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Doctoral Dissertation

Multihop Relay System in Mesh-Topology Millimeter-Wave Entrance Networks

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Dedicated to my family

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Jaturong Sangiamwong

December, 2004

Preface

This thesis presents multihop relay system in mesh-topology millimeter-wave entrance networks. The contents are composed of the outcome of research carried out during the Ph.D. course pursed at Department of Communications Engineering, Graduate School of Engineering, Osaka University, Japan.

The thesis is organized in six chapters as follows.

Chapter 1 is an introduction to the subject including the current status of research activities in broadband wireless access systems, and the overview of mesh-topology millimeter-wave entrance networks. The objective and scope of the thesis are also briefed.

Chapter 2 describes millimeter-wave broadband wireless access (MMW BWA) systems, which have hierarchical network structure of P-MP (Point-to-MultiPoint) access networks for Internet users and P-P (Point-to-Point) mesh-topology entrance networks. Concept and architecture of mesh-topology broadband entrance networks are also clarified.

Chapter 3 proposes a link quality-based path selection scheme for mesh-topology MMW broadband entrance networks. With the deployment of MMW band, system will meet a large available bandwidth and a reduced size of electronic components. However, its quality is severely affected by rainfall. Therefore, unlike wired network, the load balancing path selection scheme, which does not take the effect of link quality into account, is not well applicable to wireless network. In order to combat the above problem, a novel path selection scheme based on the fluctuated radio link quality and traffic load is proposed. Performance improvements by the proposed path selection scheme are also evaluated.

Chapter 4 proposes a novel dynamic resource assignment (DRA) scheme performing the radio path allocation and the frequency channel assignment for multi-carrier mesh-topology entrance networks. In the radio path allocation, traffic load is distributed to appropriate paths, and adaptive modulation is used to compensate rain attenuation in each radio link. The radio path allocation finally determines how many frequency channels are necessary for each radio link. On the other hand, the frequency channel assignment is used to assign a particular set of frequency channels to each radio link in the sub-optimum manner with small computational complexity. Based on performance evaluations, throughput performances of the proposed DRA scheme under various weather conditions are examined, and effectiveness of the proposed DRA scheme is also discussed.

Chapter 5 proposes a novel frequency channel blocking (FCB) scheme for mesh-topology entrance networks to enhance the DRA scheme proposed in chapter 4, in order to mitigate interference and throughput deterioration problems, especially in the case of heavy traffic load. The concept of this proposed FCB scheme is to block the use of frequency channel at any radio link in order to suppress the interference level in other links. That is, the proposed FCB scheme sacrifices the throughput of any base station to improve the total network throughput performance. However, this may lead the unfairness problem, which is one of the most important issues in multihop mesh-topology networks. Therefore, in this proposed FCB scheme, any frequency channel is determined to be blocked whether or not, based on not only network throughput but also newly defined fairness index. The results obtained from the performance evaluations confirm the effectiveness of the proposed FCB scheme.

Chapter 6 draws conclusions of the thesis by summarizing overall results obtained in this study.

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Chapter 1

Introduction

The rapid development of the Internet and the WWW (World Wide Web) has created a global multimedia network in recent years. Traditionally, multimedia communication infrastructure is accessed through computer which is physically tied to a network. The success of any new system depends on the provision of a low-cost and flexible solution for coping with increasing demand. Broadband wireless solutions are able to offer excellent way of creating scalable systems, and to serve both technical and economical aspects [1] – [7].

It is widely recognized that the significant advantage of mobile communications is to enable communications anytime and anywhere with anyone and anything [8] – [9]. To evolve into the 3G mobile communications, a world wide standard, international mobile telecommunication 2000 (IMT-2000), has been formulated by the ITU (International Telecommunications Union). The ITU IMT-2000 standard organizations are currently separated into two major organizations reflecting two 3G camps: 3GPP (3G Partnership Project for Wideband CDMA, W-CDMA, standards based on backward compatibility with GSM and IS-136/PDC) and 3GPP2 (3G Partnership Project for cdma2000 standards based on backward compatibility with cdmaOne). In addition, IMT-2000 can provide high-speed data services for multimedia in addition to voice services, i.e., 144 kbps in vehicular, 384 kbps in walking-speed outdoor, and 2 Mbps in indoor environments, respectively [10] – [11].

An explosion in the growth of demand for ubiquitous broadband services has forced the ETSI-BRAN (European Telecommunications Standards Institute - Broadband Radio Access Networks) in Europe, the MMAC (Multimedia Mobile Access Communication) in Japan, and the IEEE 802.11 in the U.S. to develop broadband WLAN standards. The first two standards respectively include the HiperLAN (High-Performance Radio LAN) type 2 [12] and the HiSWANa (High-Speed Wireless Access Networks type a) [13]. On the other hand, the IEEE

802.11 family standard includes IEEE 802.11a [14] provided rate up to 54 Mbps with an average of 20 Mbps using the 5 GHz band, and IEEE 802.11b [15] and 802.11g using 2.4 GHz band, which are being widely used for wireless Internet access due to their low cost. To meet further demand for broadband wireless access, IEEE802.11n group has recently been formed to create a new WLAN standard to enable over 100 Mbps.

One scenario for using future broadband communications is that various wireless communication systems are deployed according to the user environments such as outdoor cellular, so-called hot spots such as coffee shops and airports, offices, and homes. These wireless communication systems will be used to supplement each other. In outdoor public environments, broadband cellular systems will be deployed for services up to 100 Mbps, while private wireless local area networks (WLANs) will mainly be used in office and home environments for higher rate services. Hot spots covered by either public across these environments will be able to stay connected to the broadband backbone network. Many research projects aiming at systems beyond IMT-2000 have been launched. The recommendation for systems beyond IMT-2000 has been recently approved by ITU-R, SG8. This recommendation envisages the research target of fourth-generation (4G) cellular being 100 Mbps and that of the next-generation WLAN being 1 Gbps. Moreover, next-generation wireless access systems should provide heterogeneous services to users in a seamless manner, independent of user location by making technology invisible and embedded in natural surroundings.

Broadband fixed wireless access systems offer an alternative to cabled access networks, such as ADSL (Asynchronous Digital Subscriber Line), CATV (Cable TV) and FTTH (Fiber to the Home) because they have the capacity to address broad geographic areas without the costly infrastructure development required in deploying cable links to individual sites, and then may lead to more ubiquitous broadband access with less expensive [16] – [18].

The broadband fixed wireless access industry, which provides high-rate network connections to stationary sites, has matured to a point at which it now has the IEEE 802.16 WirelessMAN™ [19] – [22] standard for second-generation wireless metropolitan area networks, which has recently been updated to IEEE 802.16-2004. Its purpose is to facilitate the optimal use of bandwidth from 10 to 66 GHz, as well as interoperability among devices from different vendors. In addition, IEEE 802.16a extends the air interface support to lower frequencies in 2–11 GHz band, including both licensed and unlicensed spectra. Compared to higher frequencies, such spectra offer the opportunity to reach many more customers less expensively, although at generally lower data rates. This suggests that such services will be oriented toward individual homes or small to medium-sized enterprises. The progress of the standard has been studied by the keen interest of the wireless broadband industry to capture the emerging worldwide interoperability for microwave access (WiMax) market. The WiMax Forum, formed in 2003, is promoting the commercialization of IEEE 802.16 and the ETSI's HiperMAN (European Telecommunications Standard Institute's High-Performance Radio MAN).

Local multipoint distribution service (LMDS) [23], one of broadband fixed wireless access systems, is developed in the U.S. by the FCC (Federal Communications Commission). As the LMDS band allocation of FCC, LMDS systems are licensed to operate typically in 28 and 31 GHz bands. Systems operating in 24 and 38 GHz bands, moreover, are also adopted in global LMDS markets. Since its point-to-multipoint (P-MP) nature, LMDS has been considered as a cost-effective last-mile solution that service providers can adopt to connect their subscribers to a high-speed Internet backbone. In addition, LMDS system is scalable where its service coverage can be extended by adding more base stations or by subdividing an existing cell to deal with increasing customer demand.

In Japan, the subscriber access systems using 26 GHz band were introduced in [25]. At present, fixed wireless access (FWA) services are mainly provided in 22, 26 and 38 GHz bands according to the ARIB (Association of Radio Industries and Businesses) standards, ARIB STD-T58 and ARIB STD-T59 [24]. In addition, FWA using these bands needs a clear line of sight (LOS) between base station and user station. However, it may be difficult to obtain LOS because the user station is located far from the base station. One promising way to solve the above problem is to employ multihop relay system in mesh-topology wireless networks, where both user and base stations use directional antennas to reduce the interference, resulting in an increase in system capacity. Moreover, mesh-topology networks also support high-speed communications in high-level of service coverage, and are flexible in point of that an adaptive routing can be implemented to avoid rainfall outage or traffic-congested links [26] – [30]. The multihop wireless access with a mesh configuration is proposed for broadband FWA systems using millimeter-wave (MMW) and quasi-MMW bands in [31] – [36].

According to the rapid growth of demand for high-speed traffic in multimedia communications, new frequency bands should be allocated. As the discussions within WRC (World Radio Conference) 2000, several new bands, e.g., 32, 52 and 55 GHz, have been reserved internationally for the high density fixed service (HDFS) including FWA. In Japan, a new FWA system exploiting 32 GHz band has been investigated in order to deal with the rapid growth in demand for broadband access services from now on by the broadband MMW wireless access group in YRP (Yokosuka Research Park) R&D Committee, and has been called the millimeter-wave broadband wireless access (MMW BWA) system [37] – [39]. This system has a hierarchical network structure of access networks constructed with P-MP (Point-to-MultiPoint) links for customer premises equipments (CPEs) and a higher level mesh-topology network constructed with Gbps P-P (Point-to-Point) links.

The MMW BWA system investigated in this thesis has a hierarchical network structure of P-MP access networks providing several ten to hundred Mbps access capacity to each user, and multihop Gbps P-P mesh-topology entrance networks. The entrance networks are used to relay traffic from several base stations (BSs) providing P-MP access links, to a center station (CS) connecting to backbone (BB) networks via P-P wireless links. In addition, the mesh-topology broadband entrance networks investigated in this thesis aim at providing bit rate in the order of Gbps at each BS. Moreover, concept and architecture of mesh-topology broadband entrance networks are also clarified.

In addition, one of the most challenging problems facing development of next-generation broadband wireless access systems is how to provide the user access to heterogeneous services in a seamless manner, independent of user location by making technology invisible and embedded in natural surroundings [43] – [44]. Reference [45] listed the major possible solutions at present as follows: common access protocol, overlay network and multimode device.

The common access protocol becomes viable if wireless networks can support common standard protocol. One possible solution, which will require interworking between different networks, uses wireless asynchronous transfer mode (ATM). The other one possible solution is the all-IP networking [46].

Overlay network consists of several universal access points (UAPs). The UAP performs protocol and frequency translation, content adaptation, and quality-of-service (QoS) negotiation-renegotiation on behalf of users.

With the deployment of multimode devices, we can use a single physical terminal with multiple interfaces to access services on different wireless networks. The device itself incorporates most of the additional complexity without requiring wireless network modification or employing interworking devices. The considerable research and development have been done on software defined radio (SDR) [47] – [48]. The SDR will offer design and operational flexibility in wireless access systems facilitating the globally harmonized services, though it is difficult to find globally aligned spectrum.

However, in order to support wireless heterogeneous systems including fixed, nomadic and mobile access services in a seamless manner with small complexity, a new solution using the non-regenerative relaying [49], [57] – [63], [79] – [80] is considered in this thesis. The non-regenerative repeaters are installed at base stations (BSs) in entrance networks. This is because entrance networks should deal with heterogeneous systems in the wireless physical layer to support the extension of various novel advanced systems with ease. That is, entrance networks become simple, universal operated and independent of technologies.

Moreover, the use of non-regenerative relaying implies that traffic load is transmitted in the physical wireless layer. From this viewpoint, this thesis employs the concept of two-plane network [50], the IP-based control plane and the physical wireless layer-based data plane, as shown in the generalized multiprotocol label switching (GMPLS) [51] – [56]. The IP-based control plane is responsible for both routing and signaling to support dynamic provision and restoration of label-forwarding information, and explicit a route for each connection between source and destination in whole networks. In addition, the path manager at CS acquires the state including traffic information from each BS by using the routing protocol such as open shortest path first with traffic engineering extension (OSPF-TE) [52] to generate and receive the opaque link-state advertisements (LSAs) [53]. Based on received opaque LSAs, the path manager centrally performs the physical wireless path selection for communications in data plane.

The objective of this thesis is to improve the throughput performance of mesh-topology MMW entrance networks by considering and solving following two challenging issues.

The first issue is the strong impact of radio link quality degraded by rainfall to the network throughput performance in MMW entrance networks. According to the use of MMW band, network will meet a large available bandwidth and a reduced size of electronic components. However, the quality of MMW band is strongly affected by rainfall [65] – [68]. Hence, unlike wired network, the load balancing path selection scheme [73], which does not take effect of link quality into account, is not well applicable to our mesh-topology MMW broadband entrance networks. The simple route switching from deteriorated route to backup route with the bit error rate (BER) level monitoring was proposed in [50]. Reference [64] investigated the improvement of availability due to route diversity under rain condition to show the advantage of mesh-topology utilization, but the investigation was simply done in 4-node square mesh network with no consideration of routing. On the other hand, this thesis considers the availability of route as quality, and then proposes the path selection scheme based on route availability considering impact of fluctuated rainfall and traffic load [57] – [63].

The second issue is the interference problem. To solve this issue, appropriate resource assignment is necessary, and thus the dynamic resource assignment (DRA) scheme performing the radio path allocation and the frequency channel assignment for multi-carrier mesh-topology entrance networks is proposed in this thesis. However, the performance of the DRA scheme has a limitation in the case of heavy traffic load. Therefore, in this thesis, the frequency channel blocking (FCB) scheme is additionally proposed to enhance the DRA scheme.

Compared to systems using single-carrier format, systems using multi-carrier format can provide more efficient frequency resource usage and more robust to the traffic fluctuation when using the appropriate frequency channel assignment. Therefore, we pay attention to the dynamic resource assignment (DRA) scheme performing the radio path allocation and the frequency channel assignment [79] – [80] for the multi-carrier mesh-topology entrance networks in this thesis. In the radio path allocation, adaptive modulation is used to compensate rain attenuation in each radio link, and traffic load is distributed to appropriate paths. The radio path allocation finally determines how many frequency channels are necessary for each radio link.

Next, the frequency channel assignment is used to assign a particular set of frequency channels to each radio link. The frequency channel assignment in mesh-topology wireless network was performed in autonomous and decentralized manner in [31] – [35], which each BS selects its own channels based on the radio statements made in a limited area surrounding the BS and then cause the non-optimum channel assignment. On the other hand, reference [36] proposed the channel assignment in centralized manner by using the simulated annealing algorithm, and simply evaluated the performance in tree-topology network. In this thesis, we perform the sub-optimum frequency channel assignment to suppress the computational complexity in mesh-topology multi-carrier wireless entrance networks with centralized control manner. Moreover, based on performance evaluations, throughput performances of the proposed DRA scheme under various weather conditions are examined, and the effectiveness of the proposed DRA scheme is also discussed.

Moreover, in wireless entrance networks, the heavier traffic load leads the more share of any frequency channel among different radio links, and thus yields radio links to interfere one another more strongly. Therefore, traffic in a channel of those radio links may be unsuccessfully received then the total network throughput performance becomes deteriorated. In this thesis, therefore, the DRA scheme is enhanced by addition of the frequency channel blocking (FCB) scheme to combat the above-mentioned problem [88]. The concept of the proposed FCB scheme is to block the use of frequency channel at any radio link in order to alleviate the interference level in other links. That is, the proposed FCB scheme sacrifices the throughput of any BS to improve the total network throughput performance. However, this may lead the unfairness problem, which is one of the most important issues in multihop mesh-topology networks [89]. Therefore, in this proposed FCB scheme, any frequency channel is determined to be blocked whether or not, based on not only network throughput but also newly defined fairness index. A higher fairness index, bounded between 0 and 1, indicates better fairness between BSs. In the case of perfect fair which each BS has the same value of throughput normalized by its own input load, the fairness index becomes 1. On the other hand, in the case of perfect unfair which only one BS has non-zero throughput, the fairness index becomes $1/N_{BS}$ which is 0 in the limit as N_{BS} tends to ∞. In addition, performance improvements by the proposed FCB scheme are evaluated and discussed.

The remainder of this thesis is organized as follows.

Chapter 2 describes MMW BWA system, which has a hierarchical network structure of P-MP access networks for Internet users and P-P mesh-topology entrance networks. Concept and architecture of mesh-topology broadband entrance networks are also clarified.

Chapter 3 proposes a link quality-based path selection scheme for mesh-topology MMW broadband entrance networks. Since the quality of MMW band is severely affected by rainfall. Therefore, in addition to the traffic load, the fluctuated radio link quality according to rainfall is also taken into account for the path selection scheme. Performance improvements by the proposed path selection scheme are also evaluated and discussed.

Chapter 4 proposes a novel dynamic resource assignment (DRA) scheme performing the radio path allocation and the frequency channel assignment for multi-carrier mesh-topology entrance networks. The radio path allocation distributes traffic load to appropriate paths, and performs the adaptive modulation to compensate rain attenuation in each radio link. Finally, it determines how many frequency channels are necessary for each radio link. On the other hand, the frequency channel assignment is used to assign a particular set of frequency channels to each radio link in the sub-optimum manner with small computational complexity. The results obtained from performance evaluations confirm the effectiveness of the proposed DRA scheme.

Chapter 5 proposes a novel frequency channel blocking (FCB) scheme for mesh-topology entrance networks to enhance the DRA scheme proposed in chapter 4 in order to alleviate interference and throughput deterioration problems, especially in the case of heavy traffic load. The proposed FCB scheme sacrifices the throughput of any BS to improve total network throughput performance, which any frequency channel is determined to be blocked whether or not, based on not only network throughput but also newly defined fairness index which is bounded between 0 and 1. Moreover, a higher fairness index indicates better fairness between BSs. Based on performance evaluations, improvements of network throughput and fairness performances by the proposed FCB scheme are examined and discussed.

Finally, all conclusions obtained in this thesis are described in chapter 6.

Chapter 2

Mesh-Topology Millimeter-Wave Broadband Entrance Networks

2.1 Introduction

The global demand for multimedia communications has grown at a remarkable rate in recent years. Broadband fixed wireless access systems are expected to play important role in providing broadband Internet access services. This is because they not only provide high-speed access services but can also offer tremendous advantages over wired technologies such as ADSL (Asynchronous Digital Subscriber Line), CATV (Cable TV) and FTTH (Fiber to the Home), in point of their rapid deployment with low-cost infrastructure, high scalability, low maintenance and upgrade costs, and granular investment to match market growth [16] – [18].

Section 2.2 describes millimeter-wave broadband wireless access (MMW BWA) systems. Concept and architecture of multihop mesh-topology broadband entrance networks supporting heterogeneous wireless access services are also clarified in section 2.3.

2.2 Millimeter-Wave Broadband Wireless Access Systems

An explosion in the growth of multimedia communications is tremendously increasing demand, and then has motivated extensive researches in new broadband wireless access services. The IEEE Standard 802.16 has been studied and recently updated to IEEE 802.16-2004 [19] – [22]. Its purpose is to facilitate the optimal use of bandwidth from 10 to 66 GHz, as well as interoperability among devices from different vendors. The emerging worldwide interoperability

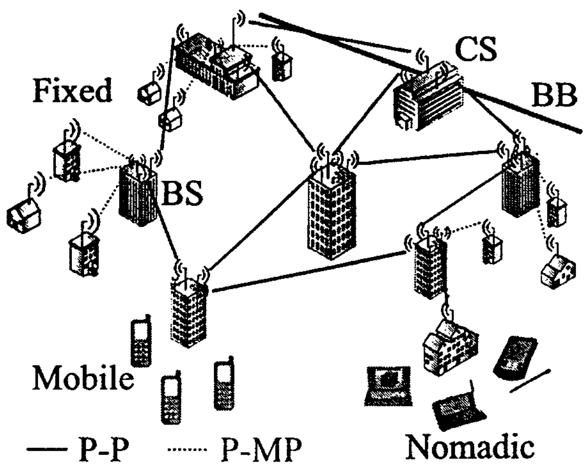


Figure 2.1: Millimeter-wave broadband wireless access system.

for microwave access (WiMax) Forum, formed in 2003, is promoting the commercialization of IEEE 802.16 and the ETSI's HiperMAN (European Telecommunications Standard Institute's High-Performance Radio MAN).

