**Outage Performance with Directional Antennas
in
Cellular Fixed Broadband Access Systems**

**by
Salina Q. Gong, B. Eng.**

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of**

Master of Engineering

**Ottawa-Carleton Institute for Electrical Engineering
Department of Systems and Computer Engineering**

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Ottawa-Carleton Institute for Electrical Engineering
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Abstract

The Cellular Fixed Broadband Access System for LMCS (Local Multipoint Communication Services) is aiming to provide broadband services to fixed subscribers through wireless access. A representative LMCS scenario involves a cellular system design with the entire allocated bandwidth used in each cell and with a highly directional antenna employed at the subscriber. The LMCS system designs rely on the assumed information regarding to radio propagation phenomena in the anticipated coverage areas. The research reported here, therefore, has the objective of verifying such information by theoretical modeling and simulation.

Simulation and analysis have been used to study the effects of a number of factors on the system performance and interference characteristics of such a LMCS system. The investigated factors include beamwidth and gain ratio of directional antennas, sectorization of hub antennas, propagation exponent, lognormal shadowing, site diversity and transmitter power control. Both models of LOS (line of sight) and NLOS (non-line of sight) have been investigated in this work. The simulation results demonstrate that highly directional antennas at the subscribers can dramatically improve the system performance for both uplink and downlink. The system design with frequency reuse of one is examined, and it is confirmed that an outage of 0.9% for a NLOS system could be achieved by using narrow beam antennas of 3 degrees with site diversity and power control techniques employed. Under the situation of LOS available for the desired links, the outage can be further reduced to as low as 0.3%.

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List of Acronyms

LMCS	Local Multipoint Communication Services
LMDS	Local Multipoint Distribution Services
LOS	line of sight
NLOS	non line of sight
FCC	Federal Communications Commission
DSP	Digital Signal Processing
TDMA	Time Division Multiplex Access
CDMA	Code Division Multiplex Access
FDMA	Frequency Division Multiplex Access
FM	Frequency Modulation
TI	Texas Instruments
CO	Connection Oriented
CL	Connectionless oriented
CBR	Constant Bit Rate
VBR	Variable Bit Rate
ABR	Available Bit Rate
QOS	Quality of Service
ISI	Inter symbol Interference
BER	bit error rate
SIR	Signal to Interference Ratio
SINR	Signal to Interference and Noise Ratio
FDD	Frequency Division Duplex
C/N	Carrier to Noise ratio
AWGN	Additive White Gaussian Noise

List of Symbols

G_s	Subscriber Antenna Gain Ratio
G_b	Base Station Antenna Gain Ratio
θ	Antenna Beamwidth
BW	Channel Bandwidth
m	Propagation Exponent
σ	Standard Deviation
Freq	Frequency
δ	SINR threshold
P_R	Received Power
P_T	Transmitting Power
G_R	Receive Antenna Gain
G_T	Transmitting Antenna Gain
h_R	Receiver Antenna Height
h_T	Transmitter Antenna Height
λ	Wavelength of Radio
I	Interference
S	Desired Signal
m_{db}	Average Signal Power in Log Scale
σ_{db}	Standard Deviation of the Signal in Log Scale
d_{ref}	Reference Distance at the Break Point
P_e	Outage Probability
$E(x)$	Mean of the variable x
N_{RX}	Noise Power
K	Boltzman's constant
T	Environment Temperature

Chapter 1

INTRODUCTION

1.1 Thesis Objectives

Recently there has been much interest in providing broadband services such as TV broadcasting, data transfer, video on demand, video conference, etc. to fixed subscribers through wireless access links. The bidirectional LMCS system (Local Multipoint Communication Services) could be used to provide broadband wireless access to fixed networks via millimeter wave transmissions at 28 GHz. There will be 6 blocks of 500 MHz of bandwidth in the 26-28GHz band released for several LMCS providers by Industry Canada [1]. Similar bandwidth allocations are proposed in the US, where the system is called LMDS (Local Multipoint Distribution Services) [2]. In the majority of LMCS (or LMDS) designs, a narrowbeam antenna is recommended to be used at the subscriber site in order to mitigate multipath effects and reduce interference [3]. Therefore, the system performance could be improved and the capacity could be increased as well.

The main objective of this thesis is to evaluate the system design of LMCS system, in particular, to investigate the effects of directional antennas on the system performance. The investigated factors include antenna beamwidth, antenna gain ratio, and the sectorization of hub antennas. The computer simulation results will verify a preliminary system design, provide realistic recommendations on further system architecture refinement, and direct the later antenna design for the subscriber-antenna of the system.

One of the key problems in the LMCS system is its coverage and availability of LOS (line of sight) transmissions. The system design based on LOS would have lower outage rate than NLOS (none line of sight) but can not provide full coverage in the servicing areas, for LOS may not be always available due to the blocking of buildings. This problem can be solved by deploying a repeater so as to provide a new LOS transmission link, but the system cost will be increased. The system designs based on the two different scenarios

of LOS and NLOS are simulated in order to find out which is preferable for LMCS in balancing the problem of coverage, system performance, capacity and costs.

In outdoor transmissions, the propagation environment has large effects on system performance. The transmitting signal can be attenuated by foliage, reflected by various obstacles and even blocked by buildings or trees. This can be modeled by average propagation loss with a certain deviation due to shadowing. System outage probability as a function of propagation exponent and standard deviation of lognormal shadowing will be investigated in this thesis.

Both the uplink and the downlink of the system need to be simulated and the system design with frequency reuse of one will be examined. Because the outage is quite high for the subscribers at the edge of each cell as shown in the analysis of the NLOS scenario, site diversity may be helpful for these corner subscribers to improve their performance, and this will be verified through the simulations. Modulation schemes and power control applications in LOS uplinks are also investigated in this thesis.

1.2 Thesis Organization

The organization of this thesis is described as follows.

