction of applications, the degree of satisfaction of node is calculated, from which the activity of node is further derived. Based on the activity, a vector of state value of each application is updated by the attractor composition model. Finally, a wireless network with the largest state value is allocated to each application. If the current allocation

can satisfy QoS requirements of applications, the activity is high and resource allocation does not change. Otherwise, the activity becomes small and the noise term drives resource allocation to find better allocation.

3.3.3 Resource Allocation based on State Vector

For attractor composition-based resource allocation, a node maintains a set of N state vectors, where N is the number of applications. State vector $\vec{m}_i$ of application i ($1 \leq i \leq N$) is defined as,

$$\vec{m}_i = (m_{i,1}, \ldots, m_{i,j}, \ldots, m_{i,M}), \tag{3.8}$$

where M is the number of wireless networks available to a node. We assume that wireless networks are indexed, but the order of indexes does not affect resource allocation.

At regular control intervals, the activity α is evaluated and the state vectors are updated accordingly.

$$\frac{dm_{i,j}}{dt} = \frac{s(\alpha)}{1 + (\max_{1 \leq k \leq M} m_{i,k})^2 - m_{i,j}^2} - d(\alpha)m_{i,j} + \eta_{i,j}, \tag{3.9}$$

where $\eta_{i,j}$ is the white Gaussian noise with mean zero and standard deviation σ. For $s()$ and $d()$, we use the same functions in Equation (3.4) and Equation (3.5), respectively. Then, wireless network indexed as j with the largest state value $m_{i,j}$ in vector $\vec{m}_i$ is assigned to application i.

3.3.4 Activity Derivation

Activity α ($0 \leq \alpha \leq 1$) indicates the goodness of the current resource allocation. In our proposal, the activity α is derived by the following equation.

$$\alpha = \frac{\sum_{t=0}^{T-1} \alpha_t^*}{T} \tag{3.10}$$

where α_0^*, i.e. α_0^* with $t = 0$, is called the current instant activity and α_t^* is the instant activity of t intervals ago. T is a constant defining the window of moving average.

In derivation of the instant activity α_0^*, we use a hysteresis function of the play model [62]

to suppress the sensitivity of activity to slight decrease in the degree of satisfaction S of node, which is derived by Equation (3.14).

$$\alpha_0^* = \frac{1}{P}\sum_{l=1}^{P} h_l(p_l(S)) \tag{3.11}$$

P is the number of play hysterons. p_l $(l = 1, \ldots, P)$ is a play hysteron, which is defined as,

$$p_l(S) = \max(\min(p_k^-, S + \zeta_k), S - \zeta_k) \tag{3.12}$$

where p_l^- is the previous value of p_l and ζ_l is the width of play hysteron p_l. h_l in Equation (3.11) is a shape function of p_l, for which we used a sigmoid function as,

$$h_l(p_l(S)) = \frac{1}{1 + \exp(-gp_l(S))}. \tag{3.13}$$

g $(g > 0)$ is a gain of a sigmoid function.

Based on preliminary experiments, we found the threshold of activity of a phase transition exists. When the activity is larger than 0.6, a basin of attractor is deep and resource allocation is stable. When the activity becomes smaller than 0.6, resource allocation begins to be affected by the noise term. If we use the degree of satisfaction S of node as the instant activity depicted as a linear line in Figure 3.2, the behavior of node in resource allocation will suffer from instantaneous changes in characteristics of wireless networks and consequently resource allocation becomes unstable.

Figure 3.2 shows the relationship between the degree of satisfaction S of node and the instant activity α_0^*. With a hysteresis function, a trajectory draws a loop as shown by a red (solid) curve. When the degree of satisfaction of node increases from zero, the activity remains low at first. However, once the degree of satisfaction of node goes beyond a certain value, the activity begins to increase exponentially. This makes a node keep looking for better resource allocation until the degree of satisfaction of node reaches about 0.67. In addition, resource allocation converges fast once the degree of satisfaction of node becomes

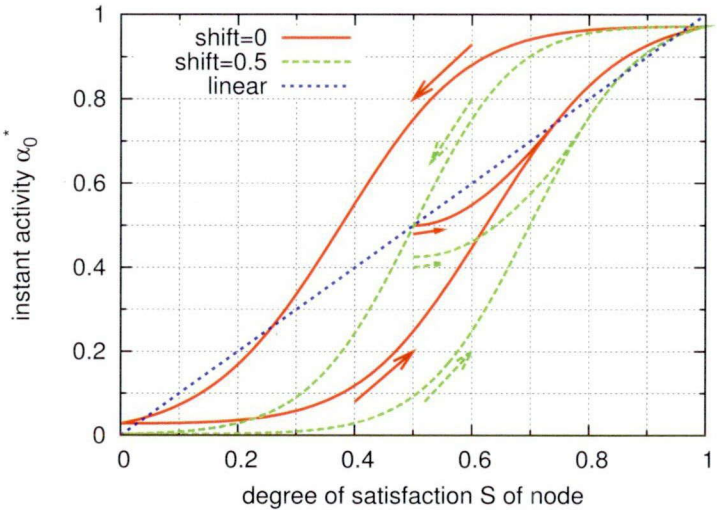


Figure 3.2: Hysteresis loop of relationship between degree of satisfaction of node and instant activity

sufficiently high. On the contrary, when the degree of satisfaction of node is decreasing, the activity is kept high until a certain point. It contributes to the insensitivity of resource allocation to slight decrease in the degree of satisfaction of node. As a result, a node keeps the current resource allocation even when the degree of satisfaction of node slightly decreases for perturbation. However, by using the hysteresis function, the activity does not drop to 0.6 until the degree of satisfaction of node decreases to about 0.43. It implies that a node does not change the current resource allocation even if the degree of satisfaction of node is as low as 0.5.

Therefore, we shift the loop to the right as shown by a green (dashed) curve in Figure 3.2. The degree of satisfaction S of node ranging from 0 to 1 is mapped to -0.5 to 1 by substituting $S \times 1.5 - 0.5$ for S in Equation (3.11) and Equation (3.12). With the shift, the degree of satisfaction of node at the point that the activity is 0.6 is about 0.74 in the right curve and 0.54 in the left curve, respectively.