Broadband fixed wireless access (FWA) is expected to play the major role in providing high-speed and flexible services [16] – [17]. Local multipoint distribution service (LMDS) is the broadband fixed wireless access system developed in the U.S. by the Federal Communications Commission (FCC) to provide services in 28 and 31 GHz bands [23]. In Japan, FWA services at present are mainly provided in 22, 26 and 38 GHz bands according to the ARIB (Association of Radio Industries and Businesses) standards of STD-T58 and STD-T59 [24]. References [31] – [36] proposed multihop wireless access systems using MMW and quasi-MMW bands with a mesh configuration.

Moreover, a new FWA system exploiting 32 GHz band has been investigated in order to deal with the rapid growth of demand in multimedia communications for broadband access services by the broadband MMW wireless access group in YRP (Yokosuka Research Park) R&D Committee, and has been called the millimeter-wave broadband wireless access (MMW BWA) system [37] – [39].

As illustrated in Fig. 2.1, this system has a hierarchical network structure of P-MP (Point-to-MultiPoint) access networks for Internet users and P-P (Point-to-Point) mesh-topology entrance network. It has been developed to provide seamless broadband Internet access services for wireless heterogeneous systems including fixed, nomadic and mobile access services as the entrance network connecting base stations (BSs) to a center station (CS) and backbone (BB) networks. The concept of the entrance network is similarly investigated in the radio access network (RAN) for the DECT (Digital Enhanced Cordless Telecommunications) [40] and the 4G mobile communication [41] – [42]. In addition, in order to support the extension of various novel advanced communications, the entrance network should be simple, universal operated and independent of technologies of those systems. Therefore, non-regenerative repeaters are installed at BSs in the entrance network because they only convert the frequency band, i.e., the entrance network deals with those systems in the wireless physical layer [49].

2.3 Broadband Entrance Network Architecture

The architecture of mesh-topology broadband entrance networks is illustrated in Fig. 2.2. Point-to-Point (P-P) links are supplying a high-bandwidth for the broadband entrance network in wireless heterogeneous systems including fixed, nomadic and mobile access services. In addition, with the implementing of links into P-P mesh-topology as the entrance network, system can support high-speed communication in high-level of service coverage, and is also flexible in point of that an adaptive routing can be implemented to avoid rainfall outage or traffic-congested links [26] – [30]. Moreover, the mesh-topology broadband entrance network investigated in this thesis aims at providing bit rate in the order of Gbps at each BS.

At present, the major possible solutions supporting heterogeneous access services are common access protocol based on all-IP networking, overlay network using universal access points (UAPs), and deployment of multimode device, i.e., software defined radio (SDR) [45] – [48]. On the other hand, in this entrance network, non-regenerative repeaters are assumed to be installed at the BSs. This is because the entrance network should deal with heterogeneous systems in the wireless physical layer in order to support the extension of various novel advanced systems with ease, i.e., the entrance network becomes simple, universal operated and independent of technologies.

The use of non-regenerative repeating scheme implies that traffic load is transmitted in the physical wireless layer. From this viewpoint, as shown in Fig. 2.2, this thesis employs the concept of two-plane network [50], composed of the IP-based control plane and the physical wireless layer-based data plane as shown in the generalized multiprotocol label switching (GMPLS) [51]. These two planes are independent from each other. The IP-based control protocol is used to set up communication paths in data plane. As illustrated in Fig. 2.2, the communication paths in data plane are managed to make a route detour to avoid link deteriorated by rainfall. The control plane is responsible for both routing and signaling to support dynamic

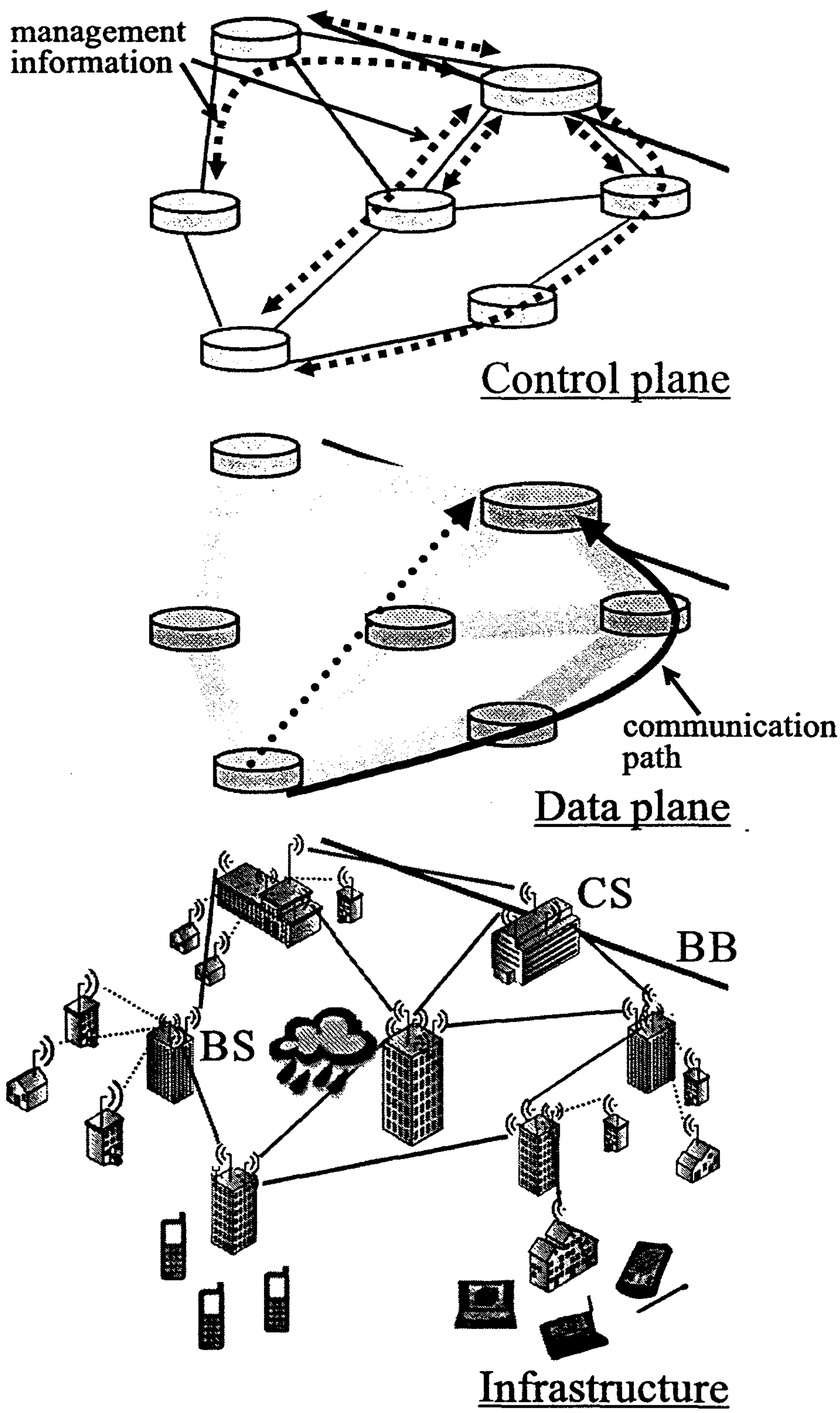


Figure 2.2: Mesh-topology broadband entrance network.

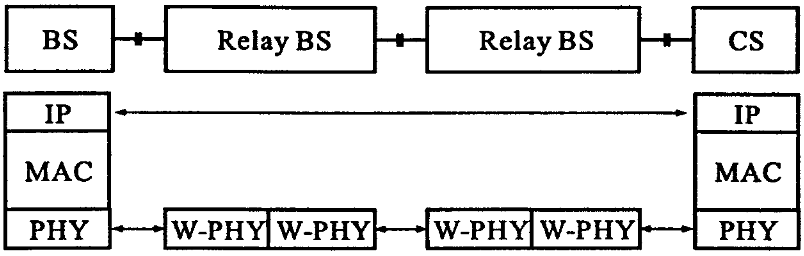


Figure 2.3: Protocol stack for data plane.

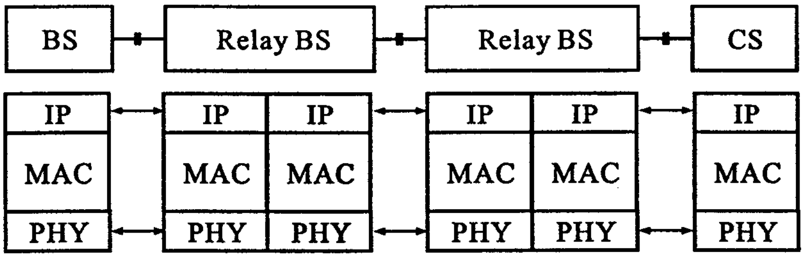


Figure 2.4: Protocol stack for control plane.

provision and restoration of label-forwarding information, and explicit a route for each connection between source and destination in whole networks. Protocol stacks of the data plane and the control plane are respectively shown in Fig. 2.3 and Fig. 2.4.

The path selection is performed centrally by the path manager at CS. The path manager acquires the state including traffic information from each BS by using the routing protocol such as the open shortest path first with traffic engineering extension (OSPF-TE) [52] to generate and receive the opaque link-state advertisements (LSAs) [53]. When the path is discovered, it is assigned as the explicit route, and then the signaling protocol such as the resource reservation protocol with traffic engineering extension (RSVP-TE) [54] – [56] is responsible for establishing a forwarding state and reserving resources along the route.

2.4 Concluding Remarks

This chapter addressed the overview of millimeter-wave broadband wireless access (MMW BWA) systems, and described the architecture of two-plane mesh-topology broadband entrance networks in detail.

Chapter 3

Link Quality-Based Path Selection Scheme

3.1 Introduction

With the deployment of millimeter-wave (MMW) band, system will meet a large available bandwidth and a reduced size of electronic components. However, its quality is severely affected by rainfall [65] – [68], which the rain attenuation characteristic of MMW band is revealed in section 3.2. Hence, unlike wired systems, not only the bandwidth but also the quality of route should be considered. The simple route switching from deteriorated route to backup route with the bit error rate (BER) level monitoring was proposed in [50]. Reference [64] investigated the improvement of availability due to route diversity under rain condition to show the advantage of mesh-topology utilization, but the investigation was simply done in 4-node square mesh network with no consideration of routing. Note that this chapter considers the availability of route as the quality which is derived in section 3.3, and then propose the constraint availability-and-bandwidth shortest path (CABSP) selection algorithm to select the path with the minimum number of hops with abundant availability and bandwidth in section 3.4.

The availability of multihop route under rainfall environment, in this chapter, is defined as the probability that rain attenuation of each hop is below a certain allowable value according to the required carrier-to-noise power ratio (CNR). In the derivation of the availability, as its definition, the use of rain attenuation distribution is necessary. As expounded in [65] – [67], rain attenuation can be approximated statistically well as the Gamma distribution. The bivariate Gamma distribution was derived for 2-hop route in [64]. This chapter theoretically

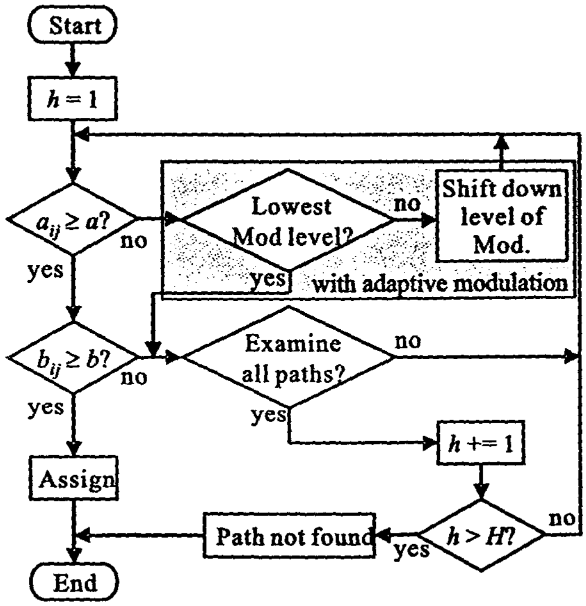


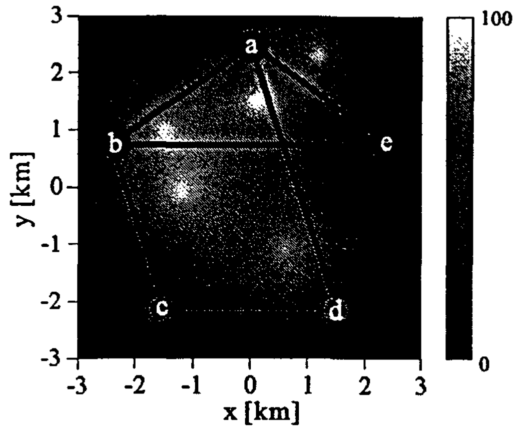
Figure 3.2: Constraint availability-and-bandwidth shortest path selection with adaptive modulation algorithm.

meets the availability requirement a, and it will be assigned as the explicit route if it also meets the bandwidth requirement b. Moreover, in the CABSP-AM algorithm, the class of service is also considered in point of that the error sensitive class needs larger required CNR than the error non-sensitive class, which the threshold of required BER are respectively set as 10^{-8} and 10^{-4}.

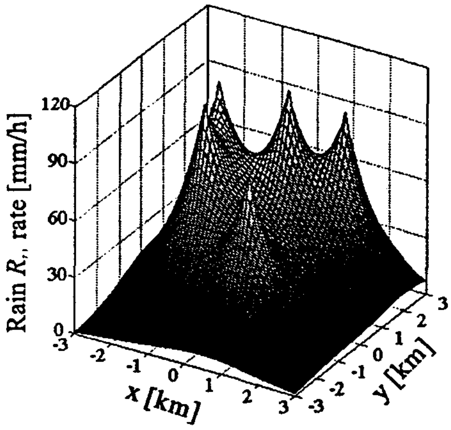
3.5 Performance Evaluations

3.5.1 Analysis Model

The analysis model is illustrated in Fig. 3.3. Four BSs ⓐ – ⓓ and one CS ⓔ each, arranged into pentagonal mesh-topology, are established connections with P-P links using parabolic antennas as the non-regenerative entrance network. Note that, in section 3.3, only the spatial correlations between hops in route were taken into account. However, the spatial correlation between routes should also be considered by way of the use of exponentially-profiled rain cells expounded in [68]. The analysis model is under the assumption of rainfall condition of five exponentially-profiled R_{75} rain cells which each have the same peak rate. Since the



(a) The bird's eyes view.



(b) The R_{75} rate (peak R_{75} rate of 76.5 mm/h).

Figure 3.3: Analysis model.

Table 3.2: Parameters used in calculations.

Carrier frequency	f_c	32 GHz
Bandwidth	B	240 MHz
Transmitted power	P_T	30 dBm
Antenna gain	$G(o)$	42 dBi
Noise figure	NF	8 dB
Atmosphere absorption factor	γ_0	0.11 dB/km
Rain rate parameter	ν	0.005
Spatial correlation parameter	α_{sc}	0.3
Required path availability		0.9999
Required BER (error sensitive, error non-sensitive)		$10^{-8}, 10^{-4}$

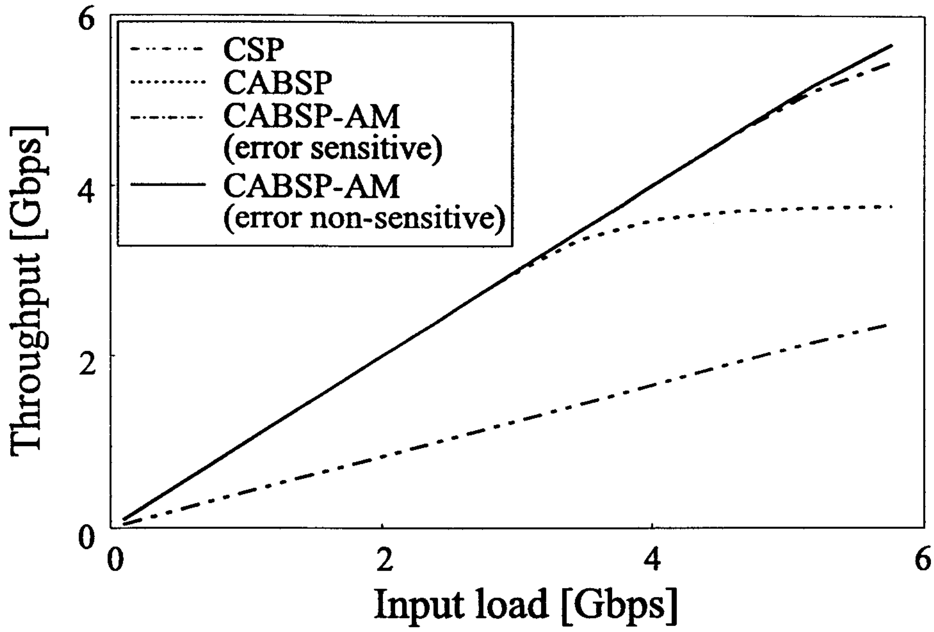
entrance network deploys the P-P MMW links, it is assumed to be the line-of-sight (LOS) under the adaptive white Gaussian noise (AWGN) channel. Table 3.2 lists the parameters used in calculations. Moreover, CSP and CABSP algorithms use fixed modulation level of 256QAM. On the other hand, CABSP-AM algorithm uses adaptive modulation (256/64/16QAM and QPSK).

3.5.2 Throughput Performance versus Input Load

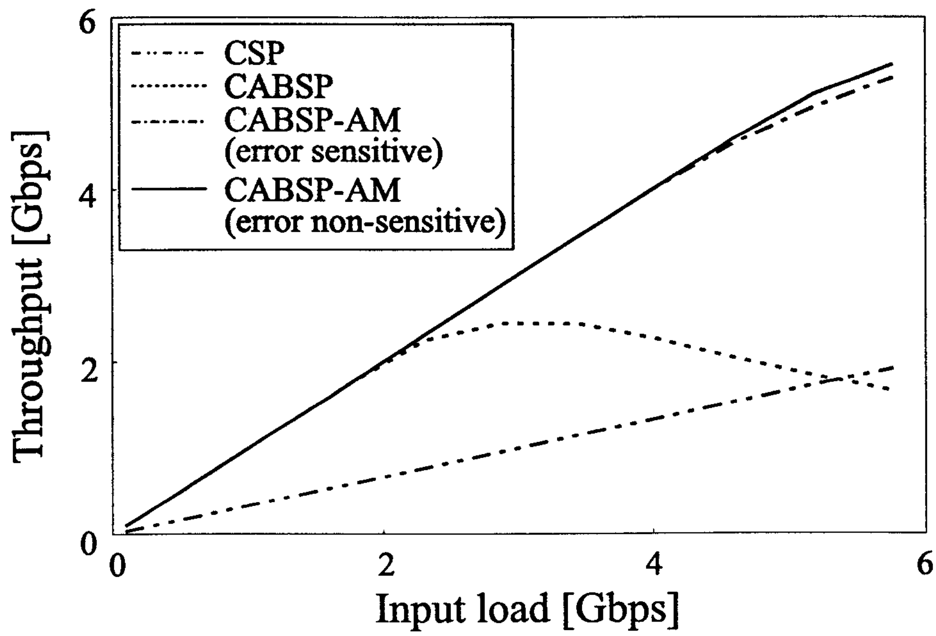
Let us first evaluate throughput performance versus input load in the case of uniform traffic, i.e., $\lambda_i = \lambda$; $\forall i \in \mathbb{BS}$ where $\mathbb{BS}$ is the set of base stations. Note that throughput performance is defined as the successful received traffic rate, considered no impact of processing delay at BSs or retransmission when packet is unsuccessfully received.