In Chapter 2, a concept of LMCS has been presented with a brief review of the service requirements and the present LMCS systems. The applications of directional antennas in LMCS are also described with their significant effects on capacity improvement and high data rate support. The following chapter (Chapter 3) provides a survey on issues of propagation environment, interference characteristics and some techniques to improve system performance.

In Chapter 4, we take the subscriber at the edge of the cell as the worst case of the downlink of LMCS, and estimate its outage probability by calculating its SIR with consideration of the lognormal shadowing effects. The analytical results are discussed and some important recommendations on LMCS system design are concluded.

After the original analysis, the system model used in the simulated systems are described in detail in Chapter 5. In Chapter 6, the simulation results on system outage of both LOS and NLOS scenarios are presented. The impact on system outage due to the beamwidth and the gain ratio of the directional antenna, the propagation environment parameters, and the applications of power control and site diversity are discussed. The system outage as a function of modulation SINR threshold is also investigated in this chapter.

Finally in Chapter 7, the thesis concludes with a discussion and recommendations for further research.

1.3 Thesis Contributions

The major contribution of this thesis is that a system model of LMCS is proposed and analyzed in order to confirm good system performance for LOS transmissions. The performance of such system which employs directional antennas at fixed subscribers has been evaluated in both the uplinks and the downlinks. It is verified that by using highly directional antennas at the subscribers and employing polarization transmissions in adjacent sectors, the system can reuse the whole allocated frequency within each cell or even within each sector of the same cell.

In order to benchmark the performance of the LOS system, the performance of a NLOS scenario for the LMCS system has also been evaluated using equal load and the same antenna pattern as criteria of comparison. The comparison of the NLOS and LOS scenarios demonstrates that line-of-sight is a very important criterion for the LMCS system performance.

Analysis and simulation results are conducted to show the significant effects of the beamwidth and the gain ratio of a directional antenna on the system outage. It is confirmed by our original analysis that subscribers in the overlapping area of the cells may receive more interference and have relatively high outage. Simulations have verified that power control and selective macrodiversity are two effective techniques to improve the reception performance for the corner subscribers.

The characteristics of the co-channel interference in LOS system have been investigated through simulations, and the results indicate the dominant interference is from the opposite sector of the same cell. This suggests fairly stringent requirements on the antenna gain ratios. Also low level modulation such as QPSK is suggested due to robustness considerations.

Chapter 2

LMCS SYSTEM AND DIRECTIONAL ANTENNAS

In this chapter, we are going to first describe LMCS system concept, present a brief review of the service requirement and discuss some basic considerations for the preliminary architecture of LMCS. At the second section of this chapter, the applications of highly directional antenna will be introduced along with its significant effects on system performance in wireless systems.

2.1 Local Multipoint Communication System (LMCS)

The concept of using millimeter wave radio frequency for fixed subscribers in United States was originally proposed by Bossard and Hovnanian from Cellular Vision for the purpose of TV broadcasting [4]. Recently, there has been much interest in providing broadband wireless access to fixed networks via millimeter wave radio transmissions. In 1995, the Federal Communications Commission (FCC) proposed frequency bands in 27.5 - 28.35 GHz and 29.1 - 29.25 GHz to offer broadband bidirectional communication services which is called LMDS (Local Multipoint Distribution Services) [2]. Soon after, Industry Canada has also started licensing applications in the 28 GHz band [1], while in Canada LMDS is also called LMCS (Local Multipoint Communication Systems).

2.1.1 Rational and Introduction of LMCS systems

LMCS (or the so called LMDS) is a terrestrial point-to-multipoint radio service providing broadband access to fixed networks. It can provide interactive video and high speed data access services along with broadcast video and telephony. The LMCS system is a cellular system with overlapping cells, its micro-cell site design and the applications of highly directional antennas enhance a high system performance with large capacities within a relatively limited frequency band (The frequency proposed by FCC is about 1 GHz with 150 MHz at uplink and 850 MHz for downlink distributions).

The first person who proposed the concept of using millimeter wave radio frequency for fixed subscriber television services was Bossard from Cellular Vision Company in 1986 and his idea was turned down for the reason that air delivery of cable television was deemed unpromising at that time [4]. Technologies were not sufficiently mature to support high data rate transmissions on mm-wave radio frequencies, and there was too limited radio spectrum available to compete with cable and fibers. Low frequencies were still favored since they can penetrate buildings and tunnels and are cheap to transmit over long distances. The higher the frequency, the larger the loss could be for long distance transmissions. Moreover, these millimeter waves not only would fail to penetrate structures and other obstacles, but also could reflect off them and off particles in the air, causing multipath.

However, the wild rush in DSPs technologies have eventually accelerated development of radio microprocessors and made it possible to support high data rate services on radio links. Moreover, the wireless communications industry has been inching up the spectrum from long and strong wavelengths to wide and weak bands of shorter wavelengths.

Though the millimeter waves do not travel far in the atmosphere and can not penetrate obstacles, good transmission is possible with overlapping small cells and LOS (line of sight) transmissions. The higher the frequency, the wider the available bandwidth, the smaller the antenna, the smaller the cell and ultimately, the cheaper and better the communications at high bit rates.

The advantages of the LMCS wireless local access over competing broadband delivery systems are its significant lower infrastructure cost and much ease installation in comparison with fiber and coaxial systems. The challenge to the system engineer is to design a LMCS system in such a way as to maximize coverage and keep a low cost.

Many LMCS systems are designed to have a cellular layout and attempt to reuse the allocated frequency in each cell. By using highly directional antennas at the fixed sub-

scriber sites and transmit orthogonal linear polarizations in adjacent cells, the interference levels from adjacent cells can be significantly reduced and the multipath effects due to the reflections over obstacles and the motions of foliage can be well attenuated (Figure 1).