3.3.5 Degree of Satisfaction

The degree of satisfaction S of node is derived from the weighted average and the weighted standard deviation of degree of satisfaction of applications to take into account both of the goodness and fairness of resource allocation.

$$S = \frac{\bar{Q}}{1 + b\sigma_Q} \tag{3.14}$$

b ($b \geq 0$) is a constant. The weighted average $\bar{Q}$ ($0 \leq \bar{Q} \leq 1$) is derived by the following equation.

$$\bar{Q} = \sum_{i=1}^{N} W_i Q_i, \tag{3.15}$$

where N is the number of applications. Each application has different level of importance from a viewpoint of a node, which is expressed by the weight W_i ($0 \leq W_i \leq 1$) of application i and $\sum_{i=1}^{N} W_i = 1$. Q_i is the degree of satisfaction ratio of application i. The weighted standard deviation σ_Q is derived by the following equation.

$$\sigma_Q = \sqrt{\sum_{i=1}^{N} W_i (\bar{Q} - Q_i)^2}. \tag{3.16}$$

Therefore, the activity becomes high when the degree of satisfaction of application is high and similar among applications.

Each application defines QoS requirements using several QoS criteria, e.g. bandwidth, delay jitter, and cost. The degree of satisfaction of application is derived from the degree that QoS requirements of an application are satisfied with a wireless network allocated to the application. The degree of satisfaction Q_i of application i is derived as follows.

$$Q_i = \bar{q}_i - \sqrt{\sigma_i^2} \tag{3.17}$$

$\bar{q}_i$ and σ_i^2 are the weighted average and weighted variance of degree of satisfaction $q_{i,s}$ of

QoS s, respectively.

$$\bar{q}_i = \sum_{s=1}^{K_i} w_{i,s} q_{i,s} \tag{3.18}$$

$$\sigma_i^2 = \sum_{s=1}^{K_i} w_{i,s} (\bar{q}_i - q_{i,s})^2 \tag{3.19}$$

Here, K_i is the number of QoS criteria specified by application i. In the case that application i uses bandwidth, delay jitter, and cost as QoS criteria, $K_i = 3$ and s is either of the three criteria. $w_{i,s}$ $(0 \leq w_{i,s} \leq 1, \sum_{s=1}^{K_i} w_{i,s} = 1)$ is the weight of QoS s on application i reflecting the importance of the QoS for the application.

The degree of satisfaction $q_{i,s}$ of QoS s on application i is derived from the QoS satisfaction ratio $x_{i,s}$ as,

$$q_{i,s} = \begin{cases} \frac{1}{1+\exp(-g_{i,s}\log(x_{i,s}))} & (x_{i,s} > 0) \\ 0 & (x_{i,s} = 0) \end{cases}, \tag{3.20}$$

where $g_{i,s}$ is a gain $(g > 0)$ of a sigmoid function. The QoS satisfaction ratio $x_{i,s}$ $(x_{i,s} \geq 0)$ of QoS s indicates how much each QoS requirement of an application is satisfied by the wireless network allocated to the application. For example, in the case of bandwidth, $x_{i,s}$ is the ratio of the available bandwidth on the allocated wireless network to the required bandwidth. Therefore, $x_{i,s} = 1.0$ means that the required QoS is fully satisfied.

A reason that we introduce a sigmoid function in Equation (3.20) is to control the sensitivity of QoS satisfaction ratio to the QoS provided by the allocated wireless network. When the gain $g_{i,s}$ is large, the slope of the sigmoid function around $x_{i,s} = 1$ becomes steep as shown in Figure 3.3. With such a function, the QoS satisfaction ratio $x_{i,s}$ remains low as far as, for example, the available bandwidth is less than the required bandwidth. It means that, once a wireless network with the available bandwidth smaller than the required bandwidth is occasionally allocated to an application, the QoS satisfaction ratio drastically decreases. Consequently, the activity decreases, and the application begins to choose a wireless network at random being driven by the noise term. Therefore, a large $g_{i,s}$ leads to the unstable resource allocation. On the other hand, a small $g_{i,s}$ makes the slope

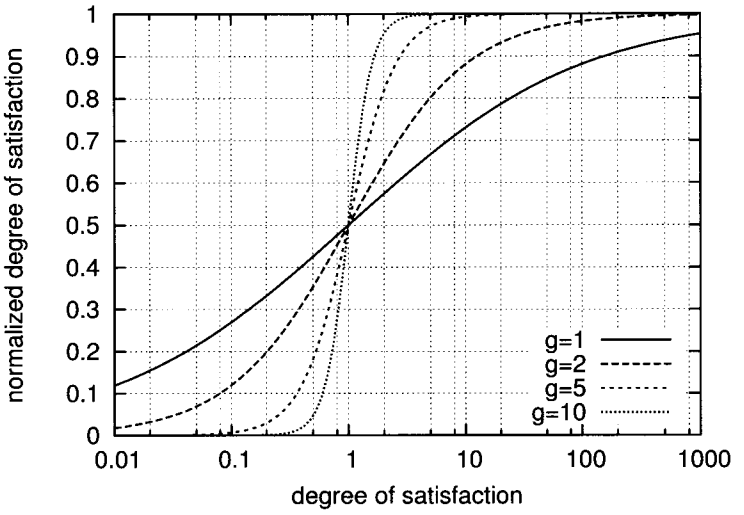


Figure 3.3: Slope of sigmoid function used in derivation of degree of satisfaction of QoS on application

gentle. Therefore, the QoS satisfaction ratio $x_{i,s}$ becomes high, even when application i is allocated a wireless network providing insufficient QoS and the QoS requirement of the application is not well satisfied. Furthermore, resource allocation becomes stable and no further improvement is expected, because the activity becomes sufficiently high.

3.4 Numerical Experiments

In this section, we show and discuss results of numerical experiments using a vehicular application scenario as an example.

3.4.1 Definitions and Settings

Considering resource allocation in a vehicular application scenario, we use the road model illustrated in Figure 3.4. The region is 300 m $\times$ 300 m large and a torus. There are two roads crossing at the center of the region. The horizontal road has four lanes and the vertical road has two lanes. Car traffic is affected by traffic signals at the intersection.