Figure 3.4 compares the total network throughput performance among conventional CSP, CABSP and CABSP-AM algorithms, in the case of peak R_{75} rates are 76.5 and 100 mm/h. We can see that the CSP method yields the throughput up to only 2 Gbps because it routes traffic with no regard of link deterioration due to rain. The CABSP method yields higher throughput than the CSP method because it routes traffic avoiding high-loss links. However, the throughput becomes saturated if total traffic load in network exceeds 4 Gbps when peak R_{75} rates is 76.5 mm/h, and first increases and reaches a peak at traffic load of 3 Gbps and then starts to decrease if traffic load increases further when peak R_{75} rates is 100 mm/h. On the other hand, the CABSP-AM method gives 3 Gbps throughput improvement over the CSP method when input load is close to 6 Gbps, and also yields higher throughput than the CABSP method because it makes more efficient use of bandwidth. The throughput improvement by the CABSP-AM method becomes evident when the rain rate increases.

In addition, the throughput performance comparison in the case of non-uniform traffic with condition of $\lambda_i = \lambda$; $\forall i_{i \neq (b)} \in \mathbb{BS}$ and $\lambda_{(b)} = 2\lambda$ is shown in Fig. 3.5. Compared with the case of uniform traffic, it is obvious that throughput performances of both CABSP and CABSP-AM algorithms become worse particularly in the case of peak R_{75} rates is 100 mm/h. When peak R_{75} rates is 100 mm/h, the CABSP method first outperforms the CSP method until input load reaches 4.5 Gbps, and then reversely if input load increases further. On the other hand, when peak R_{75} rates is 76.5 mm/h, the CABSP outperforms the CSP about 2 Gbps even when input load is close to 6 Gbps. In addition, the CABSP-AM algorithm yields higher throughput than other algorithms in both rainfall conditions, and gives about 2–3 Gbps throughput improvement compared to the CSP.

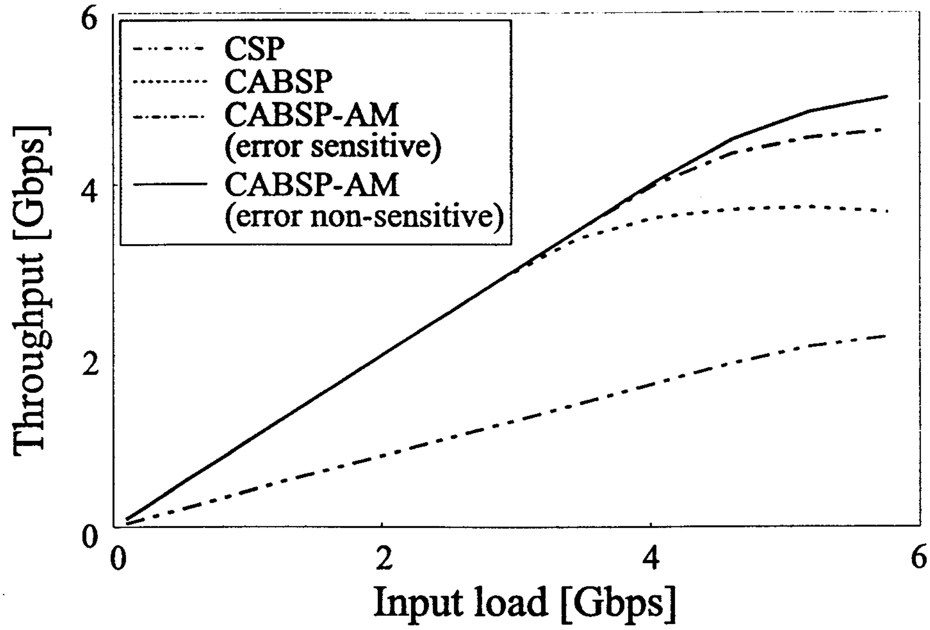


(a) Peak R_{75} rate of 76.5 mm/h.

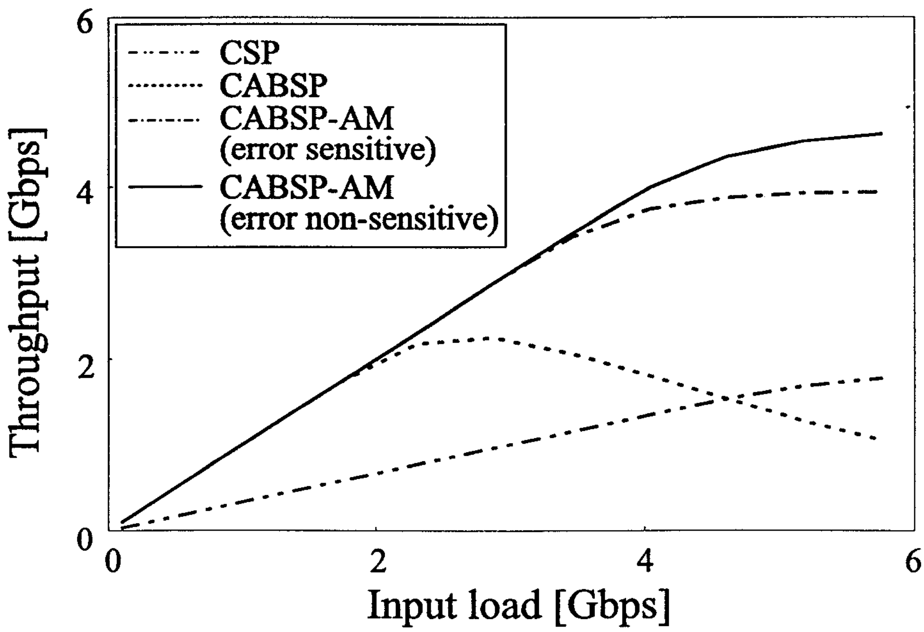


(b) Peak R_{75} rate of 100 mm/h.

Figure 3.4: Throughput performance versus input load (uniform traffic).



(a) Peak R_{75} rate of 76.5 mm/h.



(b) Peak R_{75} rate of 100 mm/h.

Figure 3.5: Throughput performance versus input load (non-uniform traffic).

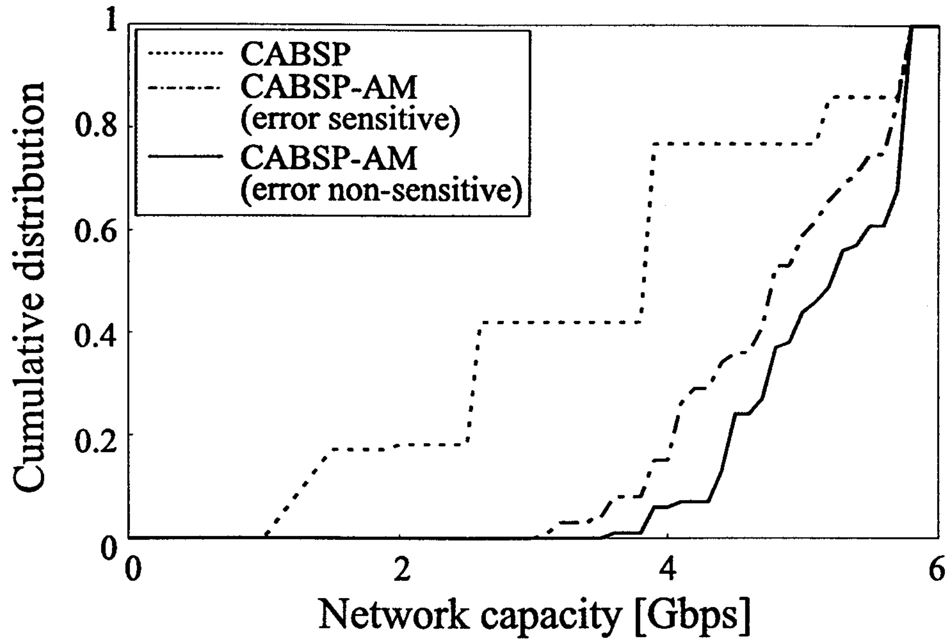


Figure 3.6: Cumulative distribution of network capacity (uniform traffic).

3.5.3 Capacity Performance under Various Rainfall Conditions

In order to assure the superiority of the proposed algorithms, the analysis is done under the various rainfall conditions by randomly locating the peak point of five rain cells which have same peak R_{75} rate of 100 mm/h.

Figure 3.6 shows the cumulative distribution of network capacity. We can see that the CABSP-AM algorithm improves the network capacity compared to the CABSP algorithm. Table 3.3 lists mean and standard deviation σ of the network capacity. The CABSP-AM algorithm can improve the network capacity in case of error sensitive class and error non-sensitive class over that of the CABSP algorithm about 1.38 and 1.48 fold, respectively. The less σ value when using the CABSP-AM algorithm indicates the smaller impact of rainfall fluctuations.

Figure 3.7 shows the cumulative distribution of network capacity in the case of non-uniform traffic ($\lambda_i = \lambda$; $\forall i_{i \neq \textcircled{b}} \in \mathbb{BS}$ and $\lambda_{\textcircled{b}} = 2\lambda$). The results assure the superiority of the CABSP-AM algorithm in point of that it is efficient even in the non-uniform traffic conditions. Table 3.4 lists mean and standard deviation σ of the network capacity. The CABSP-AM algorithm can improve the network capacity in case of error sensitive class and error non-sensitive class over that of the CABSP algorithm about 1.36 and 1.48 fold respectively.

Table 3.3: Network capacity (uniform traffic).

Scheme	Mean [Gbps]	σ [Gbps]
CABSP	3.46	1.44
CABSP-AM (error sensitive)	4.79	0.75
CABSP-AM (error non-sensitive)	5.12	0.62

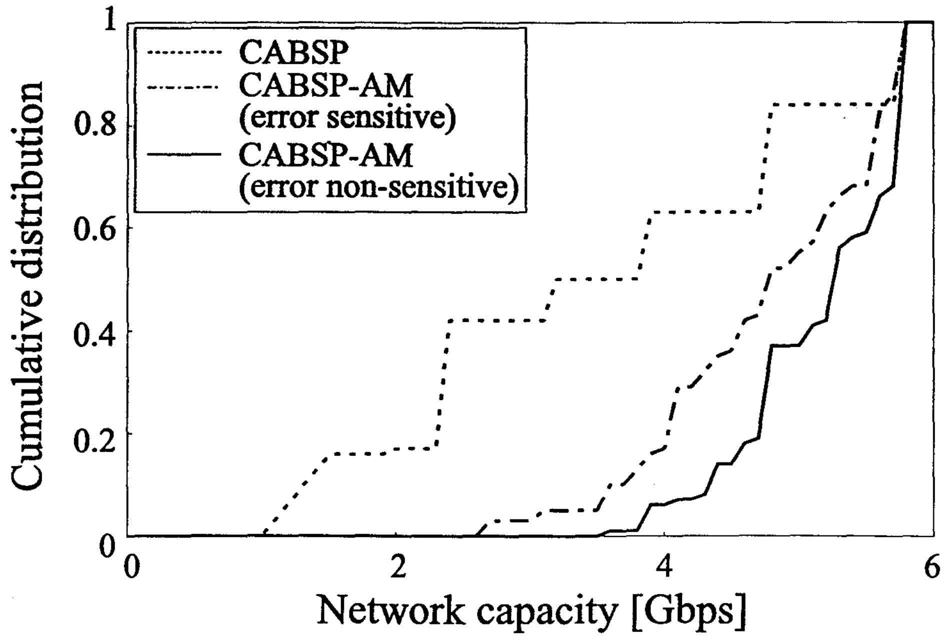


Figure 3.7: Cumulative distribution of network capacity (non-uniform traffic).

Table 3.4: Network capacity (non-uniform traffic).

Scheme	Mean [Gbps]	σ [Gbps]
CABSP	3.50	1.55
CABSP-AM (error sensitive)	4.76	0.84
CABSP-AM (error non-sensitive)	5.16	0.60

3.6 Concluding Remarks

This chapter proposed the CABSP selection algorithm for mesh-topology MMW broadband entrance networks. The CABSP selection algorithm was proposed to taking account of not only traffic load but also quality of MMW radio link severely deteriorated by rainfall. Moreover, the CABSP selection algorithm was enhanced by addition of adaptive modulation, and then called the CABSP-AM selection algorithm to further make more efficient use of bandwidth resources with consideration of the QoS requirement of each class of service in multimedia communications.

Theoretical evaluations showed that the CABSP selection algorithm yields the improvement of throughput performance over the conventional CSP selection algorithm except in the case of heavy traffic load under heavy rainfall environment. It was also shown that the CABSP-AM selection algorithm gives the quite good throughput performance which improves throughput about 2–3 Gbps over the CSP selection algorithm when input load is close to 6 Gbps.

In addition, the cumulative distribution of network capacity under various rainfall conditions indicated that the CABSP-AM selection algorithm makes the superiority over the CABSP selection algorithm about 1.36 and 1.48 fold respectively in cases of error sensitive class and error non-sensitive class.

Chapter 4

Dynamic Resource Assignment Scheme

4.1 Introduction

Compared to systems using single-carrier format, systems using multi-carrier format can provide more efficient frequency resource usage and more robust to the traffic fluctuation when using the appropriate frequency channel assignment. Therefore, this chapter proposes the dynamic resource assignment (DRA) scheme performing the radio path allocation and the frequency channel assignment in section 4.2. The radio path allocation performs the traffic load distribution selecting appropriate paths and the adaptive modulation compensating rain attenuation, and finally determines how many frequency channels are necessary for each radio link. Next, the frequency channel assignment is deployed to assign a particular set of frequency channels to each radio link. The frequency channel assignment in mesh-topology wireless network was studied in [31] – [36]. References [31] – [35] performed the assignment in autonomous and decentralized manner, which each BS selects its own channels based on the radio statements made in a limited area surrounding the BS and then cause the non-optimum channel assignment. Reference [36] proposed the channel assignment in centralized control manner by using the simulated annealing algorithm, and simply evaluated the performance in tree-topology network.

This chapter proposes the sub-optimum frequency channel assignment (FCA) in mesh-topology multi-carrier wireless entrance networks with the centralized control manner applying the linear programming (LP) method. References [83] – [86] studied the channel allocation based on the LP method [81] in the multiuser OFDM (Orthogonal Frequency Division Multiplexing) system which the BS receives the downlink channel information from all users, and using this information to assign a set of subcarrriers (channels) to each user. It is assumed that the reuse of subcarrier by different users is not allowed. Unlike systems in [83] – [86], in mesh-topology entrance networks, the share of a channel between different radio links is permitted with taking account of interference level. That is, if the number of required frequency channels is more than the number of total frequency channels in network, it is preferable that the channel should be reused between little interfered radio links. In addition, in the proposed sub-optimum FCA, the frequency channels are partitioned for each assignment round not more than the number of total frequency channels in network. The LP-based assignment tries to maximize the throughput in each assignment round considering no effect of posterior assignment round.

4.2 Dynamic Resource Assignment

In the dynamic resource assignment, traffic should be distributed into suitable radio paths. Next, the necessary frequency channels for each P-P link are determined, and then assigned appropriately.

4.2.1 Radio Path Allocation

With the deployment of the MMW, the deterioration of radio link quality according to rainfall becomes a large problem. First, in any radio link employing adaptive modulation, when the rain falls, the modulation level should be shifted down to maintain the bit error rate performance of radio link. However, when shifting down the modulation level, it requires more frequency channels to maintain the same bit rate, thus it may cause more interference to other links, and then limit the error rate performance especially in the case of heavy traffic load.

Second, the routing considering traffic load distribution should be performed to maximize the frequency utilization efficiency in network. Since there are rainfall condition variation and traffic load variation according to multimedia communications, the use of the simple shortest path first (SPF) routing algorithm cannot guarantee the performance because it computes the path obliviously to the loading of each link, thus it may easily cause the traffic congestion on some links.

Therefore, in order to perform traffic load distribution efficiently, we propose the minimum flow shortest path (MSP) selection algorithm. The traffic flow metric of path is defined as the maximum amount of traffic of all links belonging to that path. The path with the minimum traffic flow metric will be selected. If there are multiple paths with the same traffic flow metric, Step 1: Initially, $L = \{a\}$, $D_i = \lambda_{ai}$ and $H_i = h_{ai}$ for all $i \neq a$

Step 2: Find set $K \notin L$ so that $D_K = \min_{i \notin L} D_i$

Step 3: If K has more than one element,

find $k \in K$ so that $H_k = \min_{i \in K} H_i$,

$L := L \cup \{k\}$

If L contains node m, a path is found and the algorithm terminates

Step 4: For all $i \notin L$, set $D_i := \min[D_i, \max(D_k, \lambda_{ki})]$

Step 5: Go to Step 2.

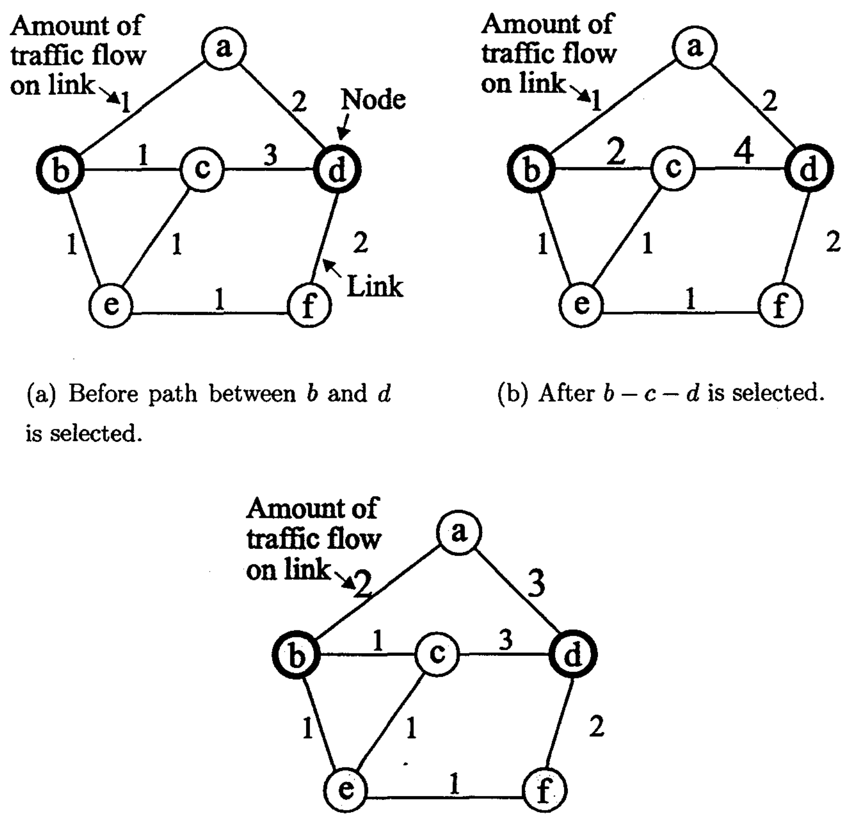
Figure 4.1: Minimum flow shortest path selection algorithm.

the shortest path with minimum number of hops will be selected. Notice that, the residual capacity is conventionally used as the cost metric in the path selection algorithm. However, in the dynamic resource assignment, the capacity of each radio link is not fixed and yet decided hence we use the amount of current traffic flow as the cost metric in the path selection.