Figure 1 Wireless Local Multipoint Communication System (LMDS)

Link budgets for LMDS systems assume an unblocked path between the base station and the subscribers. In many locations, this may not be always available due to the blockage of buildings and trees. Low power repeaters and reflectors can be used to fill in the areas where there is no available LOS transmissions between the hub and the subscribers.

The air interface format might be time division multiple access (TDMA), code division multiple access (CDMA), frequency division multiple access (FDMA) or a combination. It is possible that multiple common air interfaces may emerge. TDMA is preferable to support services with different bit rates [5], while FDMA is suitable to be used in TV broadcasting with fixed bandwidth. For the purpose of robustness, spectral efficiency, and

multiple access simplicity, CDMA might be the preferred approach, however its bandwidth requirements may be huge for high subscriber bit rates.

In order to maximize the system channel capacity people may naturally want to use high level modulation methods such as 16-QAM or 64-QAM. However, in order to maximize system robustness, most proposed LMCS systems use low level modulations such as QPSK, 4QAM, or DQPSK. Furthermore, the modulation formats with higher modulation efficiencies (which are high level formats) must require additional back-off in the transmitter power amplifier, and the phase noise also plays a significant role. Therefore, the utilization of high level modulations could increase costs and reduce the economic advantage of wireless LMDS in comparison with fiber providers.

Several LMCS system designs are proposed by companies such as CellularVision, Video/Phone, and Texas Instruments. The system design conducted by each company is quite different based on their different service provisions. The basic idea of these designs is to provide high performance services with large capacity, along with some cost trade off [3].

The CellularVision system is for analog FM video distribution with a 3 mile cell radius. Polarization reuse, directional subscriber antennas, and frequency interleaving are used in their system design. With frequency interleaving, the carrier frequencies in different cells are offset by half of the adjacent channel spacing. This technique is quite useful with the analog FM modulation format which can concentrate energy near the center of the channel. The system basically provides downlink services such as TV broadcasting and telephony.

The Video/Phone system is a high bit rate digital system which could be used to provide a wide variety of services compared with analog CellularVision. The Video/Phone system uses a 36-sector hub antenna to provide overall omnidirectional coverage with high reliability over short distances. Extra gain is available in the link budget due to the use of sector antennas at the hub. The antenna gain of a 36-sectored antenna with 10°

beamwidth can be as high as 29.7dB [3]. This extra gain and the use of power control allow for increased margin against foliage and rain attenuation.

Texas Instruments (TI) employ different idea on the antenna deployment. They use a highly directional antenna at each subscriber and use a four-sector hub antenna to provide overall omnidirectional cell coverage with a nominal radius of 5 km. This is also suggested by Hewlett Packard that a 90 degree sectored hub configuration may represent the best compromise among hub electronics costs, link margin, frequency reuse and cell to cell interference [6]. Power control is implemented to compensate for rain fading. The TI high bit rate digital system with equal data rates in both directions could be used to provide many services including video conference, data transmission, etc. For applications with asymmetrical traffic, users are multiplexed via TDMA [3]. With heavily overlapping cells, TI has declared that a coverage of 98% with an outage rate lower than 0.1% can be achieved.

The major limitation on delivering LMCS services to subscribers is the extremely challenging propagation environment at millimeter wave frequencies. The system performance is limited by the ability of the system in providing sufficient signal strength over individual radio links. The wind-induced motion of foliage can cause attenuations with significant fluctuations in the received signal level. The measurement in Brighton Beach [7] indicate that the building blockage is a major problem on the ability to provide service to particular locations. It is expected the coverage could be increased by providing selective diversity through overlapping cells.

It might be noticed that many current LMCS systems designs rely on the assumed information regarding to radio propagation phenomena in the anticipated coverage area. Therefore, the research work reported in this thesis has the objective of verifying the use of such information by theoretical modeling and computational simulations.

2.1.2 Service Requirement and Preliminary System Architecture

The wireless LMDS systems could provide wireless access to services ranging from one-way video distribution and narrowband telephony to fully-interactive switched broadband multimedia applications with low cost and fast deployment. Some of the presented considered services provided by LMCS are [8]:

- Conventional television broadcasting and high resolutional HDTV transmissions
- Specialty services and video on demand
- High-speed internet access without a telephone line
- Video conferencing
- Educational services for local school and universities
- Interactive TV programming
- High speed data transfer and local transaction services
- Digital audio and high quality image provision
- High quality digital telephony

One of the enormous incentive for the consumer of high bandwidth in the near future will be the video distributions including interactive video on demand [9]. It might be noticed that the above listed services are either connection-oriented (CO) or connectionless (CL). Connection-oriented services include constant bit-rate (CBR) with selectable fixed bandwidth and variable bit-rate (VBR) with statistically multiplexed bandwidth allocation. Connectionless services include available bit-rate (ABR) as well as high-throughput burst data service for file transfer. In order to support services with different bit rates and different requirement of QOS (quality of service), ATM may be a preferred transmission layout for the LMCS systems [10]. The QOS of these services are shown in TABLE 1 [11]-[15].

Applications	Service Type	Data Rate (Mb/s)		Typical Duration	Maximum Delay(ms)	Cell Loss Rate
		Average	Peak			
voice telephony	CO/CBR	0.06	64kb/s	10 minutes	100	10^{-3}
video telephony	CO/CBR	0.06-2	6	10-20 minutes	100-250	10^{-3}
digital audio	CO/CBR	384	384	30 minutes	10-100	10^{-5}
high-speed data transfer	CL	1-20	1-20	10-100Mb	10^3 - 10^4	10^{-9}
high-resolution image production	VBR	4-45	4-45	8 Mb	1s	10^{-9}
digital video	CO/CBR	1-6	1-6	15min-2h	0.8	10^{-7}
HDTV	CO/CBR	3-32	150	15min-2h	0.8	10^{-9}
e-mail	CL	0.01-0.1	1-10	10ms-1s	10^4 - 10^5	10^{-9}
computer data	CL	0.1-1	10-100	0.1-1s	10^3 - 10^4	10^{-9}
manufacturing (robotics control)	CL	0.01-3	0.01-3	continuous	1-10	10^{-9}

TABLE 1 Wireless services and performance requirements

The early local multipoint distribution system could only support one way distributions, but the current LMCS systems are designed to be able to provide bi-directional services. In a typical wireless LMCS system, the maximum uplink bit rate is 1.5 Mbps for each user, and the downlink bit rate can be as high as 40 - 50 Mbps per subscriber. In consideration of the characteristics of the services with variable bit rates, ATM protocols are likely to be used for the LMCS traffic management.