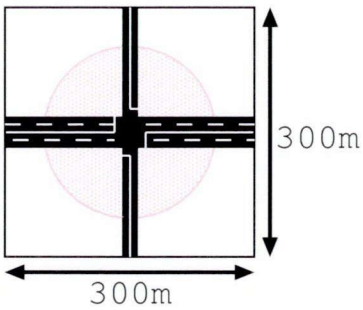


Figure 3.4: Road model used in numerical experiments

Table 3.1: Characteristics of wireless networks assumed in numerical experiments

network	capacity [Mb/s]	delay jitter [ms]	transmission cost [unit/b]
DSRC	4	100	10^{-7}
Wi-Fi	20	500	10^{-9}
WiMAX	40	200	10^{-8}
cellular	vary	100	10^{-5}

Wireless Networks

There are four wireless networks available in the region. They are DSRC (ARIB STD-T75 or later protocol), Wi-Fi (IEEE 802.11g), WiMAX, and cellular (3G-HSPA) networks. DSRC, WiMAX, and cellular networks cover the whole region, while the access area of Wi-Fi network is limited within the radius 100 m as shown by a circle in Figure 3.4. For simplicity, the distance between a node and a base station or an access point does not affect the communication speed. Therefore, dynamic changes in wireless networks are mainly caused by moving across a Wi-Fi access area and competition among applications and nodes.

Empirically determined characteristics of wireless networks are summarized in Table 3.1. Although some of them will vary time by time in reality, we assume they are constant for the sake of simplicity in the numerical experiments.

The capacity of the Wi-Fi network is shared among applications to which it is allocated. The bandwidth available to an application is given by dividing the capacity by the number

of applications using the Wi-Fi network. The capacity of DSRC and WiMAX networks are also shared among applications. In the case of the cellular network, the available bandwidth to an application varies in accordance with the number of connections. When there is only one application using the cellular network, the available bandwidth to the application is 2 Mb/s. When two or three applications are assigned for the cellular network, each of them can use 1 Mb/s bandwidth. Furthermore, when there are four through six applications, the available bandwidth to each application decreases to 0.5 Mb/s. Finally, when there are seven to twelve applications using the cellular network, an application can use only 0.25 Mb/s for each. When there are twelve applications using the cellular network, an application to which the cellular network is newly allocated cannot establish a connection. Then, the application begins to ignore the cellular network in resource allocation by setting a state value $m_{i,j}$ of the cellular network at zero, until the cellular network becomes ready to accept a new connection again. Similarly, a node out of the access area of Wi-Fi network considers only the DSRC, WiMAX, and cellular networks in resource allocation.

Regarding delay jitter and transmission cost, we use empirical values to make them different from each other while taking into account their general characteristics. For example, since a cellular network is designed for voice communication, delay jitter is set at the lowest among networks. However, it costs the most when we consider per-bit charge of data communication. Such empirical setting implies that we can call them network A, B, C, and D, instead of referring to real network technologies. Since our purpose of numerical experiments is to demonstrate how our proposal can choose an appropriate network for an application in the competitive and dynamically changing environment, those parameter settings do not affect the usefulness of our protocol very much.

At the beginning of a numerical experiment, nodes are randomly placed on the roads while keeping the density of nodes on the horizontal road 2.5 times larger than that on the vertical road. Nodes move along the road where they are initially placed. A node goes in and out an access area of Wi-Fi network. Assuming that the speed of node on the horizontal road is 40 km/h, a node stays in the access area of Wi-Fi network for random duration of time ranging from 18 s to 120 s with consideration of influence of a traffic signal at the

Table 3.2: QoS requirements of applications assumed in numerical experiments

application	bandwidth [kb/s]	delay jitter [ms]	transmission cost [unit/s]
Web (1)	300 (0.3)	10000 (0.1)	0.1 (0.6)
VoIP (3)	64 (0.5)	150 (0.4)	1 (0.1)
Video (2)	3000 (0.6)	1000 (0.1)	0.1 (0.3)

intersection. In addition, we assume that a node becomes out of an access area for constant duration of 9 s. On the vertical road, nodes move at the speed of 20 km/h. The durations that a node is in the access area is set at random from 36 s to 150 s and the duration of out of access area is 18 s.

Applications

We consider that Web browsing and mail (denoted as Web), VoIP, and video streaming (denoted as Video) applications are running. QoS requirements of applications are summarized in Table 3.2. About one-twentieth of nodes use all of three applications. That is, we denote n_1 as the number of nodes using all of three applications and n_1 is derived from the following equation:

$$n_1 = \frac{n}{20} + 1 \tag{3.21}$$

where n is number of nodes in the network. If n_1 is not an integer, we truncate the number. To put at least one node in the network, we add 1 on the above equation. The same number n_1 of nodes use Web and Video. Another number n_2 of nodes use Web and VoIP. n_2 is derived from the following equation.

$$n_2 = \frac{n}{20}. \tag{3.22}$$

The remaining nodes, i.e. $n - n_1 - n_1 - n_2$ nodes, use only Web.

As shown in the table, QoS requirements are defined in terms of the required bandwidth, the tolerable delay jitter, and the affordable transmission cost. Numbers in parentheses

define the weight values of each application i and QoS s on application i, respectively (see Section 3.3.5). For example, Web requires the bandwidth of 300 kb/s with the importance of 0.3, the tolerable delay jitter of 10 s with the importance of 0.1, and the affordable transmission cost of 0.1 unit/s with the importance of 0.6. Weight values are identical among nodes and applications. Since weight W_i of application i should be normalized as $\sum_{i=1}^{N} W_i = 1$ among N applications, Web and VoIP have their weights of 1/4 and 3/4, respectively, on a node with Web and VoIP, for example. Similarly, in a case of a node with all three applications, Web, VoIP, and Video are assigned the weight of 1/6, 3/6, and 2/6, respectively.

We consider that Web concerns the transmission cost most, while it tolerates the large delay jitter. On the other hand, VoIP should maintain the bandwidth of 64 kb/s and the delay jitter smaller than 150 ms for smooth and interactive communication at the sacrifice of cost. Video is an application that requires the bandwidth most. Although Video is a real-time multimedia application, it can tolerate delay jitter to some extent by using a play-out buffer and a pre-fetching mechanism.

Whereas the transmission cost is defined on a per-bit basis in Table 3.1, it is on a per-sec basis in Table 3.2. The per-sec transmission cost of an allocated network is derived by multiplying the required bandwidth by the transmission cost of network in Table 3.1. For example, the per-sec transmission cost of Web on a Wi-Fi network is $300,000$ b/s $\times 10^{-9}$ unit/b $= 0.0003$ unit/s, while that on a cellular network is $300,000$ b/s $\times 10^{-5}$ unit/b $= 3.0$ unit/s. Therefore, a Wi-Fi network is more appropriate for Web than a cellular network.