Let us consider a graph $G = (N, A)$ with number of nodes N and number of links A. The λ_{ij} denotes the amount of current traffic flow on link (i, j). Given any path $p = (a, b, c, ..., l, m)$ whose source node is a and destination node is m, the traffic flow metric is defined as $\lambda_p = \max(\lambda_{ab}, \lambda_{bc}, ..., \lambda_{lm})$, and the number of hops is defined as H_p. The MSP algorithm performs the path selection as shown in Fig. 4.1. Let D_i and H_i be the estimated traffic flow metric and number of hops of path form node a to node i. L denotes a set of nodes belonging to the path. Step 2 finds all paths with minimum amount of current traffic flow. If there are more than one path found, Step 3 chooses the one with minimum number of hops.

For example, let us consider the connection request of traffic flow between b and d in the topology shown in Fig. 4.2. We assume that numbers illustrated in Fig. 4.2 denote the amount of traffic flow [Mbps] on each link (λ_{ij}). Before the path between b and d is selected, the amount of current traffic flow is indicated as illustrated in Fig. 4.2(a). Moreover, the request traffic flow between b and d is assumed to be 1 Mbps in this example. By applying the SPF, paths with minimum hops, i.e., (b, a, d) and (b, c, d), become the candidates, and then one of these 2 paths is randomly selected. If the path (b, c, d) is selected, the traffic load will congest on link cd as shown in Fig. 4.2(b). On the other hand, by applying the MSP, the path (b, a, d) will be selected and then the amount of traffic flow on each link becomes as shown in Fig. 4.2(c).

Finally, the necessary frequency channels for each P-P link are determined.



(a) Before path between b and d is selected.

(b) After $b - c - d$ is selected.

(c) After $b - a - d$ is selected.

Figure 4.2: Path selection example topology.

4.2.2 Frequency Channel Assignment

Sub-optimum Assignment

In this chapter, we proposes the sub-optimum frequency channel assignment (FCA) applying the linear programming (LP) method [81] to assign a particular set of frequency channels (subcarriers) to each link.

Let us first define the parameters as follows:

N_f : Number of total frequency channels in network,

N_t : Number of frequency channels, i.e., traffic slots, required by all radio links in network,

N_s : Number of assigned frequency channels in any assignment round,

N_{ra} : Number of remaining assigned traffic slots.

All frequency channels (N_t) are not assigned at a time, but will be partitioned to not more than the number of total frequency channels (N_f) in each assignment round. Note that, in this proposed sub-optimum FCA, the LP-based assignment tries to maximize the throughput in each assignment round considering no effect of posterior assignment round.

In the LP-based channel allocation in the multiuser OFDM system, different users are not allowed to use the same subcarrier [83] – [86]. On the other hand, in the mesh-topology entrance network, the reuse of a channel between different radio links is permitted if mutual-interference level is low. That is, if the number of the required frequency channels exceeds the number of total frequency channels in network, it is preferable that the channel should be reused between little interfered radio links. Moreover, the frequency channel must be assigned so that two paths that use a same physical radio link never use the same frequency channel on that radio link.

The proposed sub-optimum FCA is performed as detailed in the flowchart shown in Fig. 4.3. When the number of required traffic slots N_t is equal or less than the number of total frequency channels N_f, the frequency channel assignment can be done simply because there are enough frequency channels to assign one by one with no concern of any interference. On the other hand, when the N_t is more than N_f, there is the share of some channels between the different radio links, hence the appropriate frequency channel assignment taking account of the interference should be considered.

At the beginning, the number of remaining assigned traffic slots N_{ra} is set to be the N_t. The N_f frequency channels are randomly assigned with no concern of any interference to the first N_f traffic slots. Note that this algorithm gives the priority of assignment to the slots of link that has more probability to interfere other radio links, i.e., the farther link from the CS has more priority to be assigned in the case of uplink communication. Since the N_f channels are assigned, the N_{ra} is subtracted by N_f. After that, if the N_{ra} is still more than the N_f, only the N_f slots can be assigned based on the LP method considering the interference to maximize the total throughput in this assignment round, and the N_{ra} is subtracted by N_f. after the assignment in this round. On the other hand, if N_{ra} is less than the N_f, all the remaining N_{ra} slots can be assigned at once, based on the LP method. As mentioned above, we perceive that the number of assigned frequency channels in any assignment round N_s can be written as $\min(N_f, N_{ra})$. The assignment is performed until all traffic slots are assigned, i.e., $N_{ra} = 0$.

Next, we describe the details of the LP-based FCA method in any assignment round. Let us define $c_{i,j}$ as the indicator of allocating the jth frequency channel to the ith traffic slot. The indicator $c_{i,j}$ is expressed as

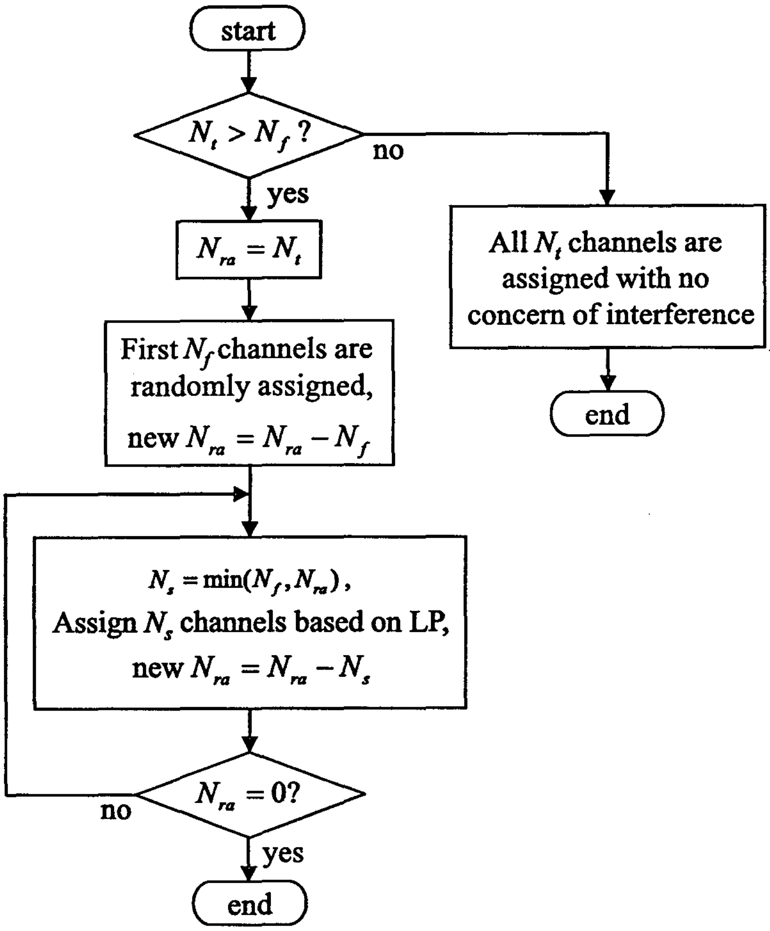


Figure 4.3: Sub-optimum frequency channel assignment algorithm.

$$c_{i,j} = \begin{cases} 1, & \text{if the } j\text{th frequency channel is assigned to the } i\text{th traffic slot,} \\ & i = 1, 2, ..., N_s,\ j = 1, 2, ..., N_f \\ 0, & \text{otherwise} \end{cases} \quad . \tag{4.1}$$

The $r_{i,j}$ denotes the throughput normalized by channel bandwidth [bps/Hz], i.e., the frequency utilization efficiency, of the ith traffic slot using the jth frequency channel, and is defined as

$$r_{i,j} = (log_2 M) \cdot (1 - PER_{i,j}) \ , \tag{4.2}$$

$$PER_{i,j} = 1 - \sum_{k=0}^{l_m} \binom{l_p}{k} \cdot (BER_{i,j})^k \cdot (1 - BER_{i,j})^{l_p - k} \ , \tag{4.3}$$

$$BER_{i,j} = \frac{2}{log_2 M} \cdot \left(1 - \frac{1}{\sqrt{M}}\right) \cdot \text{erfc}\left(\sqrt{\frac{3 \cdot \gamma_{i,j}}{2 \cdot (M-1)}}\right) \ , \tag{4.4}$$

where $PER_{i,j}$ and $BER_{i,j}$ respectively denote the packet error rate and bit error rate of case the ith traffic slot using the jth frequency channel, M is the level of modulation (M-ary quadrature amplitude modulation, M-QAM), l_p is the packet length, l_m is the maximum tolerable error bits in packet, erfc(.) is the complementary error function, and $\gamma_{i,j}$ is the carrier-to-noise-plus-interference power ratio (CNIR) of the ith traffic slot using the jth frequency channel. Note that the antenna used in our system is the directional rectangular horn with the antenna front-to-back ratio of α_{fb}.

The FCA problem can be formulated as follows:

Find a set of $c_{i,j}$ to maximize

$$\sum_{j=1}^{N_f} \sum_{i=1}^{N_s} r_{i,j} \cdot c_{i,j} \ , \tag{4.5}$$

subject to

$$\sum_{j=1}^{N_f} c_{i,j} = 1 \quad \forall i \in \{1, ..., N_s\} \ , \tag{4.6}$$

$$\sum_{i=1}^{N_s} c_{i,j} \leq 1 \quad \forall j \in \{1, ..., N_f\} \ , \tag{4.7}$$

where N_s is the number of assigned traffic slots in any assignment round, and is equal or less than N_f. The constraint (4.6) ensures that the one frequency channel is assigned to each traffic slot, and the constraint (4.7) ensures that each frequency channel can be assigned to only one traffic slot in any assignment round.

After the problem is solved, we obtain the allocation indicator matrix $\mathbf{C}$ which has entries of 0 and 1, and dimension of $[N_s \times N_f]$.

For example, as illustrated in Fig. 4.4, consider the 6 frequency channels network ($N_f = 6; j = 1, 2, ..., 6$), where the number of frequency channels (traffic slots) required by all radio

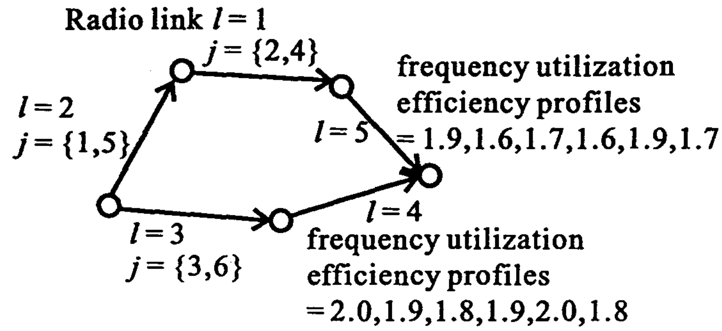


Figure 4.4: Frequency channel assignment example topology.

links in network N_t is 10 (5 links which requires 2 frequency channels each). Assume the first 6 frequency channels are assigned to the first 3 links ($l = 1, 2, 3$) as (2, 4), (1, 5), (3, 6), and then the remaining assigned traffic slots $N_{ra} = 10 - 6 = 4$. Hence in the next LP-based assignment round, the $N_s = min(6, 4) = 4$ slots will be assigned. After the assignment to first 3 links, the assigned frequency channels yield that the frequency utilization efficiency profiles of the fourth link ($l = 4$) are 2.0, 1.9, 1.8, 1.9, 2.0 and 1.8 bps/Hz, respectively to the frequency channels $j = 1, 2, ..., 6$. On the other hand, the frequency utilization efficiency profiles of the fifth link ($l = 5$) are 1.9, 1.6, 1.7, 1.6, 1.9 and 1.7 bps/Hz, respectively to the frequency channels $j = 1, 2, ..., 6$.

Since each link requires 2 frequency channels for its own, the frequency utilization efficiency profiles of each link are duplicated to form the matrix $\mathbf{R}$ whose entries are the frequency utilization efficiency profiles, $r_{i,j}$, as

$$\mathbf{R} = \begin{bmatrix} 2.0 & 1.9 & 1.8 & 1.9 & 2.0 & 1.8 \\ 2.0 & 1.9 & 1.8 & 1.9 & 2.0 & 1.8 \\ 1.9 & 1.6 & 1.7 & 1.6 & 1.9 & 1.7 \\ 1.9 & 1.6 & 1.7 & 1.6 & 1.9 & 1.7 \end{bmatrix}. \tag{4.8}$$

By using Eqs. (4.5)–(4.7), the allocation indicator matrix is solved, and then becomes

$$\mathbf{C} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}. \tag{4.9}$$

So we can perceive that the frequency channel assignment in this example is that the fourth link uses frequency channels $j = 2$ and $j = 4$, and the fifth link uses frequency channels $j = 1$ and $j = 5$.

Random Assignment

This conventional random FCA assigns a particular set of frequency channels (subcarriers) to each link independently. This algorithm is simple and requires a little computational complexity, but yields strong interference.

Idealized Optimum Assignment

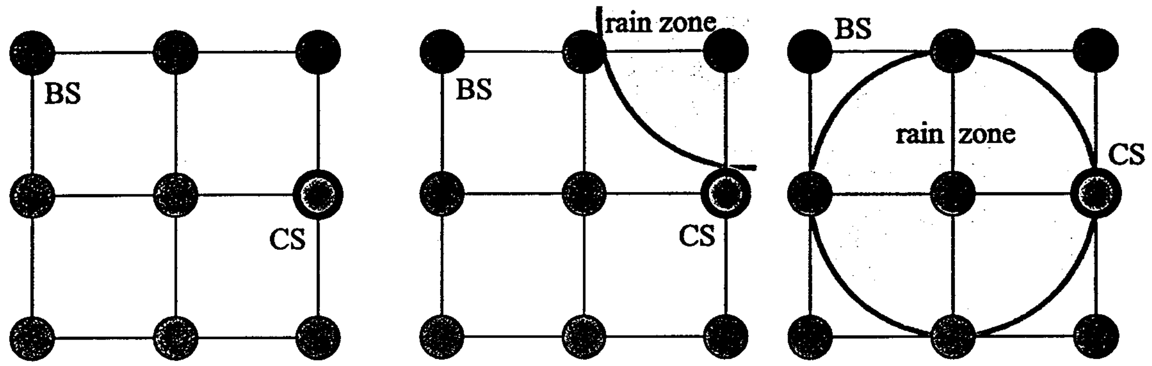
In order to examine the performance of the proposed sub-optimum assignment, it will be compared to the idealized optimum assignment. Unlike the sub-optimum assignment, the idealized optimum assignment performs the frequency channel assignment for all N_t channels at a time. Moreover, it is assumed that in the case of the idealized optimum assignment, the antenna beamwidth is close to 0°. Moreover, the α_{fb} is set to be ∞.

4.3 Performance Evaluations

4.3.1 Analysis Model

The analysis model is illustrated in Fig. 4.5. Eight base stations (BSs) and one center station (CS) each, arranged into the 3×3 square mesh-topology, are established connections with the 3 km length P-P links using parabolic antennas as the non-regenerative wireless entrance network, and are under the line-of-sight (LOS) and the adaptive white Gaussian noise (AWGN) environments. This square mesh-topology is considered in order to evaluate the performance in the severe interference condition. Assume the network in Fig. 4.5(a) is under the fine weather condition, the network in Fig. 4.5(b) is under the rainfall condition I (rain falls at the upper right corner of network), and the network in Fig. 4.5(c) is under the rainfall condition II (rain falls at the center of network).

The rain rate in the rain zone is assumed to be the heavy flat rate of 45 mm/h. This causes the rain attenuation of 10 dB/km by using the calculation from power-law relationship of ITU-R recommendation [70]. The specific rain attenuation $\gamma = k \cdot R^{\alpha}$ [dB/km] where R is the rain rate in mm/h, $k = 0.221$ and $\alpha = 1.003$ for 32 GHz band [87]. Table 4.1 lists the parameters used in the calculations.



(a) Fine weather condition. (b) Rainfall condition I. (c) Rainfall condition II.

Figure 4.5: Analysis model.

Note that we use two models of parabolic antenna, which have the same value of antenna gain of 42 dBi, but different values of antenna front-to-back ratio α_{fb} (15 and 30 dB), to simply compare performances between two different interference conditions depending on only value of α_{fb}. In practical, however, a parabolic antenna whose α_{fb} is 15 dB has antenna gain much less than 42 dBi, and thus results will different from those of case using parameters shown in table 4.1.

Nevertheless, for example, in the case of using parabolic antenna whose α_{fb} is 15 dB and antenna gain is 28 dBi, the adjustment of P-P links distance from 3 km to 1 km, and maximum transmitted power from 30 dBm to 28 dBm will gives the same results as those of case using parabolic antenna whose α_{fb} is 15 dB and antenna gain is 42 dBi, as illustrated in subsection 4.3.2 and subsection 4.3.3.

Let us define throughput performance as the successful received traffic rate. If the number of error bits of the received packet, whose length is 1500 Bytes (l_p), is no more than 2 bits (l_m), it will be successfully received, and unsuccessfully received in otherwise. Moreover, neither impact of processing delay at BSs nor retransmission when packet is unsuccessfully received is considered.

4.3.2 Throughput Performance versus Input Load

Let us first evaluate throughput performance versus input load in the case of uniform traffic and the number of total frequency channels N_f of 36.

The throughput performance of case using the proposed sub-optimum FCA with adaptive

Table 4.1: Parameters used in calculations.

Carrier frequency	f_c	32 GHz
Bandwidth	BW	720 MHz
Number of total frequency channels (Channel bandwidth)	N_f (B_f)	12 (60 MHz), 24 (30 MHz), 36 (20 MHz), 48 (15 MHz)
Max. transmitted power	P_T	30 dBm
Antenna gain	$G(o)$	42 dBi
Antenna front-to-back ratio	α_{fb}	15, 30 dB
Noise figure	NF	8 dB
Atmosphere absorption factor	γ_0	0.11 dB/km
Modulation format		QPSK, 16QAM, 64QAM, 256QAM
Packet length	l_p	1500 Bytes
Max. tolerable error bits in packet	l_m	2 bits

modulation is compared to that of the conventional scheme using random FCA. Note that these two schemes apply the MSP routing algorithm. Moreover, we classify the conventional scheme into two schemes as whether using adaptive modulation or not. In the former scheme, the adaptive modulation is applied. Meanwhile, in the latter scheme, the fixed modulation is applied. Note that modulation levels used in adaptive modulation are 256/64/16QAM and QPSK formats, and will be selected based on the CNR level comparing to the threshold CNR achieving the BER of 10^{-4} with margin of 1 dB. On the other hand, the modulation used in the latter conventional scheme is fixed as 256QAM format. Only in the case of fine weather condition, the impact of adaptive modulation will not appeared because the maximum level of modulation of 256QAM format will be used in this fine weather condition. In addition, the throughput performance of the idealized optimum is also compared to above-mentioned schemes.

The relationships between total network throughput performance versus total input load in network under fine weather condition, rainfall condition I and rainfall condition II are respectively shown in Figs. 4.6–4.8.