There are two blocks of 500 MHz of bandwidth in the 26-28GHz band released for several LMCS providers by Industry Canada [1] by the end of 1996, a further four blocks will be released within about two years. Similar bandwidth allocations are proposed in the US where the system is named as LMDS (Local Multipoint Distribution Services) which

has frequency band of 850 MHz for downlink and 150 MHz for uplink as recommended by FCC [2].

The users of LMCS systems are assumed to be in fixed locations without motion, therefore handover is not needed in LMCS. With the total 1 GHz frequency band, a key element in our system design is the use of microcells to enable convenient and high-quality wireless access and to achieve full coverage. Driven by the factors such as RF power and capacity, smaller cell sizes are very attractive if the stringent cost and reliability targets can be met. Microcells permit greater frequency reuse and can be used to serve more users in a given area and offer higher user rates for new services. The radio terminal units can be low-cost, lightweight and have long battery-life in such microcell systems. Given an average user density of 200 - 1000 subscribers per km^2 [6], cells are designed to be 1-5 km in radius, i.e., there are about 200 to 5000 users in each cell.

LOS (line of sight) is preferred and may be required for acceptable received signal level. From the comparisons between LOS and NLOS, we know that by providing LOS links, the system performance can be significantly improved. However, as the antenna heights are limited, (typically, the hub antenna height is 20 - 30 m, and the subscriber antenna is lower than 10 m), LOS may not always be available within the coverage area. Low power repeaters can be used to redirect signal with a new LOS path so as to fill in the coverage hole which is due to the blockage.

Site diversity can also be helpful to reduce coverage holes by providing more than one link for the subscriber, and it could be supported by overlapping adjacent cells. Normally, the transmitter power at the hub is 1 to 2 w for a 40-90 MHz bandwidth and the subscriber transmitting power is less than 100 mw for a bandwidth of about 1-3 MHz.

In our LMCS system, the complete system allocated frequency band is reused in each cell through the use of high directional antennas and polarization reuse in adjacent cells or in adjacent sectors of the same cell. Typically, directional antennas used at the subscribers have 2° beamwidth and 36 dB mainlobe gain. Such antennas at 28 GHz are just

pizza-sized, and can be easily installed on the roof of a building or even be deployed on the windows.

The common air interface format for downstream might be time division multiple access (TDMA), because it is good to support different bit rate services. FDMA can be used for some downlink broadcasting services such as CATV which requires fixed bandwidth. For the uplink, the air interface format could be either TDMA or CDMA.

In order to maximize the system channel capacity, high level modulation methods with high efficiency such as 16-QAM or 64-QAM may be considered with applications of adaptive equalization. As we know, low level linear modulations such as QPSK or 4QAM are more robust to interference, therefore, these are included in the system design.

The required system performance for LMCS is shown below (TABLE 1).

- blocking probability < 1%
- call dropping probability < 0.1%
- call setup time is typically less than 3 seconds with 99%
- An ATM approach requires:
 - isochronous cell loss rate < 10^{-3} , asynchronous cell loss rate < 10^{-4}
 - synchronous delay < 50 ms, asynchronous delay < 250 ms ~ 1 s

It can be noticed that one of the key elements of the LMCS system is the use of highly directional antennas at the fixed subscribers. Directional antennas with narrow beams can not only reduce interference, but also provide a extremely high gain due to its narrow beamwidth. In next section, we will discuss its functionality in more details.

2.2 Directional Antenna

Current day cellular systems are becoming congested due to the rapid increase of traffic and limited frequency spectrum. The traffic carrying capacity can be improved by reducing frequency reuse distances at the expense of worsened cochannel interference which leads to system performance degradation. However, the use of directional antennas

[16] -[20] has proved to be a powerful technique for improving the traffic capacity of a wireless system. By using directional antenna at the subscriber, the reuse factor can be relatively large without degrading the transmission performance.

Directional antennas have long been utilized in some satellite communication systems to reach maximum possible frequency reuse within the limited spectra. In the near future, it will be widely used in indoor PCS environments, outdoor broadband fixed systems such as LMDS (Local Multipoints Distribution Systems), and can even be applied to the base stations of mobile systems as “smart” antenna to track the moving subscribers.

In this section we are going to bring the fundamental concept of the directional antenna, and investigate its tremendous contributions for the improvements of wireless system performance which include capacity enhancement and high data rate support.

2.2.1 Directional Antenna Concept

A directional antenna is an antenna that radiates or receives electromagnetic energy in such a manner that more energy is radiated in, or received from, some directions than others. The directional antenna is capable of transmitting, or receiving, radio signals with greater power in certain directions and lesser or zero power in other directions[21]. Sometimes, it is also called narrow-beam antenna when its radiated energy is confined to a small solid angle and thus has a narrow main lobe. In radar systems and some cellular mobile systems, narrow-beam antennas are well suited for tracking. They are less subject to interference because of their directional capability.

An idealized flat-top power pattern of directional antenna with beamwidth ϕ in azimuth plane is shown in Figure 2 (left one). The pattern shown here has no variation for $0 < \theta < 180^\circ$ in the elevation plane, but normally θ could be designed of any value. As both ϕ and θ decrease to very small values, the antenna pattern could be shaped like a pencil and such directional antenna is sometimes called pencil antenna. Since our simulations are performed in two dimensions only, the equivalent two-dimension antenna model shown in the right part of Figure 2 is actually used in the simulations.