From the above conditions, we expect that Web mainly uses a Wi-Fi or WiMAX network for their low transmission cost and large bandwidth. A DSRC or cellular network is expected to be allocated to VoIP. Video should use any other network than a cellular network, since it requires the large bandwidth. Nevertheless, preference of each candidate network is different since different characteristics of the candidate networks lead different values of the degree of satisfaction of node. As we mentioned in the previous section, we design the degree of satisfaction of node to describe how much each QoS requirement of an application

is satisfied by the wireless network allocated to the application. Since the bandwidth is the most considerable factor for Video from Table 3.2, a Wi-Fi network is the best for Video, which has 20 Mb/s of the bandwidth. Wi-Fi network is the best for Video also from the point of view of the per-sec transmission cost, which is also considerable factor for Video. The second candidate is a WiMAX network, which has the second largest bandwidth and the second lowest per-sec transmission cost, and a DSRC network is the last, which has 4 Mb/s of the bandwidth and affordable per-sec transmission cost. The maximum number of nodes that the system can accommodate while providing them with satisfactory QoS is 99.

Comparison

For a purpose of comparison, we consider another method where each node adopts the optimal allocation using the locally available information, i.e. the characteristics of wireless networks [52, 63, 64]. At regular intervals identical to the proposal, i.e. 1 s, a node obtains the information about the remaining bandwidth, delay jitter, and cost of networks available to the node. Then, the node solves the optimization problem to maximize the degree of satisfaction of node under given conditions of wireless networks. We should note here that the maximum bandwidth available to an application is considered the same as the reminder of the capacity. In reality, there is the possibility that the amount of bandwidth that an application can use when it is assigned is larger than the reminder of the capacity at the timing of solving the optimization problem. A reason for such a pessimistic assumption is that a node does not know the number of applications, which are using the wireless network and their characteristics and it cannot estimate the amount of bandwidth to become available on allocation. On the contrary, our proposal updates state values and decides resource allocation based only on the degree that applications are satisfied with the currently allocated networks.

We change the number of nodes from 10 to 120. If there are more than more than 99 nodes, there is no resource allocation, which satisfies all of them for the shortage of network resources. The following figures are obtained from 10 numerical experiments with the

duration of 20,000 s for each of the number of nodes. For our proposal, we set parameters as $\beta = 8$, $\gamma = 3$, $\sigma = 1$, and the gain of sigmoid function $g_{i,s} = 10$ for all i and s. The window of moving average in derivation of activity α is set at $T = 10$. The number of play hysterons P is 100, the hysteresis gain of sigmoid function g is 5 in Equation (3.13), and b is 0.4 in Equation (3.14).

3.4.2 Results and Discussions

We first show a summarized result of comparison from viewpoints of the mean degree of satisfaction of node and its mean variance in Figure 3.5. The mean degree of satisfaction of node is shown by a red line for our proposal and a blue line for the compared method. We also draw a green line, which indicates the peak value of the mean degree of satisfaction of node of all experiments. The variance is indicated by plus signs for our proposal and crosses for the compared method. We derived the mean degree of satisfaction of node as follows. First, we take a sample average of the degree of satisfaction of node among nodes at each second of an experiment. Next, we average the sample averages over the whole time and get a time average of an experiment. Finally, the mean degree of satisfaction of node is obtained by averaging the time averages of all 10 experiments for each number of nodes. To derive the peak value of the mean degree of satisfaction of node, we take the sample average of the degree of satisfaction of node among nodes at each second of the compared method as we described before. Next, we choose the maximum of the sample averages over the whole time. Then, the peak value of the mean degree of satisfaction of node is obtained by selecting the maximum of the derived maximum values of all 10 experiments for each number of nodes. Although we tried to derive an optimal solution for each number of nodes, we recognized that it spends huge amounts of time to derive an optimal solution when the number of nodes is greater than 40. Thus, we use the peak value of the mean degree of satisfaction of node in place of an optimal. Derivation of the mean variance is as follows. We first derive the variance of the degrees of satisfaction of node among nodes at each second of an experiment. Next, we average the obtained per-second variance over the

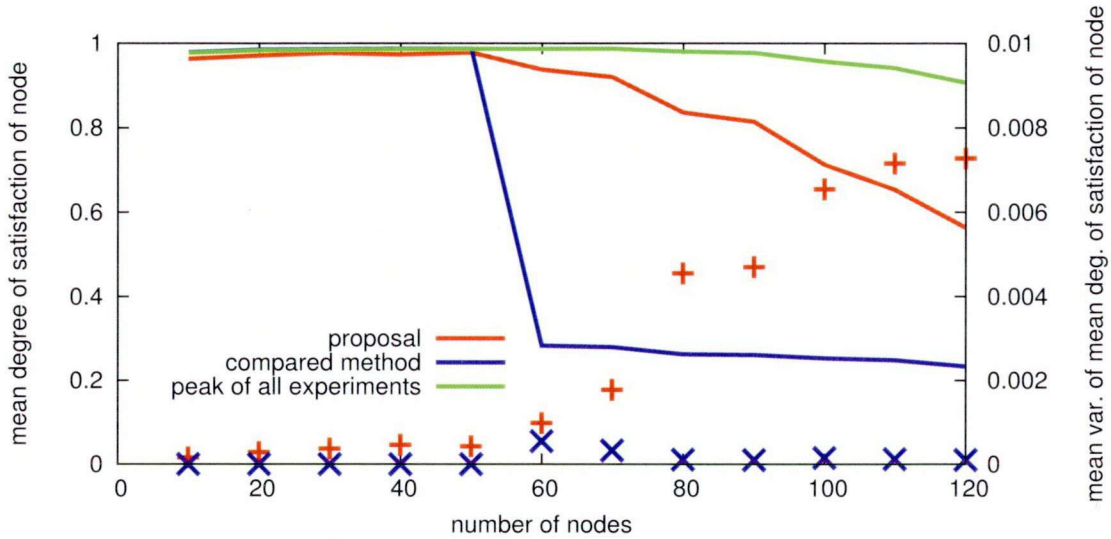


Figure 3.5: Mean and mean variance of degree of satisfaction of node against different number of nodes

whole time of an experiment. Finally, the mean variance of degree of satisfaction of node is obtained by averaging the per-experiment variance among 10 experiments for each number of nodes.