From Fig. 4.6, it is obvious that when the antenna front-to-back ratio α_{fb} is 15 dB, throughput of the random FCA scheme becomes saturated if input load exceeds 4 Gbps. Meanwhile,

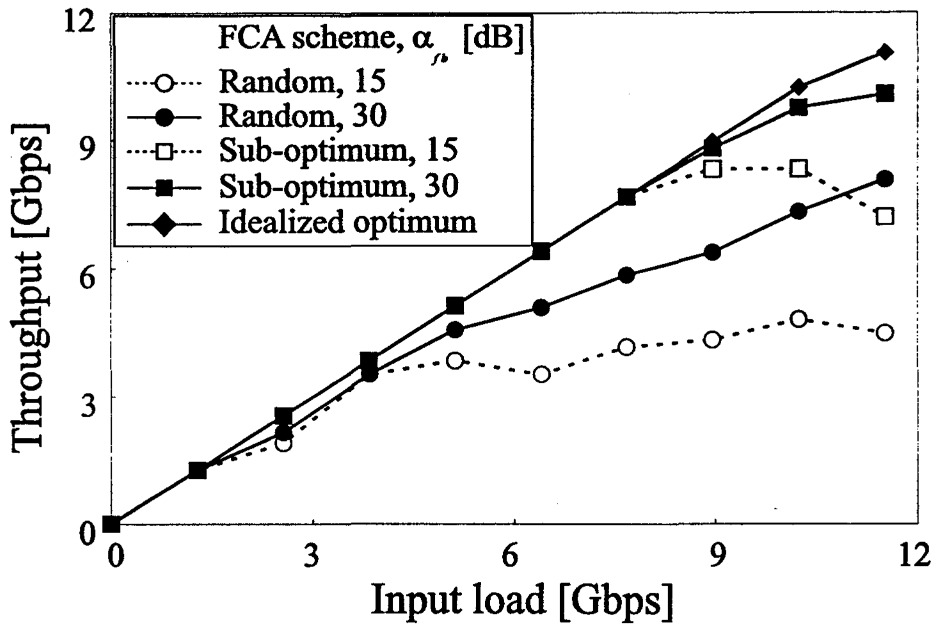


Figure 4.6: Throughput performance versus input load under fine weather condition.

throughput of the proposed sub-optimum FCA scheme first increases and reaches a peak at input load of 9 Gbps and then starts to decrease a little if input load increases further. On the other hand, when α_{fb} is 30 dB, we can see that the random FCA scheme offers quite good throughput, but less than that of the proposed sub-optimum FCA scheme. In addition, we can see that the proposed sub-optimum FCA scheme yields almost the same throughput performance as that of the idealized optimum.

Comparing to the case of α_{fb} of 30 dB, the case of α_{fb} of 15 dB is under more severe interference condition because the one radio wave is more affected by the inverse direction propagated interference wave. When input load becomes more than 9 Gbps, the number of frequency channels required by all radio links in network becomes larger then causes lots of interference. With the use of the antenna with the α_{fb} of 15 dB, the interference condition becomes more severe then the received packet tends to be more unsuccessfully received. Hence throughput degradation becomes appeared. On the other hand, the use of the antenna with the α_{fb} of 30 dB can alleviate the effect of interference even when input load becomes more than 9 Gbps.

From Fig. 4.7, in the case of rainfall condition I, when α_{fb} is 15 dB it is clear that the random FCA using fixed modulation and the random FCA using adaptive modulation schemes yield almost the same throughput. This is because although the adaptive modulation in the

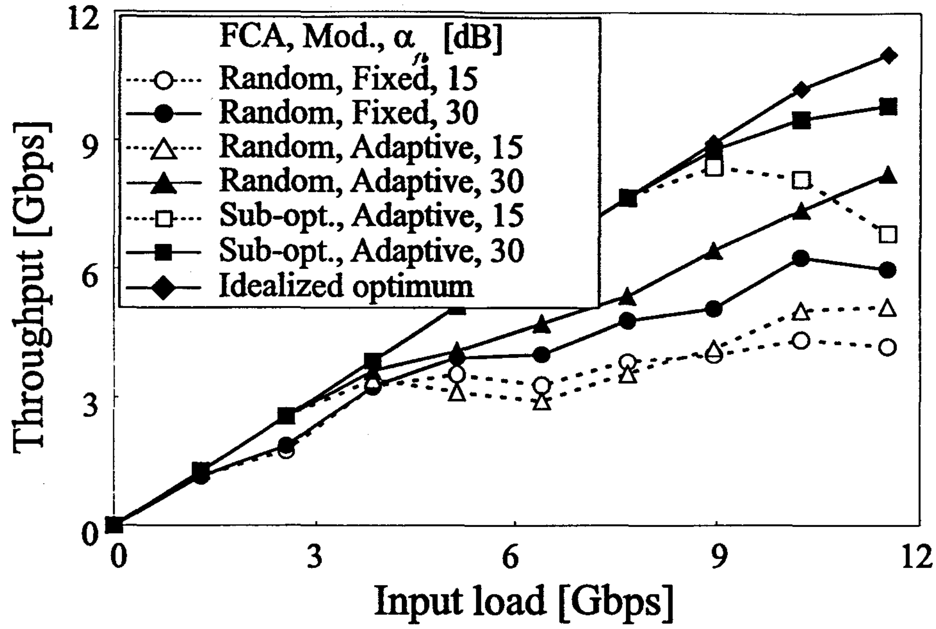


Figure 4.7: Throughput performance versus input load under rainfall condition I.

latter scheme is expected to improve the throughput performance, but it also leads a more number of frequency channels to maintain the same traffic bit rate. Hence it causes more severe interference condition especially in this case of α_{fb} of 15 dB, and thus the throughput improvement becomes insignificant. We also observed that the proposed sub-optimum FCA with adaptive modulation scheme outperforms both random FCA schemes. Moreover, when input load exceeds 9 Gbps, the throughput degradation of the proposed scheme in this rainfall condition I is more evident than the case of fine weather condition.

In contrast, when α_{fb} is 30 dB, the random FCA with fixed modulation scheme yields the throughput degradation in the rainfall condition I compared to the fine weather condition. This is because the radio link quality is deteriorated by rain attenuation. Moreover, it is obvious that the random FCA with adaptive modulation scheme yields a little improved throughput compared to that of the random FCA with fixed modulation scheme because of a more link margin obtained by using adaptive modulation. However, it quite degrades the throughput when compared to the proposed scheme.

From Fig. 4.8, in the case of rainfall condition II, it is clear that the random FCA using fixed modulation and the random FCA using adaptive modulation schemes yield almost the same throughput in both cases of α_{fb} of 15 and 30 dB. We can see that, when α_{fb} is 30 dB, the random FCA with fixed modulation scheme gives the better throughput in the rainfall condition II

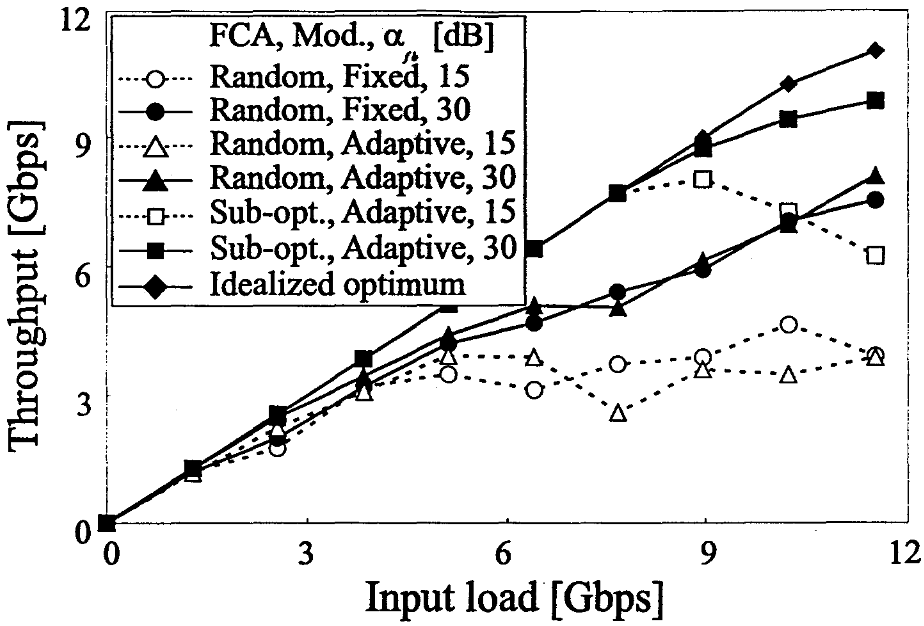


Figure 4.8: Throughput performance versus input load under rainfall condition II.

compared to the rainfall condition I. This is because the rain falls at the center of network then interference becomes weak, and thus the throughput becomes a little degraded when compared to the fine weather condition. On the other hand, the random FCA with adaptive modulation scheme yields a little degraded throughput in the rainfall condition II compared to the fine weather condition, which is almost the same as that of the random FCA with fixed modulation scheme. In addition, the proposed sub-optimum FCA with adaptive modulation scheme more outperforms the both random FCA schemes as the input load increases, except when α_{fb} is 15 dB and input load exceeds 9 Gbps. Moreover, we can see that when input load exceeds 9 Gbps, the throughput degradation of the proposed scheme compared to the idealized optimum in the rainfall condition II is more than that in the fine weather condition.

4.3.3 Throughput Performance versus Number of Total Frequency Channels

Next, we evaluate total network throughput performance versus number of total frequency channels, N_f, when using the proposed DRA scheme. In the proposed DRA scheme, MSP routing algorithm, sub-optimum FCA and adaptive modulation are used. The results under fine weather condition, rainfall condition I and rainfall condition II are respectively shown in

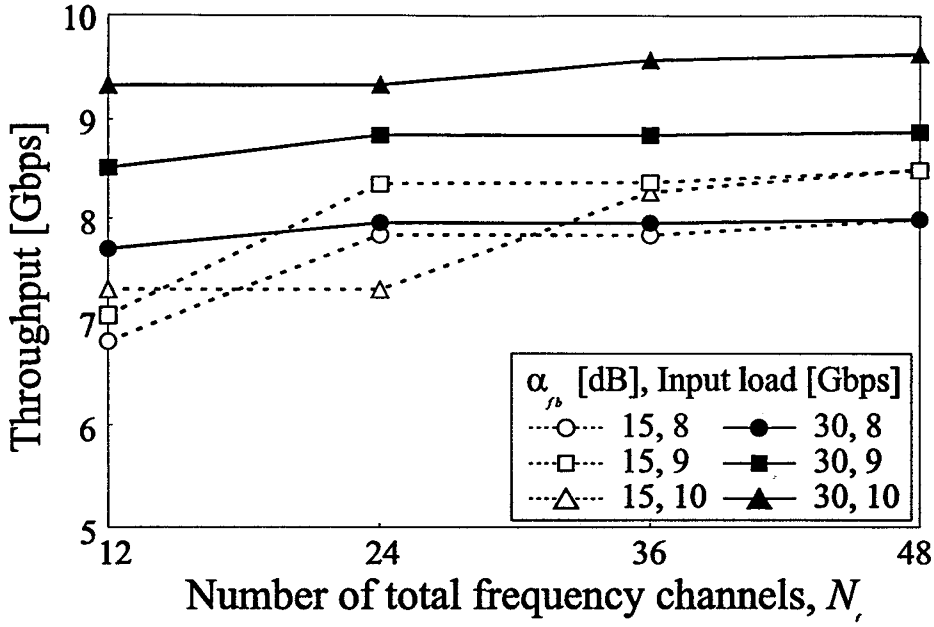


Figure 4.9: Throughput performance versus number of total frequency channels under fine weather condition.

Figs. 4.9–4.11.

It is clear that when α_{fb} is 15 dB, the throughput performance is dependent on number of total frequency channels, N_f, and weather condition. In the case of fine weather condition, the N_f of 12 and 24 yield the degraded throughput performance since interference becomes larger as decreasing the N_f. Meanwhile, in the case of rainfall condition I and rainfall condition II, the N_f of 36 yields the best throughput performance compared to the other cases of N_f (12, 24 and 48) when input load is more than 9 Gbps. This is because when N_f is 48, traffic load was distributed then causing lots of inverse direction propagated waves. Hence, we obtained the results opposite to those we have intended. In contrast, when α_{fb} is 30 dB, since the effect of interference can be well mitigated, the throughput performance is almost the same in all cases of N_f and weather condition.

Therefore, we can perceive that the proposed DRA scheme can guarantee the throughput performance even in the case of α_{fb} of 15 dB when N_f is 36 and input load is less than 9 Gbps.

Next, performance evaluations are done in the case of non-uniform traffic and α_{fb} of 15 dB, where input load of each BS is generated randomly between 1 to 1.25 Gbps. Note that the average total input load of network becomes 9 Gbps. Figure 4.12 shows the results evaluated under various weather conditions. It is obvious that the throughput performance is almost

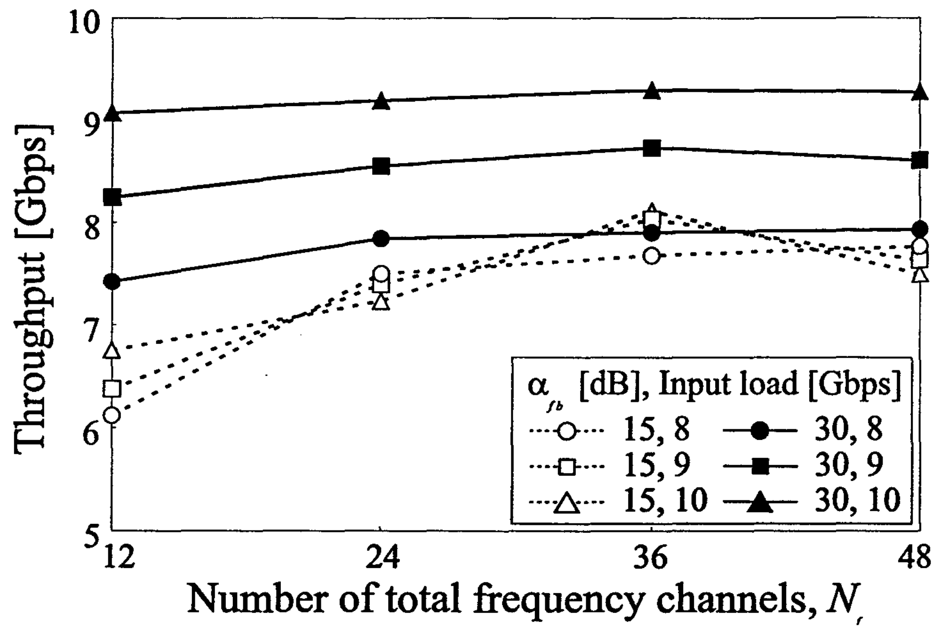


Figure 4.10: Throughput performance versus number of total frequency channels under rainfall condition I.

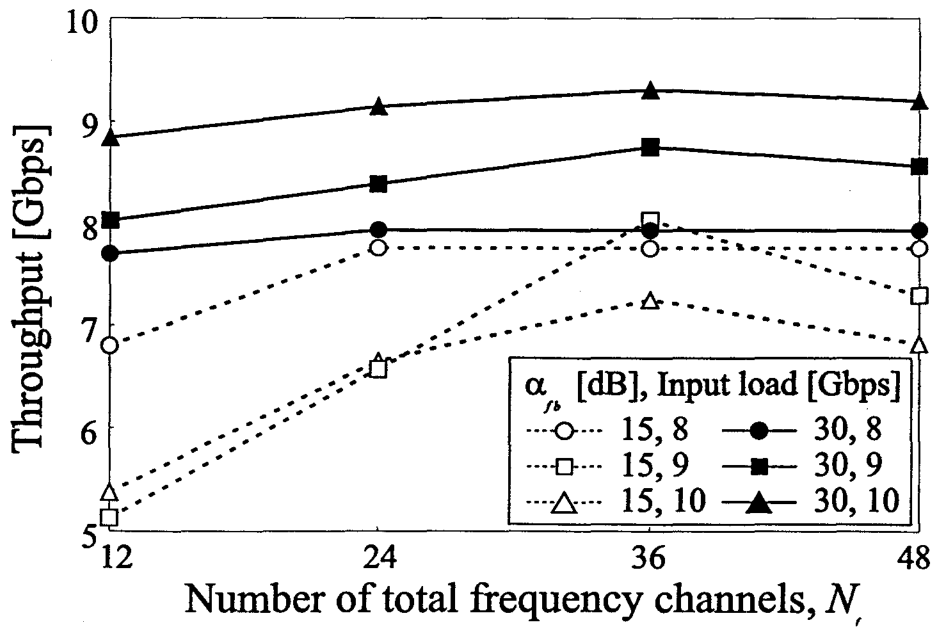


Figure 4.11: Throughput performance versus number of total frequency channels under rainfall condition II.

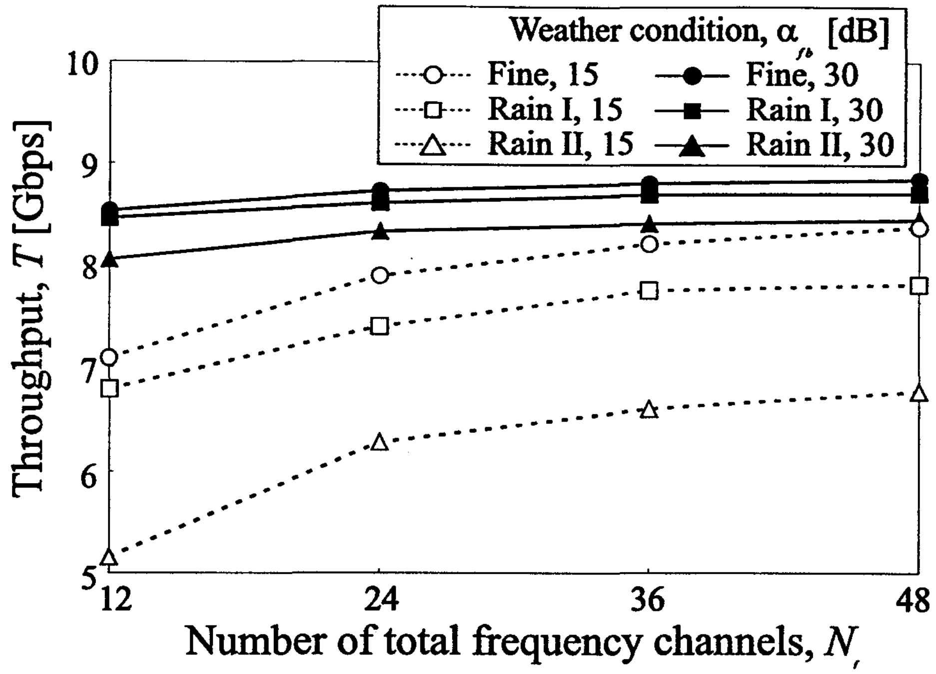


Figure 4.12: Throughput performance versus number of total frequency channels (non-uniform traffic).

the same in all cases of N_f and weather condition when α_{fb} is 30 dB. In contrast, when α_{fb}. is 15 dB, the throughput performance is improved as increasing the N_f because the frequency channel assignment can be more flexibly executed. Moreover, the throughput performance is remarkable degraded in the case of rainfall condition II compared to the other cases of weather conditions.

4.3.4 Computational Complexity

Finally, we examine the computational complexity of the proposed sub-optimum FCA and the case of idealized optimum. As revealed in subsection 4.2.2, the computational complexity of the idealized optimum case is $(N_f)^{N_t}$.

On the other hand, the computational complexity of the proposed scheme can be expressed as

$$\lfloor N_t/N_f \rfloor \cdot (N_f)^2 + rem\,[N_t/N_f] \cdot N_f \ , \tag{4.10}$$

Table 4.2: Computational complexity normalized by that of case using sub-optimum FCA.

Scheme	Weather condition		
	Fine	Rainfall I	Rainfall II
Idealized optimum	10^{183}	10^{194}	10^{197}

where $rem\,[a/b]$ denotes the remainder obtained when dividing a by b. Therefore, we can perceive that the proposed scheme outperforms the idealized optimum case more efficiently as the N_t increases. Since the computational complexity of the proposed scheme is small, it is expected to dynamically track and perform the resource assignment well. Therefore, we can perceive that the proposed DRA scheme using the sub-optimum frequency channel assignment can yield the satisfaction sub-optimum throughput with the small computational complexity.

The computational complexity of case idealized optimum, for example, is determined in the case of N_f of 36 and input load of 10.25 Gbps, and then normalized by the computational complexity of case using sub-optimum FCA. The results are shown in table 4.2. We can see that the computational complexity of case idealized optimum is very larger than the case using sub-optimum FCA.