Figure 2 Directional antenna

Directional antennas can be used on either mobile terminals such as moving vehicles, or fixed terminals with fixed locations. In the case of a mobile antenna, the azimuth (Az) and elevation (El) angles are changed while the terminal is in operation, but in the case of fixed antennas, the azimuth and elevation angles are fixed [22]. A fixed directional antenna is relatively cheap due to its simplicity without requirement of adaptability. The directional antenna provided by Texas Instrument for LMCS system at 28 GHz is just pizza-sized and costs only \$200. However, when tracking and adjustment are requested, a much more complex adaptive antenna array of multiple elements would be required. In the consideration of its complexity and cost issues, some people believe that the applications of directional antenna at the base stations may be more feasible than at the moving subscribers.

Theoretically a properly designed adaptive array is able to null out interference from different directions, and the beamwidth of the antenna can be extremely sharp if the number of the elements of the antenna array is large enough and the elements are properly adjusted [22]. The gain of the antenna is inversely proportional to the beamwidth, thus a highly directional antenna could have quite high antenna gain in its main lobe. -

In the following sections, we are going to focus on the directional antenna with single narrow beam, and investigate how such kind of antenna can improve system performance in both mobile systems and fixed wireless systems.

2.2.2 High Data Rate Support by Directional Antenna

It is known that the maximum data rate is limited by multipath effects. In a common wireless propagation environment, transmission is mainly conducted by the way of reflection and scattering from the surfaces of the obstructions such as buildings and by diffraction over them. Then various incoming microwave components arrive at the receiver from different directions with different time delays. This phenomenon is called “multipath” and the signal amplitude fluctuations are called multipath fading (or fading). If the delays are greater than the bit duration of the transmitted signal, intersymbol interference (ISI) will be caused due to this channel distortion. High bit rate transmission could tolerate smaller time delays than lower rate.

To achieve the desired high data rates, the design approach can be focused on either

- accepting the presence of multipath and mitigating it with multitone or equalization techniques, or
- using LOS links with narrow beam antennas to eliminate virtually all multipath and thus use simple unequalized (FSK, PSK) modulation schemes.

Since equalization, diversity or multitone techniques are deemed to be impractical or too expensive, the second approach which concentrates on antenna/beamsteering techniques may be more suitable for a high speeds system with simple 2- or 4-level modulations.

Experiments have been done by AT&T Bell Laboratories where they use a 19 GHz 622 Mbps BPSK link and 15 degree beamwidth horn antennas at subscribers in an office building. The measurement results demonstrate an error-free performance on both LOS and non-LOS links. It is reported by Driessen[19] that the amount of multipath will

depend on the number of ray paths between base stations (transmitter T) and portables (receiver R), which in turn will depend on the directivity (beamwidth) of the antennas at T and R, as well as details of the environment. If omnidirectional antennas are being used at both T and R, then there will be many possible ray paths, whereas if highly directional antennas are used, then there may be only a single LOS path.

Based on these measurement results, Gans, et al[20] have also found that for an indoor environment with a typical maximum path loss of 60 dB, the rms delay spread is at a order of 100 ns with a frequency of 19 GHz. Since equalization is not employed, a BER of less than 10^{-8} requires an rms delay spread less than about 10% of symbol period. Thus this rms delay spread limits the maximum data rate to about 1 Mbps which could not meet the service requirements of current broadband systems. However, the analysis results promise a data rate in excess of 1 Gbps by using directional antennas ($<15^\circ$) at both ends of links.

Gans [20] also points out that the feasibility of high data rates not only depends on the decrease in multipath, but also depends on the received signal power margin. In order to reduce critical areas and reduce complexity of directional antenna, he recommends employing directional antenna at both hubs and subscribers to support high data rates without degrading system performance. His analytical results indicate that 15° of beamwidth is not narrow enough to obtain isolated path in some critical area and high directivity is an important parameter in the directional antenna applications.

It could be noted that the environment may actually generate multiple rays which are closely spaced and in the same direction of the antenna main lobe. Higher directivity reduces the total power of the weaker rays with respect to the strongest ray within the beam, but does not necessarily reduce the delay spread of the signals in the beam. Therefore, as the antenna directivity is increased, the data rate is limited to 1 Mbps by the delay spread until the directivity exceeds some value, at which point the data rate dramatically increases to some high margin [20].

The test results for Cellularvision [8] by D. E. M. Allen & Associates LTD in Calgary has shown that 95% of locations could completely avoid multipath by using narrow beam antenna with 2° beamwidth. Such a narrow beam may not be practical for mobile system because of the mobility of subscribers. However, more and more fixed wireless systems are trying to approach this sharp-beam antenna applications.

At millimeter wave of 28 GHz, it is quite difficult to design the transceiver to provide high transmitting power. By using highly directional antenna, the transmitting power can be amplified by the high antenna gain which is a result of the narrow beamwidth of the directional antenna.

In conclusion, higher data rate could be achieved by either increasing the transmitting signal power to tolerate higher noise power due to the wider bandwidth, or supporting such broadband services in higher carrier frequency in a range of tens of GHz. By using directional antennas, the transmission margin can be increased due to the high gain of the narrow beam, and the effect of multipath can be significantly reduced by the high directivity of the antenna.

2.2.3 Directional Antenna on Capacity Improvement

It is known that the current wireless systems are becoming congested due to the growing competition for spectrum. Many different approaches have been proposed to maximize data throughput while minimizing spectrum requirements for future personal communications systems. One way to increase capacity without added spectrum is to reduce cell sizes and reduce frequency reuse factor, while smaller ratio of frequency reuse within small area will bring more interference. However, using directional antenna at either hubs or subscribers could improve signal to interference ratio (SIR) by its directivity and therefore increase system capacity.