As shown in the figure, the compared method achieves the mean degree of satisfaction of node higher than 0.9 when the number of nodes is small. However, once the number of nodes exceeds 60, the performance considerably and suddenly deteriorates to about 0.28. A reason is as follows. When there are 60 nodes, 8 among them use Video. The required bandwidth of one Video is 3 Mb/s and it amounts to 24 Mb/s in total. Once all Video applications are assigned for a Wi-Fi network, which has 20 Mb/s of the bandwidth, the Wi-Fi network runs out of bandwidth and the degree of satisfaction of applications assigned for the Wi-Fi network considerably deteriorates. The degree of satisfaction of node is captured at this moment. Then, the allocated network of such unfavored applications is changed to another network. For example, Video and Web are assigned for a WiMAX network, which has the second largest bandwidth per node and the second lowest per-sec transmission cost except the Wi-Fi network. Since the reallocation is done on many nodes at a time, the WiMAX network becomes tight of bandwidth and the Wi-Fi network returns to the best

media for the applications, which are changed their resource allocation. The degree of satisfaction of node is also captured at this moment. Then, the Wi-Fi network runs out of bandwidth again. For the above reason, the mean degree of satisfaction of node is about 0.28 in the case of the number of nodes exceeds 60.

On the other hand, our proposal can sustain the mean degree of satisfaction of node at the moderate level even when there are 120 nodes in the region. As we can see in Figure 3.5, our proposal is much closer for the peak value of the mean degree of satisfaction of node than the compared method. Since our proposal takes a probabilistic approach in finding a good solution as biological systems do, an application is occasionally assigned for the second best network. Such allocation results in the sub-optimal resource allocation as indicated by the lower mean degree of satisfaction of node in the case of small number of nodes in Figure 3.5. However, at the same time, it enables nodes to find the moderate solution at the sacrifice of the degree of satisfaction of applications to some extent in the environment where the optimal solution to satisfy all applications does not exist.

It is also a reason why the mean variance of degree of satisfaction of node increases as the number of nodes increases with our proposal in Figure 3.5. On the contrary, the mean variance remains small with the compared method. It is because that all nodes solve the same optimization problem to maximize the degree of satisfaction of node under the same given condition, including characteristics of available networks and accommodating applications.

Next, we show time variations in resource allocation, state values, degrees of satisfaction, and activity of Video on a certain node on the horizontal road in one numerical experiment with 60 nodes in Figure 3.6. There are Web, VoIP, and Video applications running on the node. In the top and middle graphs, dots and lines colored with red, green, blue, and aqua correspond to DSRC, Wi-Fi, WiMAX, and cellular networks, respectively. At the top, a wireless network allocated to the application is indicated by dots. The middle is for the time series variation of state values $m_{i,j}$. At the bottom is the graph for the degree of satisfaction Q_i of the application (blue line), the degree of satisfaction S of node (orange line), and the activity α (aqua line).

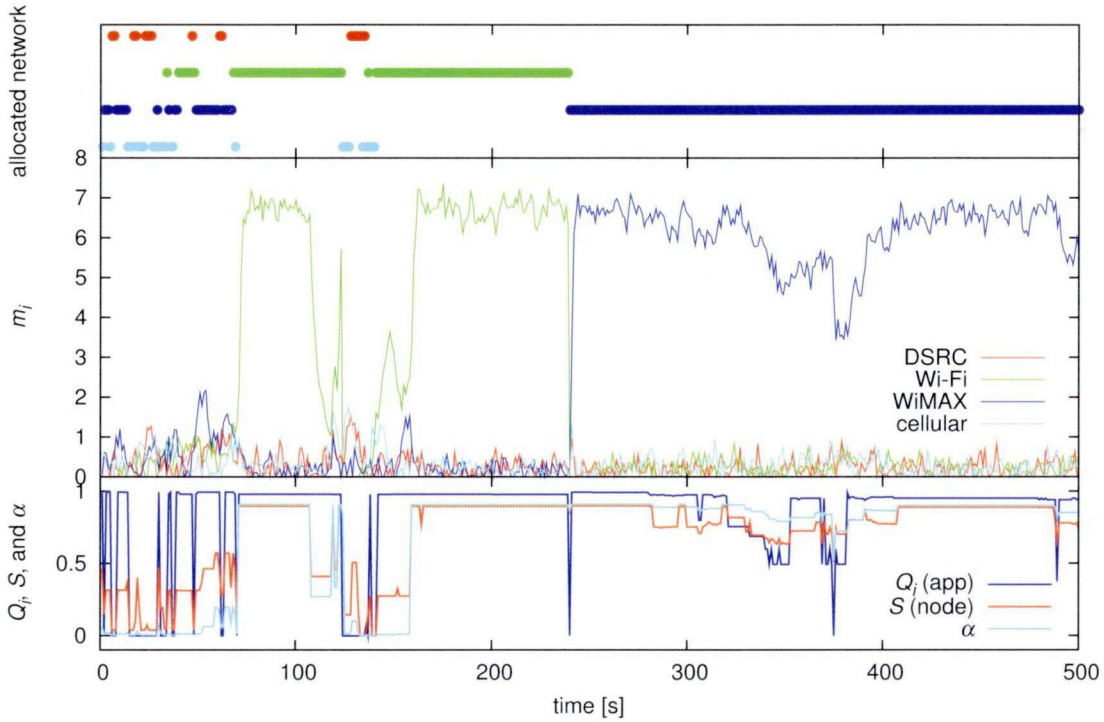


Figure 3.6: Time variation of allocated network, state values, degrees of satisfaction of application and node, and activity of Video with proposal on 60 nodes

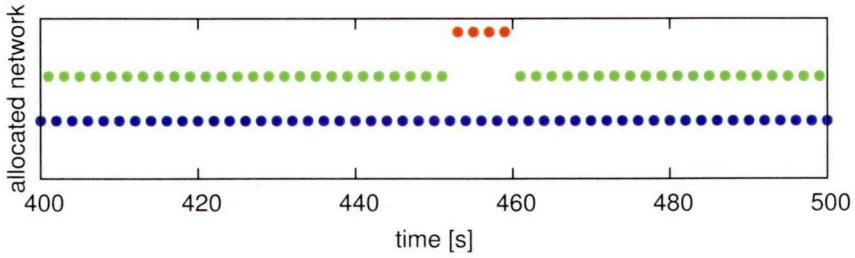


Figure 3.7: Time variation of allocated network of Video with compared method from 400 s to 500 s on 60 nodes

Until 70 s, a wireless network allocated to Video keeps changing since the activity is low. During the course of random allocation, there are some instants when either of a Wi-Fi or WiMAX network is selected. As a result, the degree of satisfaction of Video increases to 1 (see the blue line in the bottom graph of Figure 3.6). However, although not shown in the figure, other applications are not satisfied with the assigned networks, which disturb the degree of satisfaction of node from increasing. Consequently, the activity does not increase enough. Then at 70 s, occasionally all applications are assigned for appropriate networks as a result of random walking. The activity increases to 0.90 and the resource allocation becomes stable. At 108 s, the activity decreases to 0.41 by being affected by resource allocation at other node. However, resource allocation does not change, because the condition of networks resumes soon.