4.4 Concluding Remarks

This chapter proposed the DRA scheme including the radio path allocation and the sub-optimum frequency channel assignment for multi-carrier mesh-topology MMW broadband entrance networks. The radio path allocation includes adaptive modulation compensating for rain attenuation and traffic load distribution selecting appropriate paths. On the other hand, the frequency channel assignment is used to assign a particular set of frequency channels to each radio link.

Performance evaluations confirmed that the proposed DRA scheme yields higher throughput performance than the random frequency channel assignment. In addition, in the case that the number of total frequency channels, N_f, is 36, the throughput of the proposed DRA scheme is almost the same as that of the idealized optimum if the total input load in network is no more than 9 Gbps. When the total input load in network exceeds 9 Gbps, the throughput of the DRA scheme gradually decreases as the input load increases in the case that the antenna front-to-back ratio, α_{fb}, is 15 dB. On the other hand, in the case of α_{fb} of 30 dB, the throughput of the DRA scheme is degraded a little when compared to that of the idealized optimum. In addition, the increase of N_f improves the throughput performance. Moreover, it was also shown that the proposed DRA scheme can yield quite small computational complexity compared to that of the idealized optimum.

Chapter 5

Frequency Channel Blocking Scheme

5.1 Introduction

In chapter 4, the dynamic resource assignment (DRA) scheme including the radio path allocation and the sub-optimum frequency channel assignment is proposed for multi-carrier mesh-topology entrance networks. Nevertheless, the throughput degradation problem occurred when traffic load becomes heavy especially in the case of low value of antenna front-to-back ratio (α_{fb}). This is because heavier traffic load leads larger number of required frequency channels (traffic slots) by all radio links in network, and thus yields the more share of any channel among different radio links. The reuse of a channel among radio links may cause strong mutual interference, and thus traffic in a channel of those radio links is unsuccessfully received.

Therefore, in this chapter, the frequency channel blocking (FCB) scheme is proposed in section 5.2 to combat the above-mentioned problem. The concept of this scheme is to block the use of frequency channel at any radio link, in order to suppress the interference level. However, the blocking of frequency channel at any BS may lead the unfairness problem which is one of the most important issues in the multihop mesh-topology networks [89]. Hence, the proposed FCB scheme should be performed based on not only the network throughput but also the newly defined fairness index.

5.2 Frequency Channel Blocking

To combat the throughput degradation problem when traffic load becomes heavy, especially in the case of low value of antenna front-to-back ratio (α_{fb}), the DRA scheme proposed in chapter 4 is enhanced by the frequency channel blocking (FCB) scheme. The concept of this

FCB scheme is to block the use of frequency channel at any radio link, in order to suppress the interference level, i.e., to sacrifice the throughput of any BS in order to improve the total throughput of network. However, the sacrifice of throughput of any BS may lead the unfairness problem which is one of the most important issues in the multi-hop mesh-topology network [89]. Hence, in the proposed FCB scheme, any frequency channel is determined to be blocked whether or not, based on not only the network throughput but also the newly defined fairness index.

Note that, in this chapter, network throughput and fairness index are defined as follows:

The throughput, T, can be explained as the successful received traffic rate [bps]. If the number of error bits of the received packet, whose length is 1500 Bytes (l_p), is no more than 2 bits (maximum tolerable error bits in packet, l_m), it will be successfully received, and unsuccessfully received in otherwise. Moreover, the retransmission when packet is unsuccessfully received is not considered.

The fairness index, F, can be written based on the definition shown in [89] as

$$F = \frac{\left(\sum_{i=1}^{N_{BS}} T_{norm,i}\right)^2}{N_{BS} \cdot \left(\sum_{i=1}^{N_{BS}} T_{norm,i}^2\right)}, \tag{5.1}$$

$$T_{norm,i} = \frac{T_i}{L_i}, \tag{5.2}$$

where T_i, L_i and $T_{norm,i}$ respectively denote the throughput, the input load and the normalized throughput of the ith BS. We can observe that the fairness index calculated by using Eq. (5.1) and Eq. (5.2) is bounded between 0 and 1. A higher fairness index indicates better fairness between BSs. In the case of perfect fair which each BS has the same value of normalized throughput, the fairness index becomes 1. On the other hand, in the case of perfect unfair which only one BS has non-zero throughput, the fairness index becomes $1/N_{BS}$ which is 0 in the limit as N_{BS} tends to ∞.

The concept of the frequency channel blocking is simply clarified in the following example. As illustrated in Figs. 5.1–5.3, let us consider the 4 frequency channels network. There are 3 BSs transmitting traffic to CS in the mesh-topology entrance network. Note that, in Figs. 5.1–5.3, traffic slot transmitted through network is numbered by (i, j), where i and j respectively denote the number of source BS and the number of used frequency channel.

Without consideration of the FCB, it is assumed that frequency channels are assigned as illustrated in Fig. 5.1, and the share of frequency channel between radio links BS2-CS and

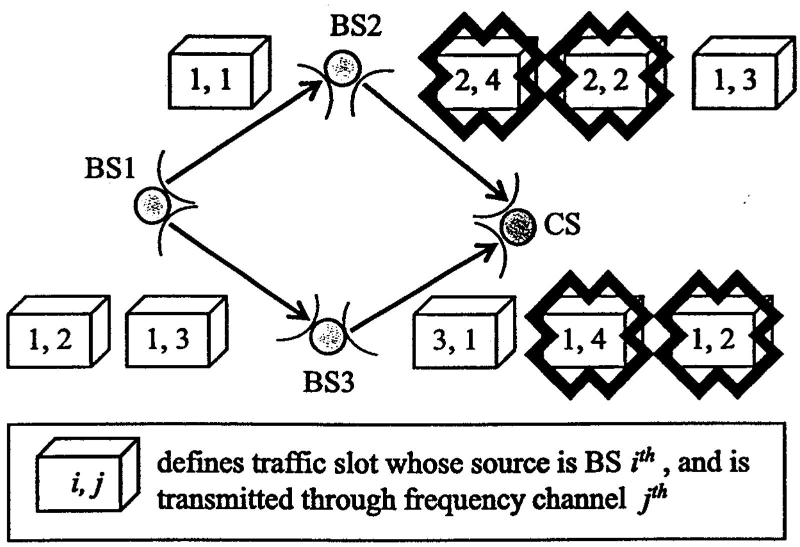


Figure 5.1: Frequency channel blocking example – Without consideration of the FCB.

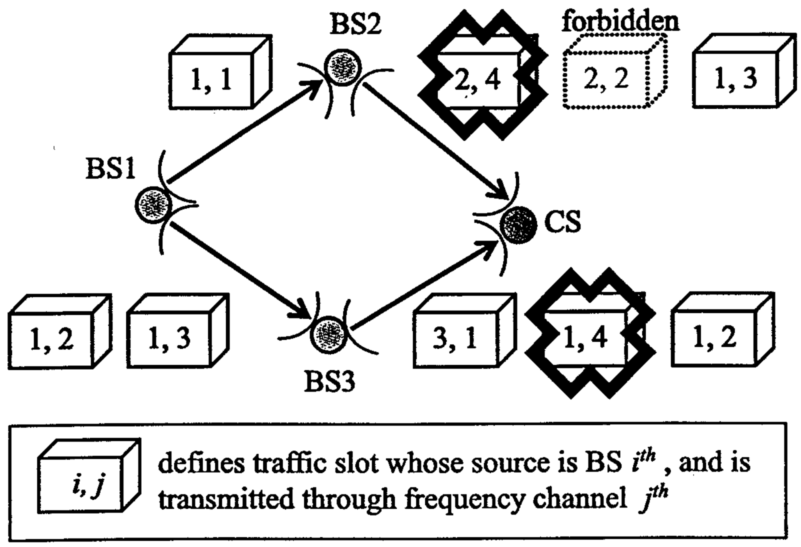


Figure 5.2: Frequency channel blocking example – First FCB executed at radio link BS2-CS.

BS3-CS yields strong interference to each other then traffic will be lost in both radio links. On the other hand, the reuse of frequency channel between other radio link pairs yields quite weak interference. By using Eq. (5.1) and Eq. (5.2), the fairness index of case without consideration of the FCB becomes 0.533.

In contrast, with consideration of the FCB, the first frequency channel blocking is assumed to be executed at radio link BS2-CS as illustrated in Fig. 5.2. The frequency channel, $j = 2$, used to transmit traffic in this radio link is blocked. As the result, the traffic transmitted through the frequency channel, $j = 2$, in radio link BS3-CS will not be interfered. Thus, the overall successful received traffic (throughput) in the network will be increase. Moreover, the fairness index of this case becomes 0.641 which overcomes the case without consideration of the FCB.

Figures 5.3(a) and 5.3(b) show the second FCB executed at radio link BS2-CS and radio link BS3-CS, respectively. Both cases yield the same total network throughput, but the different network fairness index. The second FCB executed at radio link BS2-CS leads the network fairness index of 0.667. On the other hand, the second FCB executed at radio link BS3-CS leads the network fairness index of 0.923. Therefore, we can perceive that the FCB should be executed at each radio link in manner of round seqûential.

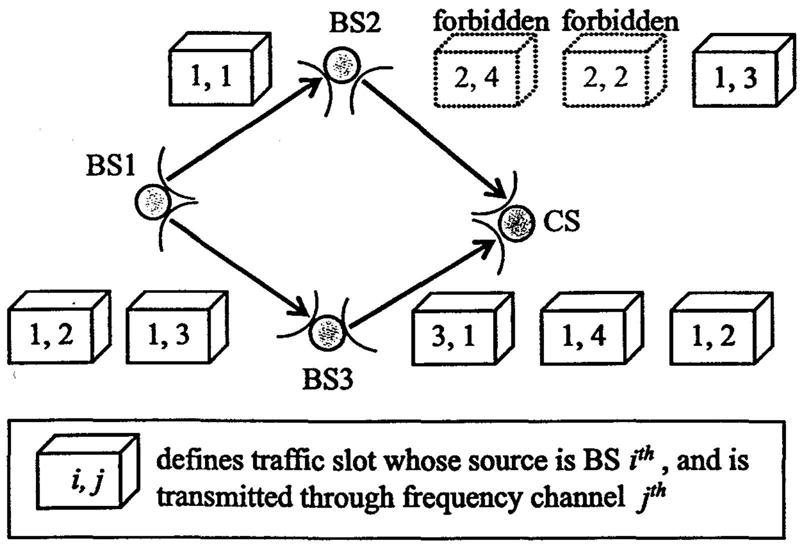
The proposed frequency channel blocking is performed as detailed in the flowchart shown in Fig. 5.4. Let us define the parameters as follows:

N_{BS} : Number of BSs in network,

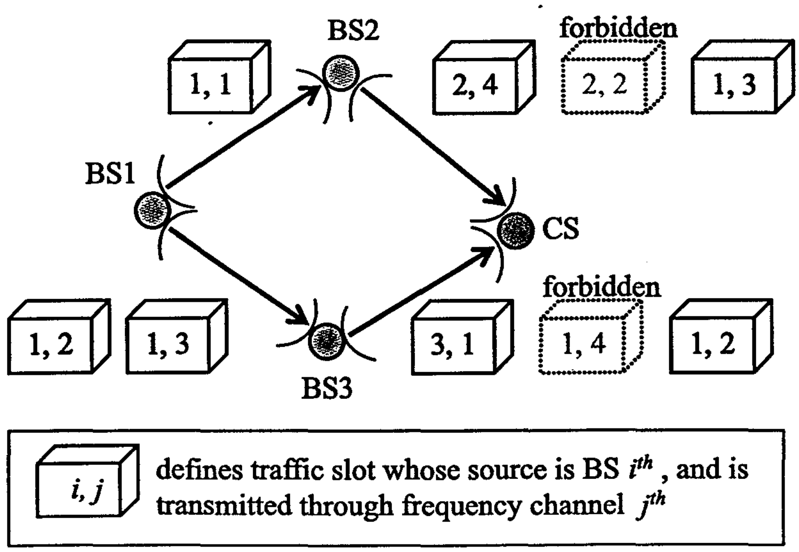
N_{bc} : Number of frequency channel blocking cancellations.

At the beginning, the initial value of network throughput and fairness index, when the frequency channel blocking scheme is not performed, are calculated. The frequency channel blocking first tries to forbid one dummy frequency channel. Note that at each time in blocking one dummy frequency channel, the frequency channel assignment will be redone. After that, the total throughput and the fairness index of network are calculated, and thus respectively set as T_{dum} and F_{dum}.

Since both the network throughput and the fairness index are significant, in this letter, we propose a novel criterion determining whether the blocking is permitted or not by comparing the product of network throughput multiplied by fairness index before and after the blocking has been done. If the product after the blocking has been done is more than that before the blocking is done, the blocking will be permitted. That is, the latest blocking will be accepted if the following equation



(a) Second FCB executed at radio link BS2-CS.



(b) Second FCB executed at radio link BS3-CS.

Figure 5.3: Frequency channel blocking example – Second FCB execution.

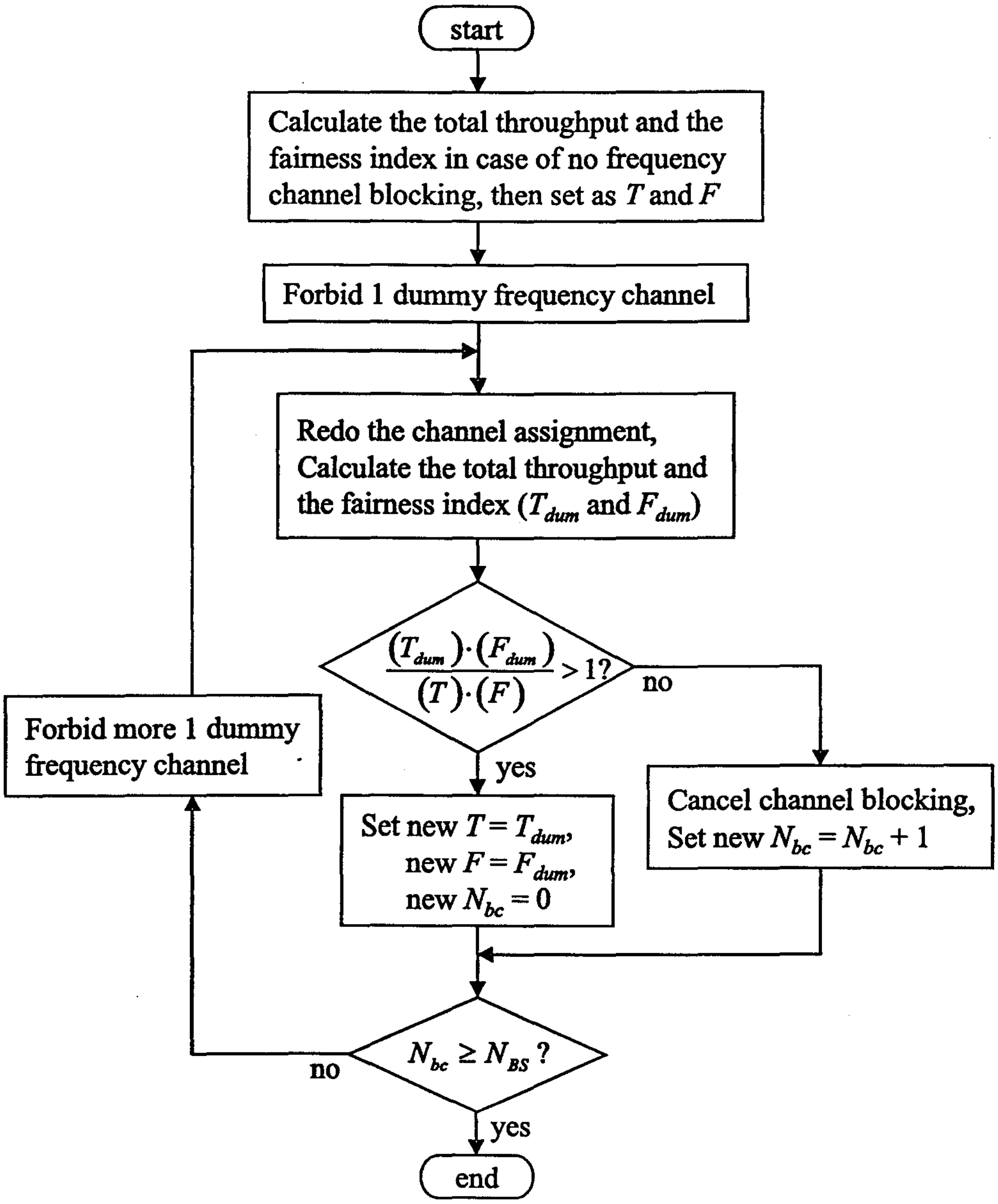


Figure 5.4: Frequency channel blocking algorithm.

$$\frac{(T_{dum}) \cdot (F_{dum})}{(T) \cdot (F)} > 1 , \tag{5.3}$$

is satisfied, and cancelled in otherwise.

If the frequency channel blocking is accepted, the new value of T and F can be written as T_{dum} and F_{dum}, respectively. Moreover, the number of frequency channel blocking cancellations (N_{bc}) is set to be 0. On the other hand, if the frequency channel blocking is cancelled, the N_{bc} is added by 1.

If condition of $N_{bc} \geq N_{BS}$ is still not satisfied, algorithm tries to additionally forbid more one frequency channel at other one radio link. That is, in this proposed FCB algorithm, algorithm tries to forbid frequency channel until there is no one blocking acceptance for all BSs. Finally, plural frequency channels could be forbidden.

5.3 Performance Evaluations

The analysis model and parameters used in calculations are the same as in chapter 4.

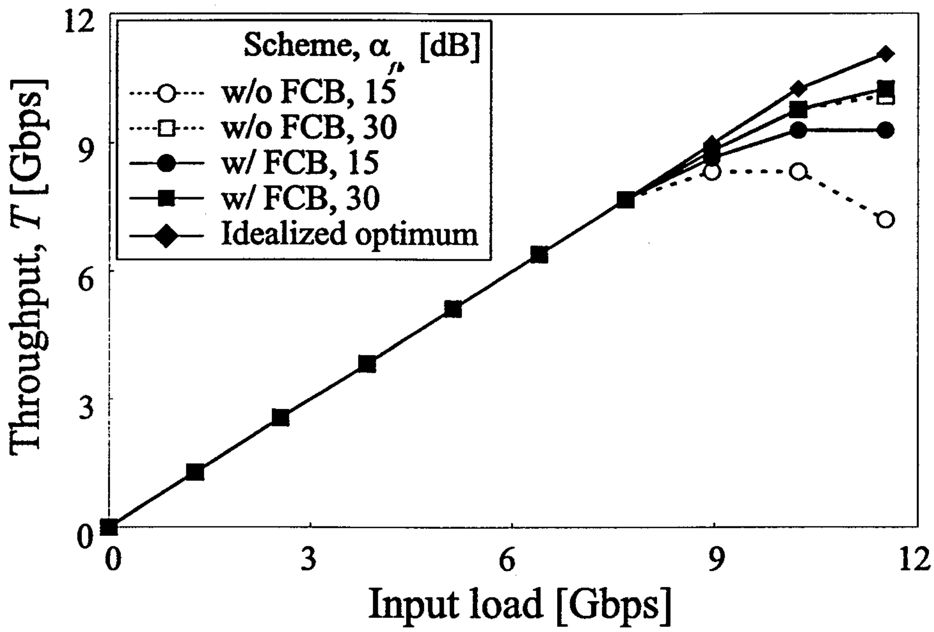
5.3.1 Throughput and Fairness Index Performances versus Input Load

Let us first evaluate throughput and fairness index performances versus input load in the case of uniform traffic and number of total frequency channels, N_f, of 36. Moreover, neither impact of processing delay at BSs nor retransmission when packet is unsuccessfully received is considered.