Rappaport and Joseph have compared 5 different antenna patterns in a CDMA system and they found the system capacity can be improved significantly by using directional antenna at base stations [23]. In their simulation, the 5 antenna patterns are omni, 60° sectorized, adaptive, 30° flat-topped and adaptive-sectorized antennas. The last one is an application of adaptive array overlaid with a 120° sectorization antenna pattern.

Their simulation results indicate that without consideration of the sidelobe, a 60° sectorized antenna pattern could achieve a BER one order of magnitude less than that of an omni system, while a 30° flat-top antenna pattern with a sidelobe 6 dB lower than the main lobe can reduce the BER almost two orders of magnitude. Rappaport points out that for a given bit error rate, two or four times of users can be supported by using directional antennas as that of an omni system. Therefore, the capacity improvements are primarily due to the directivity of the antenna.

It is found that system performance could be further improved dramatically when sectorization is combined with the adaptive antenna approach. Adding the three element array to the sectorized system could provide a reduction in BER of three orders of magnitude. In terms of capacity, the results indicate that using adaptive antennas at the base station could increase the number of users by a factor of 2 to 4, while maintaining an average BER of 10^{-3} on the reverse link. Similarly, the bit error rate on the reverse channel could also be improved by adding adaptive antennas at the portable unit.

Most analytical results conducted by Rappaport is confirmed by other simulations performed by A. Pote and R. Carver [17]. Pote and Carver simplify the directional antenna by assuming that the antenna has a gain across the beamwidth and has zero outside the beam, i.e., the antenna has no sidelobe. Their simulation interest is on the fixed system without adaptability requirement, thus there is no analysis on the performance of adaptive antenna. Pote and Carver's simulation results on the directional antenna with a fixed angle predict similar BER as those of Rappaport's by using same user density. The propagation exponent and beamwidth of the directional antenna are found to be quite sensitive parameters for the system performance in the simulations conducted by Pote and Carver [17].

In short, directional antenna has been verified to have significant contributions in the capacity improvements of CDMA mobile systems and the high data rate support in wireless systems. However little knowledge is available on its applications on LMCS system with TDMA access format. Detailed effects of antenna beamwidth and gain ratios are scarce too. In later chapters, we are going to discuss the characteristics of propagation environment, investigate how directional antennas can enhance the performance of TDMA systems, and verify our preliminary architecture design of LMCS system.

Chapter 3

RELEVANT COMMUNICATION THEORY

3.1 Path Loss

3.1.1 Free Space Loss

The free space loss predicts the signal attenuation between the transmitted power and the received power when the transmission is remote from the earth with a clear, unobstructed line-of-sight path between the transmitter and the receiver. If the distance from a receiver antenna to a radiating transmitter antenna is d , the transmitter antenna gain is G_T and receiver gain is G_R , then we obtain

$$\frac{P_R}{P_T} = G_T \cdot G_R \cdot \left(\frac{\lambda}{4\pi d} \right)^2 \quad (1)$$

where P_R represents the signal power received at the receiving antenna and P_T is the power of the same signal at the output of the transmitter. λ represents the frequency of the signal[24].

The frequencies in the region of several gigahertz or tens of gigahertz have several attractive features. Compared with lower frequencies, such high frequencies could provide more plentiful bandwidth and avoid man-made noise interference from ignition systems. At high frequencies such as 28 GHz for LMCS, the size of an efficient antenna can be on the order of centimeters, and antenna separations as small as several cm can provide uncorrelated received signals suitable for achieving diversity in the received signal.

3.1.2 Propagation Over a Reflecting Surface

For distances less than a few tens of kilometers, it is often permissible to neglect earth curvature and assume the surface to be a plane.

If we consider both the directional path and the ground reflected propagation path between the transmitter and receiver, and assuming the distance between them is much larger than the heights of both transmitting antenna and receiving antenna, then:

$$\frac{P_R}{P_T} = G_T G_R \left(\frac{h_T h_R}{d^2} \right)^2 \quad (2)$$

The propagation loss is related to d^{-4} instead of d^{-2} in free space transmission. It should be emphasized that the Equation 2 only applies at ranges when $d \gg h_T$ and $d \gg h_R$. When the receiver is close to the transmitter, e.g. $d < 15$ km, the following equation is recommended to be used with propagation exponent m between 2 and 4 [24].

$$\frac{P_R}{P_T} \propto G_T G_R \frac{1}{d^m} \quad (3)$$

In a LMCS system the cell radius is typically less than 5km and cells are heavily overlapped. The significant interference usually comes from a distance of less than about 10 km, so we chose m to be 3 instead of 4.

3.2 Large Scale Fading (Shadowing)

Shadowing is manifested as large scale variations in mean signal level, occurring over distances of many wavelengths. The local average signal strength may vary vastly at different locations which have same transmit/receive separation but different propagation paths. Measurements indicate that the shadowing closely fits a log-normal distribution [25]. The log-normal variation implies that the measured signal level in dB unit at a certain T-R separation follow a Gaussian distribution. That is,

$$x = 10 \log r \quad (4)$$

$$P_r(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left(-\frac{(x - u)^2}{2\sigma^2} \right) \quad (5)$$

where r is a log-normal random variable with a mean of u and a standard deviation of σ .

Typically the deviation of shadowing for outdoor radio propagation is around 4 to 10 dB (under the condition that both hub and subscriber use omni-antennas). In our system analysis, we usually chose 10 dB as the deviation of basic signal process, i.e. the random interference from the main lobe of the base sector antenna to the main lobe of the narrow-beam subscriber-antenna.

3.3 Multipath and Fading

Propagation between the transmitter and receiver could be either line-of-sight or non line-of-sight, or a combination. The non LOS propagation is mainly by reflection and scattering from the surfaces of the obstructions such as buildings and by diffraction over them. Thus various incoming microwave components arriving at the receiver from different directions have different time delays. This phenomenon is called "multipath" and any signal amplitude variations due to movement of transmitter, receiver or reflectors are called multipath fading (or fading).