After a few seconds, the node goes out of the Wi-Fi access area. It triggers re-allocation of wireless networks for the decline of the activity. Although the node enters the Wi-Fi access area at 133 s, the activity is small until 159 s. It is because that the node is trying to adapt to the appearance of the Wi-Fi network during this period. At 240 s, the node goes out of the Wi-Fi access area again. In this case, the node could successfully allocate the WiMAX network to Video. The resource allocation is stable and does not change until 1220 s. In this way, our proposal can allocate wireless network resources adaptively and stably to applications on a node.

On the contrary, allocated networks flip-flop greatly in the compared method as shown in Figure 3.7. From 400 s to 452 s, a node alternately allocates Wi-Fi and WiMAX networks to

Video. From 452 s to 460 s, the node is out of the Wi-Fi access area and DSRC and WiMAX networks are allocated alternately. It is because that the compared method determines resource allocation in a greedy manner and as such multiple nodes switch wireless networks at the same time, even if timing of control is not synchronized. Now, assume that no application on the node is assigned for a Wi-Fi network. Because of vacancy, multiple nodes consider that the Wi-Fi network can provide an application with the plenty of bandwidth. Therefore, they decide to allocate the Wi-Fi network to one or more bandwidth-consuming applications. Once resource allocation is performed based on the derived optimal solution, the Wi-Fi network becomes fully congested and the degree of satisfaction of application considerably deteriorates. At the same time, a wireless network that those applications used before becomes empty. Then, nodes will switch from the Wi-Fi network to the former network at the next control timing. With our proposal, a similar phenomenon can be observed during the random allocation phase, but nodes eventually can find the globally appropriate solution and resource allocation converges.

We show the result of another node in the same numerical experiment in Figure 3.8. In this case, only Web is accommodated on the node and the WiMAX network is selected constantly after 4 s. We checked the results of other nodes in the same numerical experiment and we can say that nodes accommodating one application can find appropriate solution quickly and tends to keep the resource allocation for a longer time than nodes accommodating two or three applications.

On the other node with Web, VoIP, and Video applications in another numerical experiment with 20 nodes, the node assigns the WiMAX network for Video constantly (Figure 3.9). Since the total network capacity (66 Mb/s) is much larger than the total required bandwidth of each application (18.2 Mb/s), the resource allocation of the node is not affected by another node. Thus, as shown in Figure 3.9, the node assigns one network for Video constantly.

Then, we show the results of other numerical experiments with 100 nodes in Figures 3.10. In the Figure 3.10, Web, VoIP, and Video are accommodated on the node and the figure shows the result of Video. The total network capacity (66 Mb/s) is smaller than the total

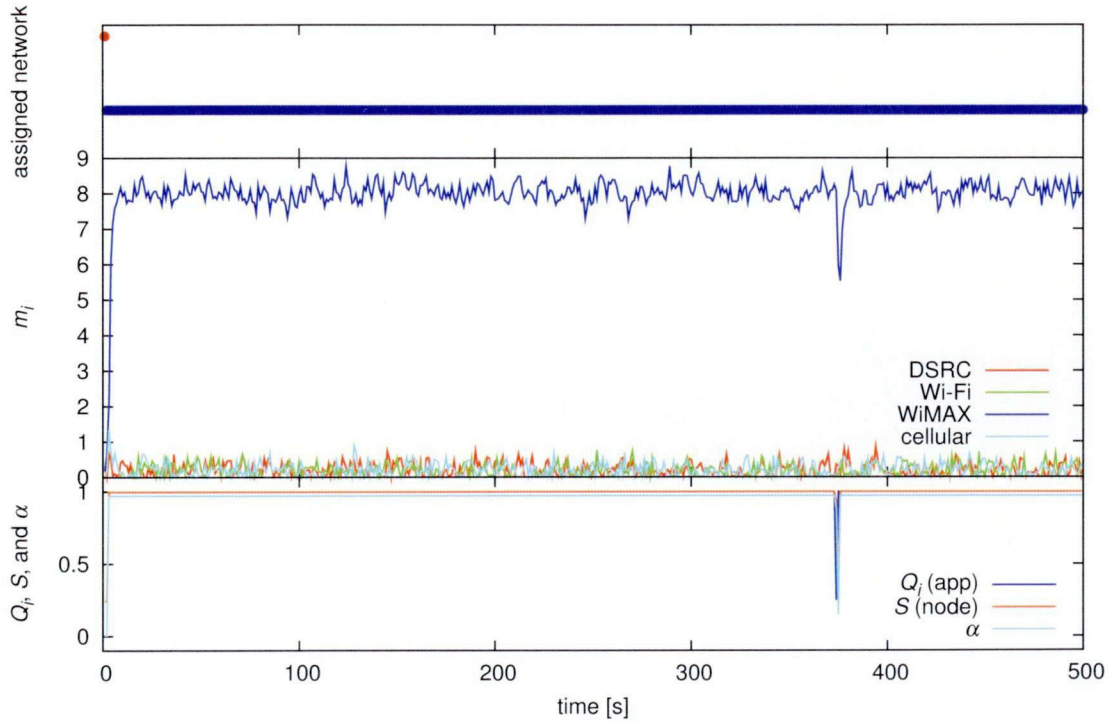


Figure 3.8: Time variation of allocated network, state values, degrees of satisfaction of application and node, and activity of Web with proposal on 60 nodes