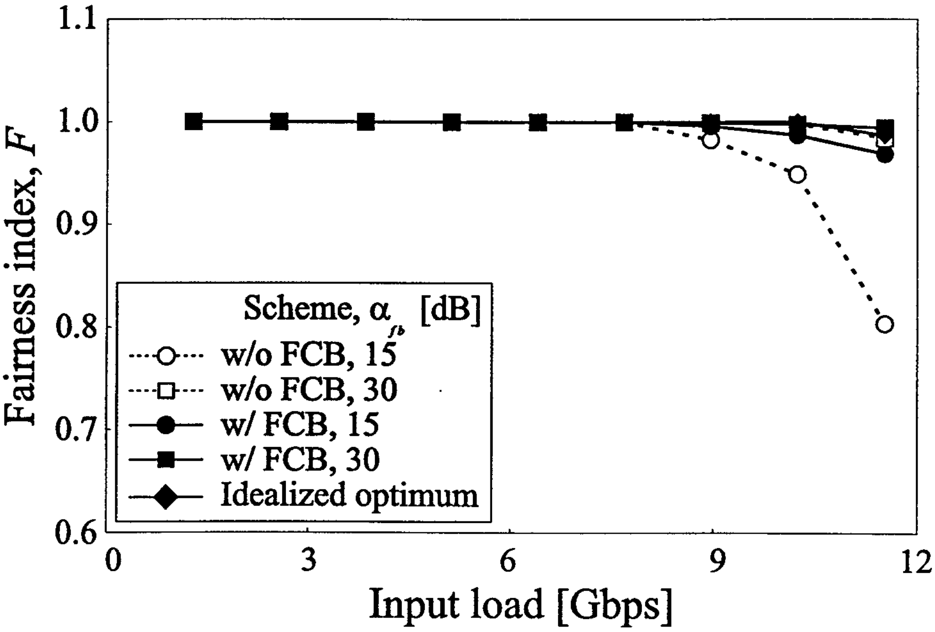
Throughput and fairness index performances of the conventional scheme using DRA scheme proposed in chapter 4 are compared to those of case using DRA scheme enhanced by the proposed FCB scheme. In addition, the performances of case of the idealized optimum are also compared. It is assumed that in the case of the idealized optimum, the antenna beamwidth is close to 0°. Moreover, the α_{fb} is set to be ∞.

The relationships between total network throughput performance versus total input load in network under fine weather condition, rainfall condition I and rainfall condition II are respectively shown in Figs. 5.5–5.7.

Figure 5.5(a) shows the throughput performance in the case of fine weather condition. In the case of α_{fb} of 30 dB, it is obvious that even if the FCB scheme is not applied, a quite good throughput can be obtained, which is little degraded when compared to that of the idealized



(a) Throughput performance.



(b) Fairness index performance.

Figure 5.5: Throughput and fairness index performances versus input load under fine weather condition.

optimum. Meanwhile, the use of FCB scheme gives a very little improvement of throughput over the conventional scheme without FCB. In contrast, in the case of α_{fb} of 15 dB, we can observe that the throughput of the case without FCB first increases and reaches a peak at input load of 9 Gbps and then starts to decrease little if input load increases further. On the other hand, the FCB yields throughput improvement about 2 Gbps over the conventional scheme without FCB when input load is close to 12 Gbps.

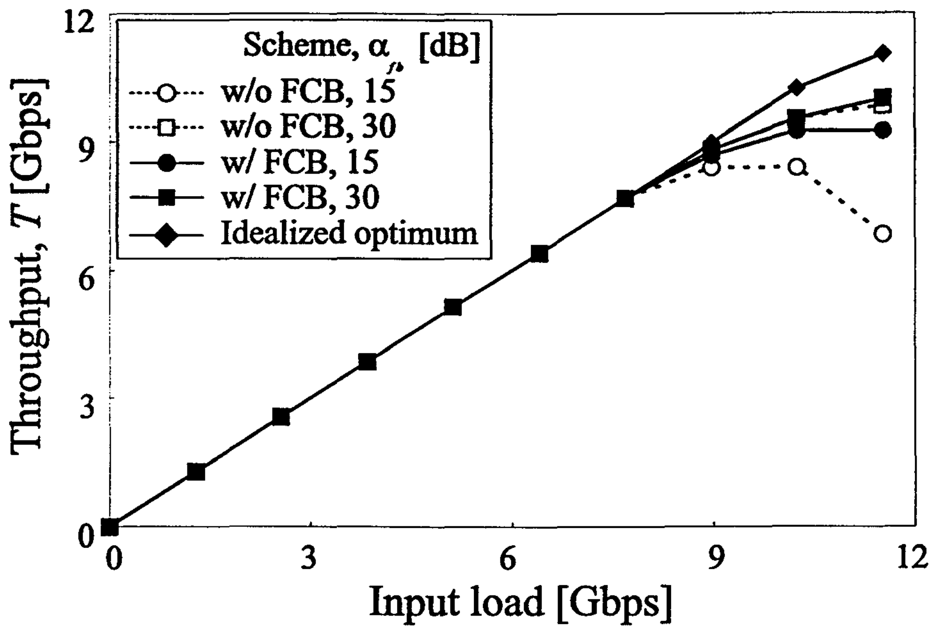
Figure 5.5(b) shows the fairness index performance in the case of fine weather condition. In the case of α_{fb} of 15 dB, it is obvious that the scheme without FCB remains the fairness index close to 1 when the input load is less than 9 Gbps, and yields the deteriorated fairness index when input load exceeds 9 Gbps. On the other hand, the fairness index of the case using FCB scheme is close to 1 even if input load becomes more than 9 Gbps when the α_{fb} is 30 dB, which is almost the same as that of the idealized optimum.

From Fig. 5.6(a), in the case of rainfall condition I, it is clear that the results are similar to those of case fine weather condition in point of the throughput improvement over the case without FCB scheme by the case using FCB scheme is evident only when the α_{fb} is 15 dB. In addition, we also observed that the throughput performance of this rainfall condition I is little degraded when compared to that of the fine weather condition.

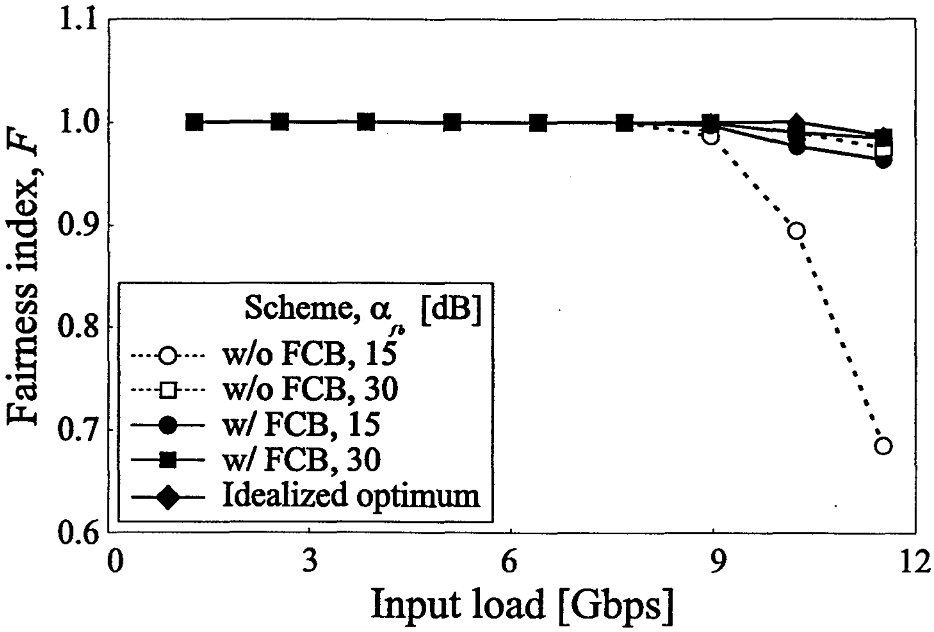
Figures 5.6(b) shows the fairness index performance of the case rainfall condition I. In the case of α_{fb} of 30 dB, the fairness index of both cases of with and without FCB are almost the same which close to 1. In contrast, in the case of α_{fb} of 15 dB, the fairness index performance degradation of the case conventional scheme using no FCB when input load exceeds 9 Gbps in the case of the rainfall condition I is more noticeable compared to the case of the fine weather condition. On the other hand, the fairness index of the scheme using FCB is close to 1 even if input load becomes more than 9 Gbps.

Figure 5.7(a) shows the throughput performance in the case of rainfall condition II. When the α_{fb} is 15 dB, the scheme using FCB yields the throughput improvement about 3 Gbps compared to the conventional scheme without FCB when input load is close to 12 Gbps. That is, the case when FCB is applied more outperforms the case when FCB is not applied in this rainfall condition II compared to the other weather conditions. In contrast, when the α_{fb} is 30 dB, the throughput performance of this rainfall condition II is almost the same as that of the other weather conditions.

From Fig. 5.7(b), in the case of rainfall condition II, it is obvious that the fairness index of all schemes are almost the same which close to 1 when the α_{fb} is 30 dB. In contrast, when the α_{fb} is 15 dB, the fairness index performance degradation of the case without FCB when

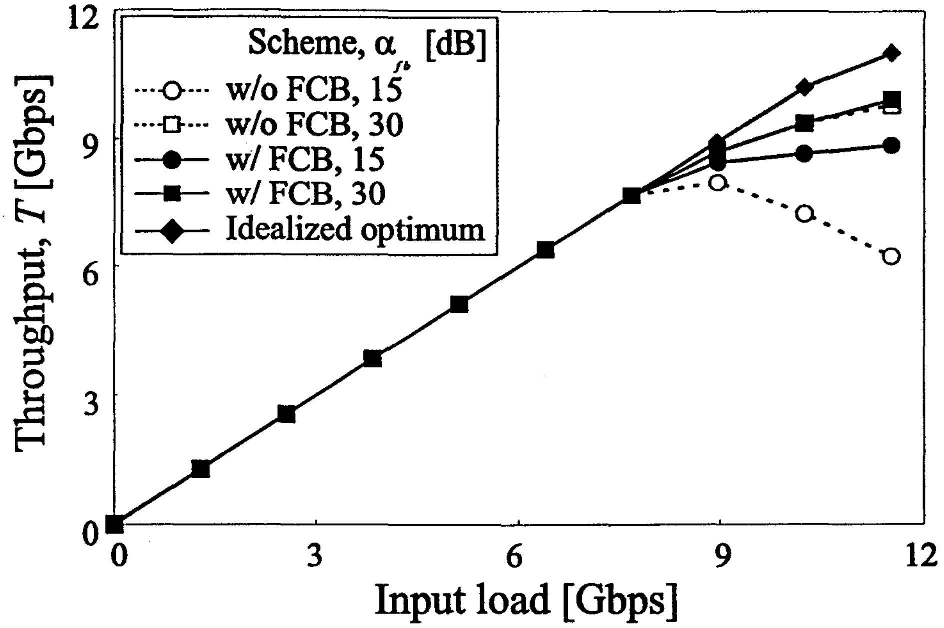


(a) Throughput performance.

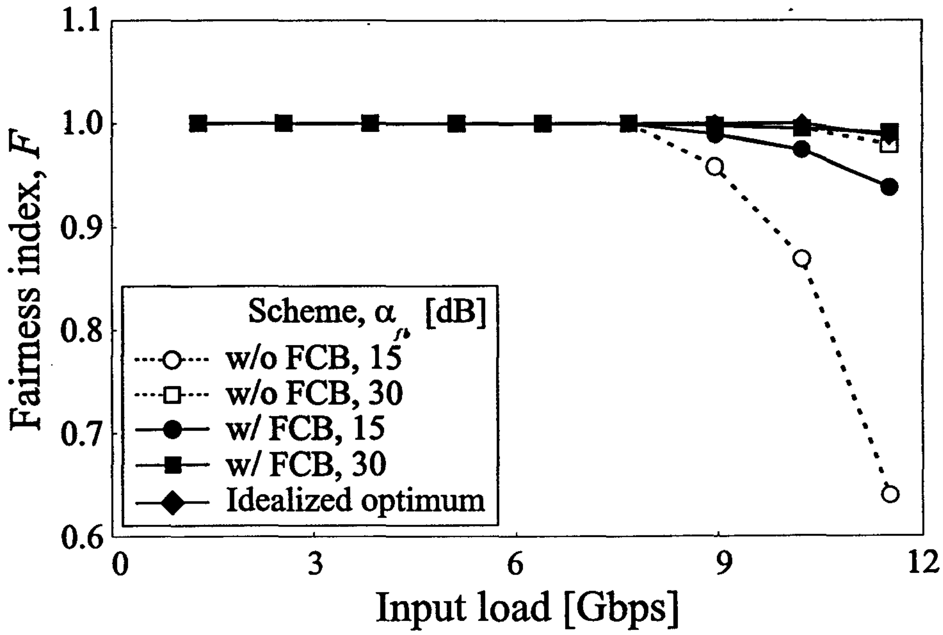


(b) Fairness index performance.

Figure 5.6: Throughput and fairness index performances versus input load under rainfall condition I.



(a) Throughput performance.



(b) Fairness index performance.

Figure 5.7: Throughput and fairness index performances versus input load under rainfall condition II.

input load exceeds 9 Gbps in the case of the rainfall condition II is more noticeable compared to the case of the rainfall condition I. In addition, the fairness index of the case using FCB decreases a little if input load exceeds 9 Gbps.

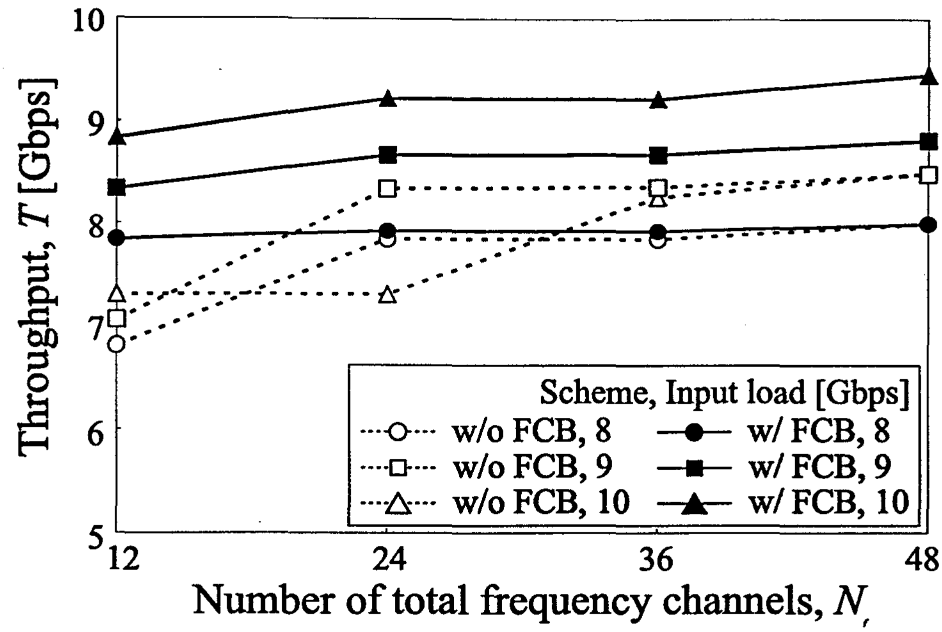
Moreover, from Figs. 5.5–5.7, it is clear that throughput and fairness index improvements by the FCB scheme in the case of the fine weather condition, the rainfall condition I and the rainfall condition II are respectively more evident.

5.3.2 Throughput and Fairness Index Performances versus Number of Total Frequency Channels

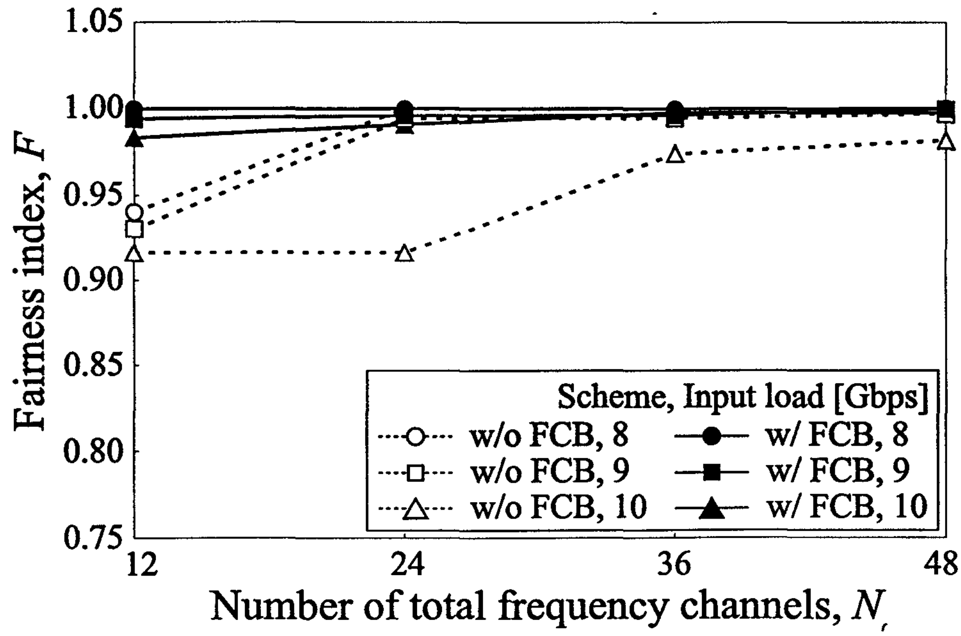
Next, we evaluate total network throughput and fairness index performances versus number of total frequency channels in the case of uniform traffic and α_{fb} of 15 dB. The results under fine weather condition, rainfall condition I and rainfall condition II are respectively shown in Figs. 5.8–5.10.

From Fig. 5.8(a), Fig. 5.9(a) and Fig. 5.10(a), it is clear that when the FCB is not applied, the throughput performance is dependent on N_f and weather condition. In the case of fine weather condition shown in Fig. 5.8(a), the N_f of 12 and 24 yield the degraded throughput performance since interference becomes larger as decreasing the N_f. Meanwhile, in the case of rainfall condition I and rainfall condition II respectively shown in Fig. 5.9(a) and Fig. 5.10(a), the N_f of 36 yields the best throughput performance compared to the other cases of N_f (12, 24 and 48) when input load is more than 9 Gbps. In contrast, when using the FCB scheme, since the effect of interference can be well mitigated, the throughput performance is almost the same in all cases of the number of frequency channels and the weather condition.

From Fig. 5.8(b), Fig. 5.9(b) and Fig. 5.10(b), it is obvious that in the conventional scheme without FCB, the fairness index performance is much degraded in the case of N_f of 12 compared to the other cases of N_f (24, 36 and 48) in all weather conditions. On the other hand, when the FCB is applied, the fairness index performance is almost the same in all cases of N_f and weather condition, which is close to 1.