The signal amplitudes could vary significantly between locations which are just short distance away with a fading about 20 dB normally[26]. This is because the phase relationships among the incoming waves are different. These small scale fluctuations caused by the local multipath follows a Rayleigh distribution for non-line-of-sight situation and typically has a Ricean distribution for line of sight.

Small-scale fading behaves quite differently for signals with different bandwidths in a given multipath channel. When the transmitted signal has a narrow bandwidth, large signal fluctuations (fading) will occur at the receiver due to the phase shifts of the many unresolved multipath components. However, when the transmitted signal has a bandwidth much greater than the bandwidth of the channel, the multipath structure is completely resolved by the received signal at any time, and the received power has less variation since the individual multipath amplitudes do not change rapidly over a local area [26] [27]. For broadband signals (i.e. whose transmission bandwidth is much greater than channel coherence bandwidth), such as those high data rate services in LMCS, the fade depth tends to be

relatively small, and fading of the received signal power is less noticeable than for the narrowband signals. Fading is also less evident when there is little or no movement of the transmitter or receiver.

3.4 Interference

3.4.1 Cochannel Interference

When two or more communication radio channels are assigned to the same frequency, the interference between the signals from these two channels is called co-channel interference. One way to reduce co-channel interference is to decrease the frequency reuse, i.e., co-channel cells must be separated by a minimum distance to provide sufficient isolation due to propagation loss.

Suppose the cell radius of a cellular system is R , and the distance between two co-channel cells is D , the signal to interference ratio (SIR) can be increased by decreasing the ratio of D over R , or increasing the frequency reuse factor. The frequency reuse factor is defined as the ratio of the total allocated bandwidth to the amount of bandwidth allocated to a given cell.

3.4.2 Adjacent Channel Interference

Adjacent channel interference is the interference from signals in frequency channel which is adjacent to the desired communicating channel. Adjacent channel interference results from imperfect receiver filters which allow adjacent channel signals to leak into the passband. It can be minimized through careful filtering and channel assignments. By keeping as large as possible the frequency separation between each channel in a given cell, the adjacent channel interference may be reduced considerably.

In a LMCS system, as each cell reuses the whole frequency band of the system, the co-channel interference becomes a fundamental consideration in system performance analysis. Adjacent channel interference is assumed to be well filtered at the receiver and will not be considered in the analysis.

Since the employment of a narrow-beam antenna at the subscriber could reduce multipath components significantly, and techniques such as diversity are quite effective to further mitigate the small scale fading, therefore the co-channel interference considerations for frequency reuse systems are more dependent on large scale signal variations which are log-normal distributed.

3.5 Diversity

Diversity is a technique implemented at a receiver to find independent (or uncorrelated) signal paths for communication based on the random nature of radio propagations. If one radio path undergoes a deep fade, another path which is independent from this one may have a strong signal. By having more than one path to select from, the signal received at the receiver may be improved.

Diversity techniques include space diversity, polarization diversity, time diversity, and frequency diversity. A system employing space diversity uses multiple antennas which are spatially separated so that the received signals at each antennas are uncorrelated. Space diversity can be classified as micro-diversity and macro-diversity. Micro-diversity can be used to reduce multipath and mitigate small-scale fading, and macro-diversity is effective against shadowing.

Site diversity is a kind of macro-diversity to improve reception performance by allowing the subscriber to select the best link (by its SINR) from the nearby base stations. We are going to investigate this diversity method on the performance improvement of LMCS systems in this project.

3.6 Power Control

In cellular radio systems, power control is used to ensure the smallest transmitting power which is still necessary to maintain a good quality link. Power control can be used for both uplink and downlink. It not only helps to reduce power consumption, but also dramatically improves the SIR at the receiver.

The "near-far problem" in cellular system occurs when many users share the same channel and some users far from the base stations may receive high interference from those near the base stations. Power control can be used to reduce the power of the users who are near the base stations to an acceptable level so as to increase the SIR reception of the users who are far from the base stations. Therefore, the system outage rate can be decreased and the capacity could be improved. Power control can be used in both TDMA and CDMA systems, although it is far more critical to the performance of CDMA systems.

Chapter 4

ANALYSIS ON THE SYSTEM PERFORMANCE OF LMCS WITH DIRECTIONAL ANTENNAS

It is known that in a multipath base station radio system, co-channel interference limits the reuse interval between cochannel coverage areas [28] [29]. When the system allocated bandwidth is limited, the reuse frequency interval has to be designed to be as small as possible in order to achieve large system capacity. However, system error performance can be significantly affected by the interference from adjacent cells [30], and small reuse intervals results in more cochannel interference.

The wireless LMCS system is designed to attempt to reuse the allocated frequency bandwidth in each cell or even in each hub antenna sector. In such a case, the co-channel interference is the most fundamental consideration due to the heavy reuse of radio frequencies.

The performance of radio channels fluctuates with the multipath and shadowing loss of the desired signals and interfering signals. The application of directional antennas at the subscribers could reduce the multipath of the desired links and significantly suppress the co-channel interfering signals. In this chapter of analysis, the system is modeled by a cellular layout of regular hexagonal cells, and the system performance is demonstrated by outage probability and investigated at the downlink. The system is evaluated based on the signal to interference ratio (SIR) of the subscriber which is located at the corner of each Hexagonal cell (Figure 3). Such a corner subscriber may suffer much more interference than those near the base stations, and it is evaluated as one of the worst cases in the LMCS system. In this and the next chapters, all channels are pessimistically assumed to be in use at all times, i.e., subscriber traffic statistics are not taken into account.

The subscriber is allowed to select the best reception from the nearby hubs, and such selective site diversity can efficiently reduce the effect of shadowing on the system performance [30] [31] [32].