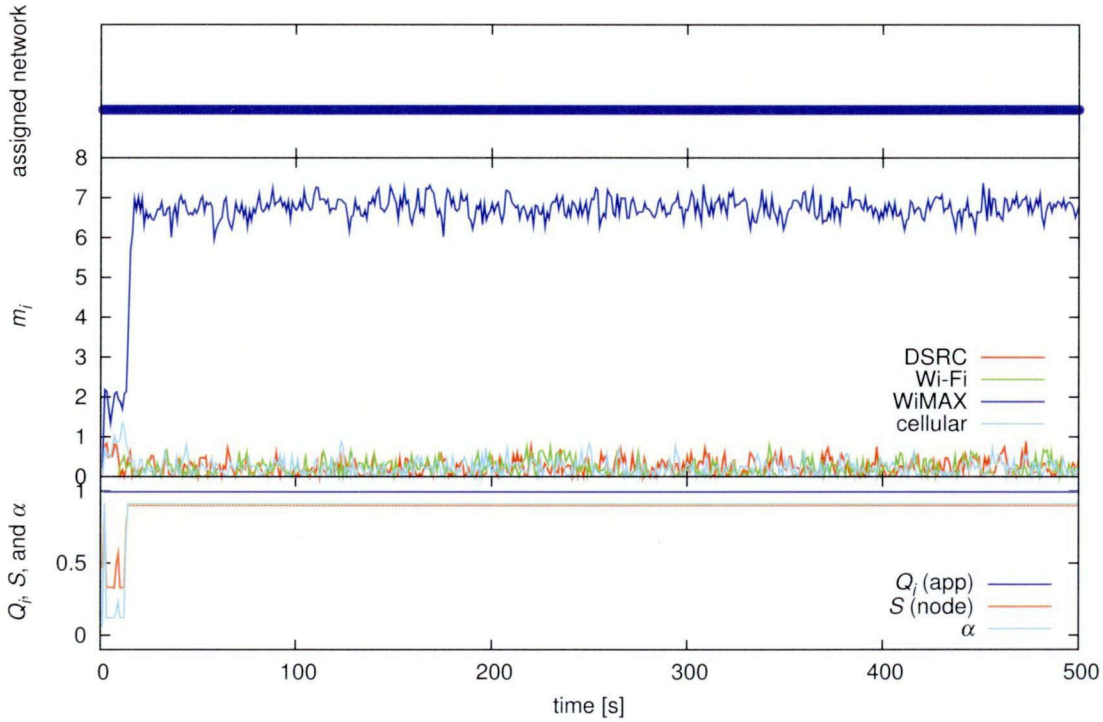


Figure 3.9: Time variation of allocated network, state values, degrees of satisfaction of application and node, and activity of Video with proposal on 20 nodes

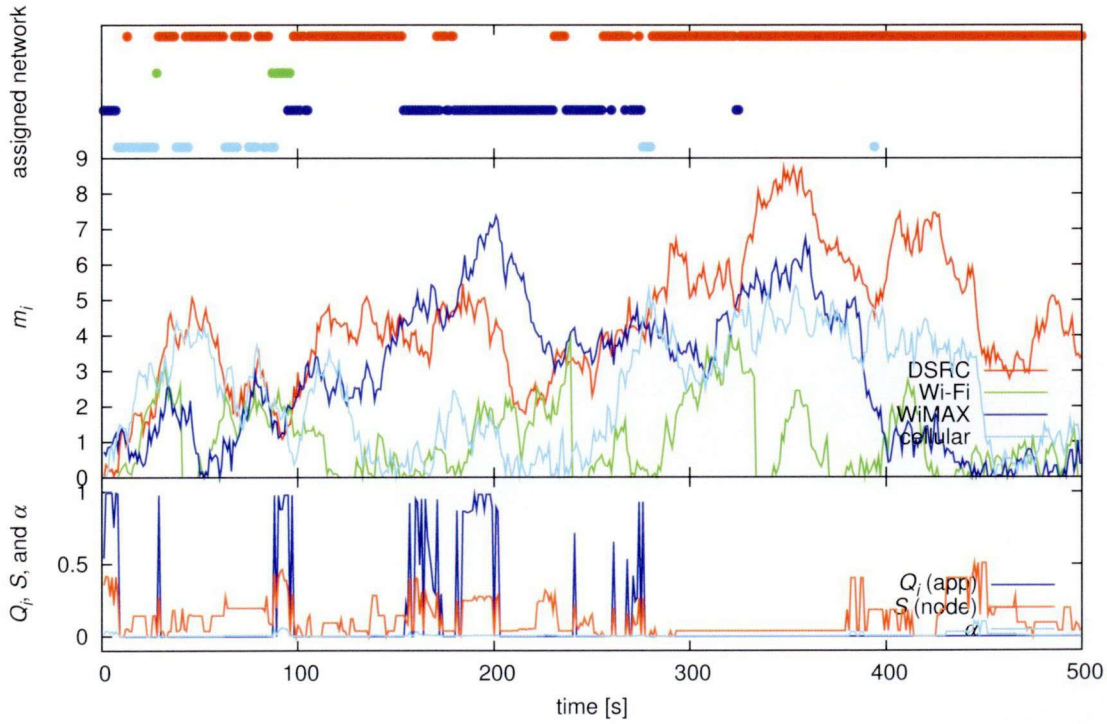


Figure 3.10: Time variation of allocated network, state values, degrees of satisfaction of application and node, and activity of Video with proposal on 100 nodes

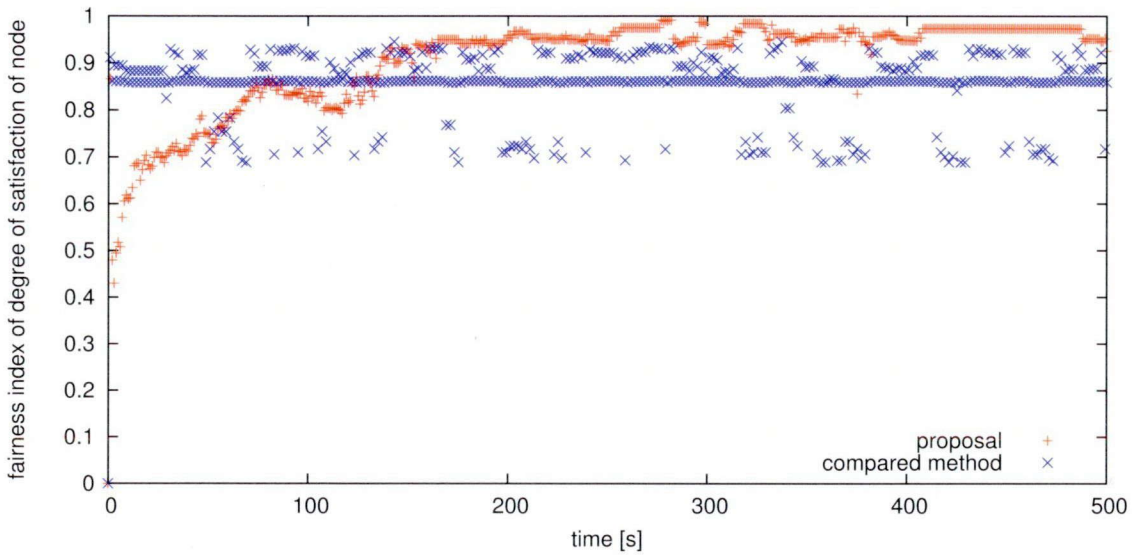


Figure 3.11: Fairness index of degree of satisfaction of node on 60 nodes

required bandwidth of each application (66.7 Mb/s) at 100 nodes. As shown in Figure 3.10, resource allocation for the Video is not stable since the activity is always low. Although the node finds an appropriate solution for the Video at a certain moment, e.g. from 90 s to 97 s and from 184 s to 199 s, the activity keeps low and the resource allocation keeps random walking. This is because the node cannot find the appropriate solution for other applications running on the node.