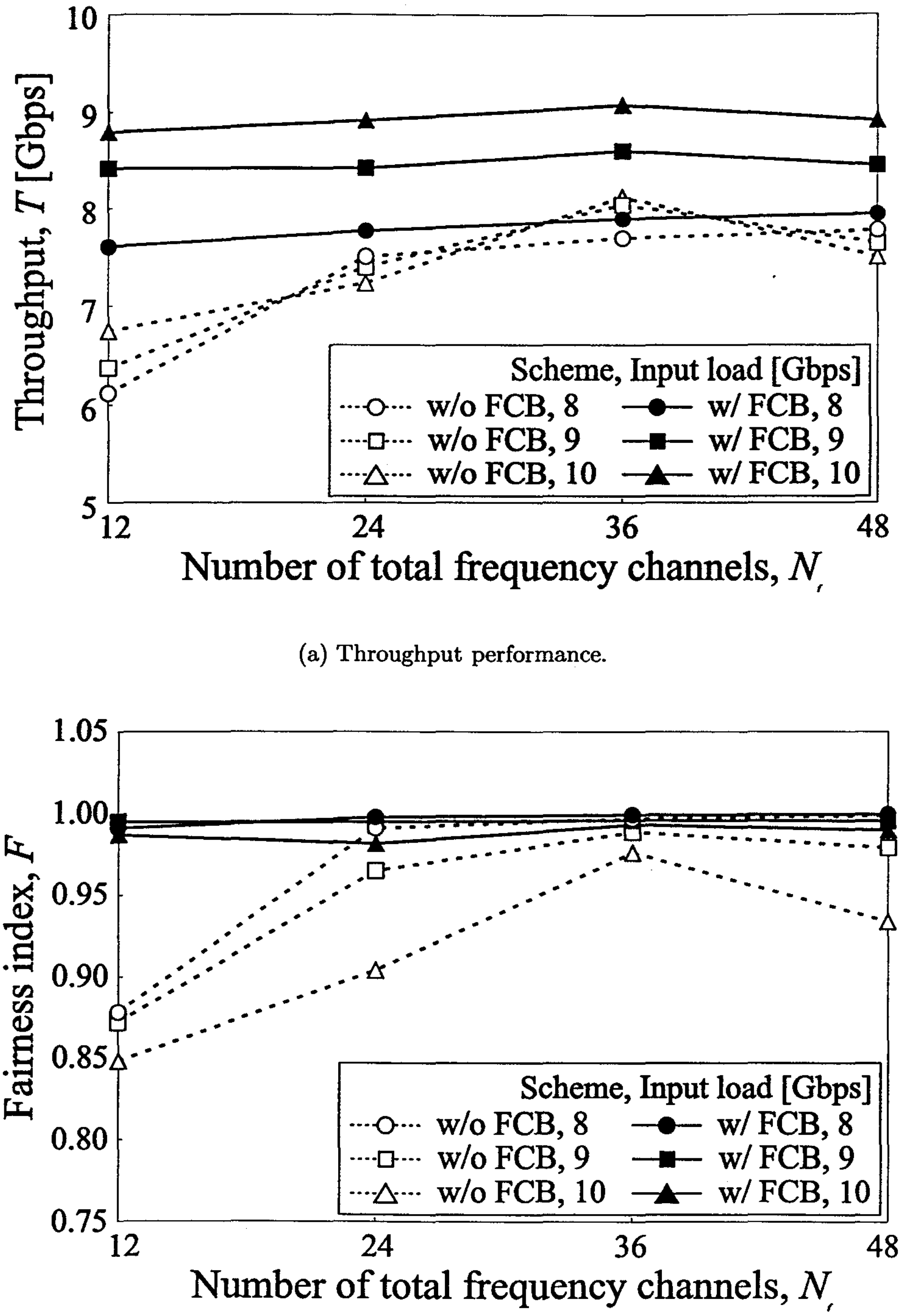


(a) Throughput performance.



(b) Fairness index performance.

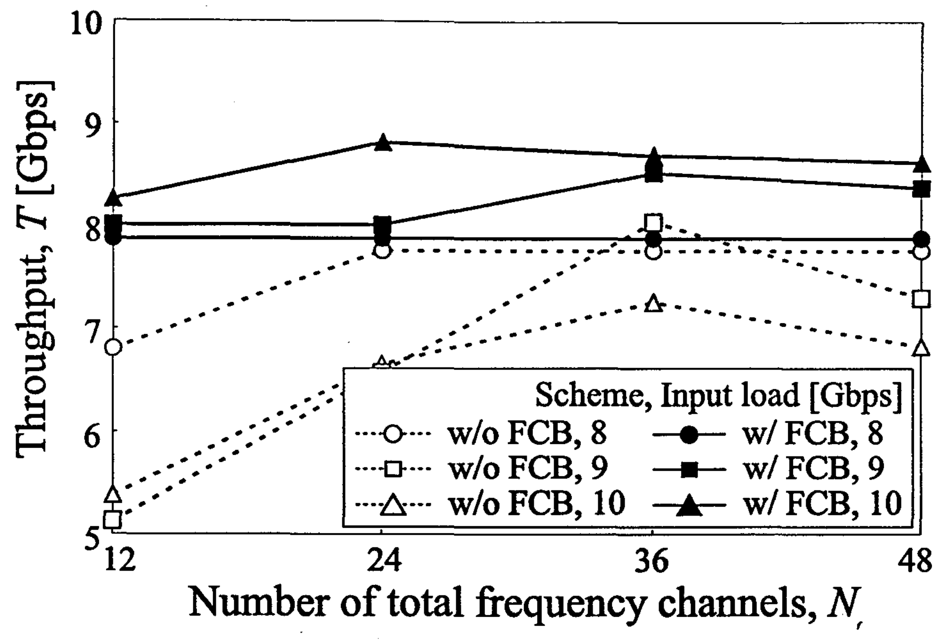
Figure 5.8: Throughput and fairness index performances versus number of total frequency channels under fine weather condition.



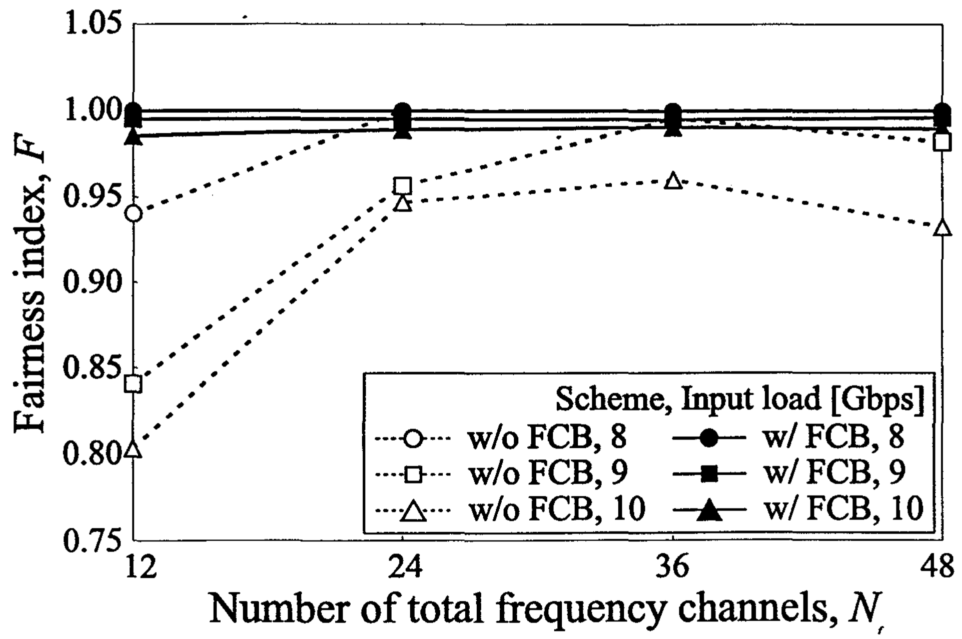
(a) Throughput performance.

(b) Fairness index performance.

Figure 5.9: Throughput and fairness index performances versus number of total frequency channels under rainfall condition I.



(a) Throughput performance.



(b) Fairness index performance.

Figure 5.10: Throughput and fairness index performances versus number of total frequency channels under rainfall condition II.

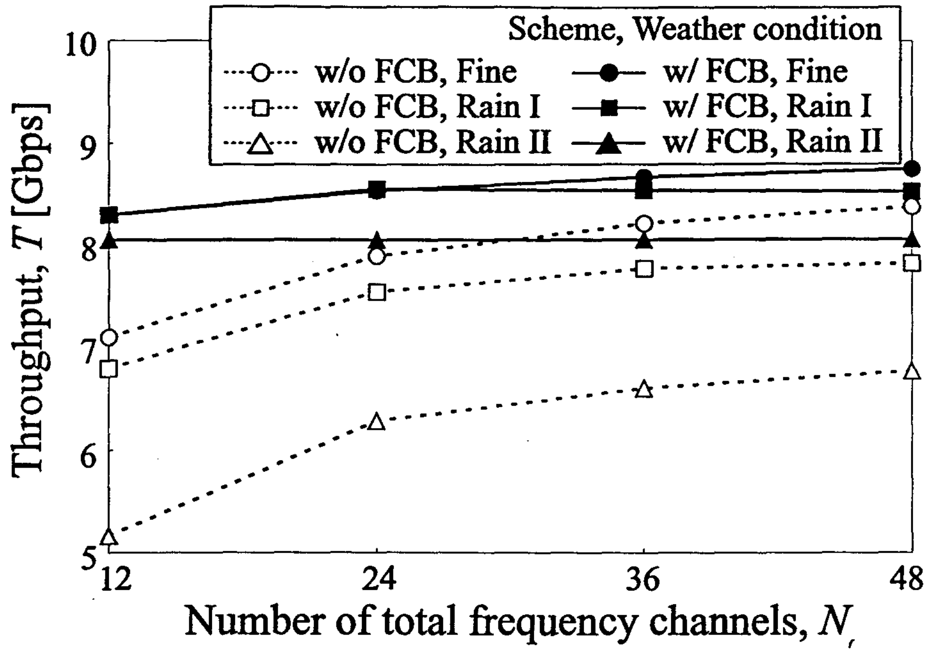


Figure 5.11: Throughput performance versus number of total frequency channels (non-uniform traffic).

Next, performance evaluations are done in the case of non-uniform traffic, which input load of each BS is generated randomly between 1 to 1.25 Gbps. Note that the average total input load of network becomes 9 Gbps. Figures 5.11 and 5.12 respectively show the throughput performance and the fairness index performance versus number of total frequency channels N_f, when the α_{fb} is 15 dB. When the FCB is not applied, we can observe that both throughput and fairness index performances are improved as increasing the N_f. In addition, the case using no FCB yields the best throughput and the best fairness index performances in the case fine weather condition, and yields the worst throughput and the worst fairness index performances in the case rainfall condition II.

In contrast, when using the FCB scheme, the N_f of 12 yields the degraded throughput performance in the cases of fine weather and rainfall condition I. On the other hand, in the rainfall condition II, the throughput performance is almost the same in all cases of the number of frequency channels, which less than that of cases of fine weather and rainfall condition I. Moreover, we can see that the fairness index performance is almost the same in all cases of the number of frequency channels and the weather condition, which is close to 1.

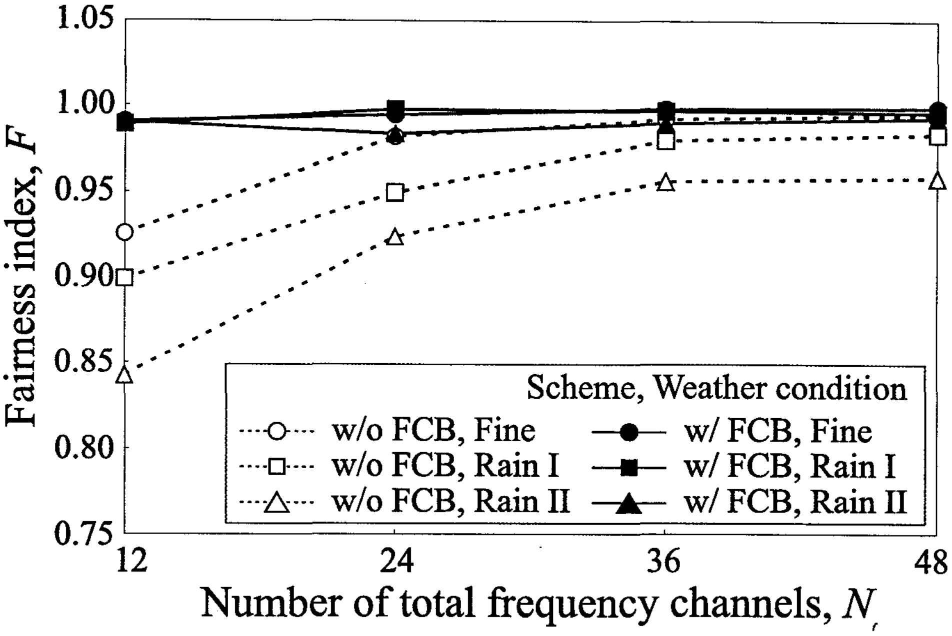


Figure 5.12: Fairness index performance versus number of total frequency channels (non-uniform traffic).

5.3.3 Computational Complexity Comparison

Finally, we examine the computational complexity of the conventional scheme and the proposed scheme using FCB. As revealed in Section 5.2, since the frequency channel assignment is redone at least N_{BS} times when using the FCB. Therefore, the computational complexity of the proposed scheme is more than the case using no FCB in order of $O(N_{BS})$.

We can perceive that the proposed FCB scheme can yield the satisfaction throughput and fairness index performances with the more computational complexity of $O(N_{BS})$ times compared to the case when FCB is not applied, but much less than the computational complexity of the idealized optimum case.

The computational complexity of case using FCB and case of idealized optimum, for example, are determined in the case of N_f of 36 and input load of 10.25 Gbps, and then normalized by the computational complexity of case without FCB. The results are shown in table 5.1. It is clear that the addition of computational complexity by using FCB is very small compared to the case of idealized optimum.

Table 5.1: Computational complexity normalized by that of case without FCB.

Scheme	Weather condition		
	Fine	Rainfall I	Rainfall II
Idealized optimum	10^{183}	10^{194}	10^{197}
w/ FCB	13.6	13.7	16

5.4 Concluding Remarks

This chapter proposed the FCB scheme to enhance the DRA scheme proposed in chapter 4 for multi-carrier mesh-topology MMW broadband entrance networks. The proposed FCB scheme is performed based on not only network throughput but also newly defined fairness index.

Performance evaluations confirmed that the proposed FCB scheme yields the network throughput improvement about 2–3 Gbps over the conventional DRA without FCB scheme when input load is close to 12 Gbps in the case that the antenna front-to-back ratio, α_{fb}, is 15 dB. In addition, the conventional DRA without FCB scheme obtains fairness index about 0.6–0.8, while the fairness index of case using the FCB scheme is close to 1. It was also shown that the performance improvements by the FCB scheme are more noticeable in the case of α_{fb} of 15 dB compared to the case of α_{fb} of 30 dB.

Moreover, it was obvious that the use of FCB scheme gives almost the same fairness index which is close to 1 in all cases of number of total frequency channels, N_f, and yields almost the same throughput performance in all cases of N_f except the case of N_f of 12 which a little degraded throughput is obtained. Additionally, the use of FCB scheme leads more computational complexity in order of $O(N_{BS})$ times compared to the conventional DRA without FCB scheme. However, the computational complexity of the proposed scheme is small enough compared to the case of idealized optimum.

Chapter 6

Conclusions

This thesis has presented multihop relay system in mesh-topology millimeter-wave (MMW) entrance networks. The important results of the research are summarized as follows.

Firstly, background and current status of research activities in broadband wireless access systems were presented in chapter 1. Challenging issues of development of mesh-topology MMW entrance networks were also pointed out as the strong impact of rainfall on the MMW link quality investigated in chapter 3, and the interference problem investigated in chapter 4 and chapter 5.

Next, chapter 2 addressed the overview of MMW broadband wireless access systems, and described architecture of mesh-topology broadband entrance networks in detail.

According to the severe deterioration of MMW radio link quality by rainfall, chapter 3 proposed the CABSP selection algorithm to consider not only traffic load but also quality of MMW radio link for path selection in mesh-topology MMW broadband entrance networks. Moreover, the CABSP selection algorithm was enhanced by addition of the adaptive modulation technique, and then called the CABSP-AM selection algorithm to further make more efficient use of bandwidth resources with consideration of the QoS requirement of each class of service in multimedia communication. Through performance evaluations, the following results were obtained:

- The CABSP selection algorithm yields the improvement of throughput performance over the conventional CSP selection algorithm except in the case of heavy traffic load under heavy rainfall environment.

- The CABSP-AM selection algorithm improves throughput about 2–3 Gbps over the CSP selection algorithm when input load is close to 6 Gbps.

- In addition, the cumulative distribution of network capacity under various rainfall conditions indicated that the CABSP-AM selection algorithm makes the superiority over the CABSP selection algorithm about 1.36 and 1.48 fold respectively in cases of error sensitive class and error non-sensitive class.

Chapter 4 proposed the DRA scheme including the radio path allocation and the sub-optimum frequency channel assignment for multi-carrier mesh-topology MMW broadband entrance networks. The radio path allocation includes the adaptive modulation compensating for the rain attenuation and the traffic load distribution selecting the appropriate path. On the other hand, the frequency channel assignment is used to assigns a particular set of frequency channels to each radio link. Through performance evaluations, the following results were obtained:

- The DRA scheme improves network throughput over the conventional scheme using the random frequency channel assignment, and yields almost the same throughput as that of the idealized optimum when input load is no more than 9 Gbps.

- When total input load in network exceeds 9 Gbps, the throughput of the DRA scheme gradually decreases as input load increases in the case that the antenna front-to-back ratio, α_{fb}, is 15 dB. On the other hand, in the case of α_{fb} of 30 dB, the throughput of the DRA scheme is degraded a little when compared to that of the idealized optimum.

- The increase of the number of total frequency channels, N_f, improves the throughput performance.

- In addition, the DRA scheme can yield quite small computational complexity compared to that of the idealized optimum.

In chapter 5, the FCB scheme was proposed to enhance the DRA scheme proposed in chapter 4 for multi-carrier mesh-topology MMW broadband entrance networks. The proposed FCB scheme is performed based on not only network throughput but also newly defined fairness index. Through performance evaluations, the following results were obtained:

- In the case of α_{fb} of 15 dB, the FCB scheme yields the network throughput improvement about 2–3 Gbps over the conventional DRA without FCB scheme when input load is close to 12 Gbps.

- In addition, when α_{fb} is 15 dB and input load is close to 12 Gbps, the conventional DRA without FCB scheme obtains fairness index about 0.6–0.8, while the fairness index of case using the FCB scheme is close to 1.

- Performance improvements by the FCB scheme are more noticeable in the case of α_{fb} of 15 dB compared to the case of α_{fb} of 30 dB.

- The use of FCB scheme gives almost the same fairness index which is close to 1 in all cases of N_f, and yields almost the same throughput performance in all cases of N_f except the case of N_f of 12 which a little degraded throughput is obtained.

- Moreover, the use of FCB scheme leads more computational complexity in order of $O(N_{BS})$ times compared to the conventional DRA without FCB scheme. However, the computational complexity of the case using FCB scheme is small enough compared to the case of idealized optimum.

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1. J. Sangiamwong, K. Tsukamoto, and S. Komaki, "Link Quality-Based Path Selection Scheme in Millimeter-Wave Broadband Entrance Network for Wireless Heterogeneous Systems," *IEICE Trans. Commun.*, vol.E87-B, no.5, pp.1219–1226, May 2004.

2. J. Sangiamwong, K. Tsukamoto, and S. Komaki, "Dynamic Resource Assignment Scheme in Mesh-Topology Millimeter-Wave Broadband Entrance Networks," *IEICE Trans. Fundamentals*, vol.E87-A, no.10, pp.2668–2675, Oct. 2004.

3. J. Sangiamwong, K. Tsukamoto, and S. Komaki, "Frequency Channel Blocking for MMW Entrance Networks," *IEICE Electronics Express*, to be published.

International Conferences

1. J. Sangiamwong, N. Harada, K. Tsukamoto, S. Komaki, E. Okamoto, and H. Ogawa, "Non-Regenerative Route Diversity Effect under Rainfall Environment in Millimeter-Wave Broadband Wireless Access Systems," *Proc. of TSMMW2002*, pp.219–222, Japan, March 2002.

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1. J. Sangiamwong, K. Tsukamoto, and S. Komaki, "A Study on Transmission Quality of Mesh-Topology MMW Broadband FWA using Non-Regenerative Repeater," IEICE Technical Report, MoMuC2001-33, pp.25–30, July 2001.

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3. J. Sangiamwong, M. Takeda, N. Harada, K. Tsukamoto, S. Komaki, Y. Shoji, and H. Ogawa, "Development of Gigabit Millimeter-Wave Broadband Wireless Access System — (3) QoS-based Adaptive Modulation under Rainfall Environment," Proc. of IEICE Spring Conf., B-5-281, p.740, March 2003.