Finally, we evaluate the fairness of resource allocation by using the fairness index [48]. The fairness index ϕ of n nodes is derived by the following equation.

$$\phi = \frac{\left(\sum_{k=1}^{n} S_k\right)^2}{n \sum_{k=1}^{n} S_k^2} \tag{3.23}$$

n is number of nodes and S_k is the degree of satisfaction S of node k ($1 \leq k \leq n$). The fairness index of 1.0 means that the degree of satisfaction of node is identical among nodes. Figure 3.11 illustrates results of the case of 60 nodes. Although the fairness index is low

at the beginning, it gradually increases and becomes as high as 0.9 (average is 0.97) with our proposal. On the other hand, the average of fairness index is about 0.85 and it greatly fluctuates with the compared method. As conclusion, nodes can fairly share the limited network resources by using our proposal.

3.5 Summary

In this chapter, we proposed a novel resource allocation mechanism where each node autonomously determines wireless network resources to assign to each of networked applications running on it under dynamically changing environment. Our proposal employs the attractor composition model, which is based on an autonomous and adaptive behavior of biological systems. Since adaptation requires the certain duration of random walk phase, a vehicular network is one of tough applications of our proposal. However, as shown in the results, our proposal could adaptively and stably allocate wireless network resources to applications with consideration on their QoS requirements and fairly share network resources among nodes. It also is shown that our mechanism superiors to a mechanism where a node determines resource allocation by solving an optimization problem.

In general, it is said that biological models are insensitive to parameter setting. Next, we need to confirm this statement by conducting additional simulation experiments by changing the number of wireless networks and their characteristics, QoS requirements of applications, and mobility using more realistic simulation scenarios. In [65, 66], for example, the authors introduced an irregular radio model termed Radio Irregularity Model (RIM), which is based on *degree of irregularity* (DOI) model introduced in [67], for making a variation of communication range by taking into account the radio transmit power, power loss, the background noise, and the interference among different communication signals. By taking into account the RIM, we can conduct more realistic simulations and obtain more reliable results. In addition, we recognized that it is hard to derive optimal resource allocation in the whole network by huge amounts of calculation time. Thus, we can confirm the superiority of our proposal in terms of calculation time. Another direction is to extend

our proposal to fit to the actual environment. For example, Web browsing can tolerate instantaneous interruption of connection. Therefore, it is possible to keep assigning a Wi-Fi network to a Web application whereas a Wi-Fi network provides intermittent connectivity to a fast moving node. Finally, we plan to build a prototype and perform realistic experiments in the future.

Chapter 4

Conclusion

Matching between various kinds of mobile applications and various means of wireless media is necessary for satisfying QoS requirements of applications in wireless networks. In this thesis, we focused on wireless networks, which consist of nodes having multiple interfaces and studied communication mechanisms, which flexibly utilize multiple wireless media, i.e. channels and networks, to adapt against dynamic changes in wireless communication or environment.

In the former study, we considered a QoS-aware routing mechanism for multi-channel multi-interface wireless ad-hoc networks. Despite the convenience, a wireless ad-hoc network suffers from the limitation on the wireless capacity, which makes it non-trivial to accommodate real-time multimedia traffic for remote monitoring, video conferencing, and VoIP communication. To provide real-time multimedia applications in a wireless ad-hoc network with QoS consideration, we proposed a QoS-aware routing mechanism, which effectively utilize multiple channels available in the ad-hoc network. Our mechanism consists of three cooperative techniques; efficient message distribution, logical routing, and effective use of multiple channels. By embedding bandwidth information in control messages of OLSRv2, we achieved efficient bandwidth information propagation. By applying the distributed bandwidth information with topology information of OLSRv2 for the logical

routing, a source node adaptively establishes a logical path having the maximum available bandwidth to avoid congested physical links and satisfy application QoS requirements. In addition, our proposal utilizes multiple channels effectively when packet transmission. Through simulation experiments, we confirmed that our proposal can distribute the load over a network and achieves better performance than the existing QoS-aware routing protocol. We also conducted the practical experiments using the ad-hoc wireless relay nodes with our implementation and we verified the practicality of our proposal by confirming operation of logical routing in the actual environment. Thus, we conclude the former study that we realized the adaptive routing mechanism, which consider bandwidth as QoS requirement of applications, by flexible use of multiple channels available on physical links.

In the latter study, we extended our view to a case with multiple networks, which are heterogeneous in network characteristics. We proposed an autonomous and adaptive resource allocation mechanism among multiple nodes and multiple applications taking into account required QoS of applications and network characteristics. Although some resource allocation mechanisms can be formulated as an optimization problem to maximize a certain criterion, such as the total degree of satisfaction of nodes, it requires energy- and bandwidth-expensive message exchanges to maintain the up-to-date state information. Therefore, our proposal have adopted the *attractor composition model*, i.e. a noise-driven mathematical model of autonomous and adaptive behavior of biological systems to find a stable solution, for resource allocation. By adopting the *attractor composition model* to our proposal, each node tries to maximize the degree of satisfaction of itself. If the current solution, i.e. resource allocation, of a node is inappropriate for the current condition, the node begins to change the solution randomly until a new good solution is found. By taking numerical analyses, we confirmed that through mutual but indirect interaction among nodes, limited network resources are fairly shared among nodes. We also confirmed that our mechanism can adaptively allocate wireless network resources to applications, while considering their QoS requirements and fairly sharing network resources among nodes. Hence, we conclude the latter study that we realized the autonomous and adaptive resource allocation mechanism among multiple nodes and among multiple applications with consideration of QoS

requirements of applications and network characteristics.

To meet a dynamic change on different wireless networks, we studied adaptive communication mechanisms by flexible use of multiple media in wireless networks. We conclude this thesis that adaptive mechanism in wireless networks is a key feature of future networks to satisfy QoS requirements of applications, which suffer more heterogeneous networks available for heterogeneous users and applications. We believe that those above discussions contribute to the design and management of future wireless networks.

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