Through using directional antennas with very narrow beams at subscribers, multipath is reduced significantly and the rms delay spread is quite small, about 10 ns or even less[33]. Hence, we can neglect the effect of inter-symbol interference (ISI) which is caused by multipath delay spread. The performance investigations below are focused on co-channel interference estimations and the outage calculations based on signal-to-interference ratio (SIR).

4.1 Downlink Signal-to-Interference (SIR) Estimations

The wireless LMCS system is a cellular system of multiple base stations which provide broadband services through radio links to subscribers at fixed locations. The system is designed to employ frequency division duplex (FDD) to separate the uplink and downlink, with a hybrid of TDMA and FDMA as a basic multiplexing scheme in the system. This scenario is used in later analysis and simulations.

Figure 3 Cellular LMCS System with Directional Subscriber Antennas

I_D , I_H and I_L are cochannel interferences to the desired subscriber

The hub antenna is either omnidirectional or sectored

The co-channel interference is calculated based on the propagation model which assumes space loss over reflecting earth plane, and includes a log-normal shadowing effect. As most of the transmitted signals are high bit rate services with wide bandwidths, the local received power fluctuations of such a broadband signal are relatively small, and are assumed to be mitigated by positioning antennas within an area of a few wavelengths to maximize signal strength. Therefore, fast fading (Rayleigh or Rician) is not included in the interference estimation of the LMCS system.

In consideration of power consumption and coverage requirement, small cells are preferable in LMCS systems and here we assume the cell radius is 5 km. It is noticed from Figure 3 that most of interference is contributed by the nearest three tiers of base stations around the considered subscriber. Therefore, most interferences have distances less than 20 km. According to the discussion in section 3.1.2, the value for the propagation exponent m in the distance dependence of interference is typically less than 4 for moderate distances. In fact, the path loss exponent is also related to the antenna height, and are affected by the number of obstacles in between the transmission link [25] [34]. When the antenna height is relatively low and the distance is not very large as in the case of our NLOS system, the path loss exponent should be between 2 to 4. Hence in our non line of sight system analysis, the exponent m of 3 is selected as an example.

4.1.1 Considerations on the Distribution of the Interference

As stated before, the transmitted radio signal is lognormal distributed while the short scale deviation is assumed to have been reduced significantly. Thus the desired signal and the interference from each base station are random variables with lognormal distributions [35]:

$$s = 10\log S \quad (6)$$

$$i_i = 10\log I_i \quad (7)$$

$$f(s) = \frac{1}{\sigma_s \sqrt{2\pi}} \exp\left(-\frac{(s - \bar{s})^2}{2\sigma_s^2}\right) \quad (8)$$

$$f(i_i) = \frac{1}{\sigma_{ii} \sqrt{2\pi}} \exp\left(-\frac{(i_i - \bar{i}_i)^2}{2\sigma_{ii}^2}\right) \quad (9)$$

where I_i is the interference from the i th base station, and S is the signal power, σ_s and σ_{ii} are the deviations of the signal s and the i th interference i_i . The total interference received by a specific subscriber at a corner is:

$$I = \sum I_i \quad (10)$$

The treatment of multiple lognormal interferers is complicated by the fact that there is no theoretical closed-form expression for the sum of lognormal interferences. The sum of lognormal random variables is still assumed to be log-normal distribution in the investigations conducted by Chan [36], Wilkinson [37], and Schwartz [38]. In Chan's paper the mean and the variance of the sum of interferences were assumed to be the same as those of each individual interference under the interference-limited condition and the assumption that each interference is at the same level. Wilkinson's approach [37] leads to useful results only for a limited range of small values of spread deviation which is not in the range of practical interest of outdoor environment. Schwartz and Yeh [38] presented another approximate technique in their paper for the evaluation of the mean and variance of the power sums with lognormal components. The accuracy of Schwartz's approximation is well confirmed with deviation ranging from 2 dB up to 14 dB by comparing with Monte Carlo simulation results. Given each basic process with variance of 10 dB, the calculated sum of up to 10^5 of such random processes leads to a variance of 5.5 dB for the equivalent lognormal process. This is under the condition that both base station and subscriber use omni-antennas. Following Schwartz's estimation method, we calculate the mean and deviation of the sum of interferences with the assumption that the signal transmitted from the main lobe of the base sector antenna to the high beam of the subscriber-

antenna has a lognormal random distribution with deviation σ . Given the σ is equal to 10dB, the evaluation result shown in Figure 8 later indicates that the deviation of the sum for this non-omni system is greater than 5.5 dB which is derived in the Monte Carlo simulation for omni-system [35]. The mean and deviation estimation of the sum of the interferences will be discussed in details in section 4.3.2.

4.1.2 Downlink SIR Calculations Under the Condition of No Shadowing

As the system frequency reuse factor is one, co-channel interference to the subscriber could come from adjacent base stations when the system is heavily loaded. Most of the co-channel interferences are mainly contributed by the base stations which are quite near the subscriber, thus the interference which is not within the nearest three tiers of cells is neglected in this estimation.

Given a 120°-sectored system with regular hexagon-cell-coverage and each base station located at the center as shown in Figure 3, it is observed that within the nearest of the three tiers of cells around the desired corner subscriber, there is one interference coming from the main lobe of the base-antenna to the main lobe of the subscriber-antenna. This interference (I_D) is the most significant interference to the subscriber. 6 interferences are from the main lobe of the base-antenna to the sidelobe of the subscriber (I_H), and other interferences are from the sidelobe of the base to the sidelobe of the subscriber (I_L). After determining which type of interference it is (either I_D , I_H or I_L), we calculate the average power of each of these interferences by,

$$I_D = P_T \cdot G_S \cdot G_B \cdot \left(\frac{c}{4\pi f}\right)^2 \cdot \frac{1}{d^m} \quad (11)$$

$$I_H = P_T \cdot (G_S/\alpha) \cdot G_B \cdot \left(\frac{c}{4\pi f}\right)^2 \cdot \frac{1}{d^m} \quad (12)$$

$$I_L = P_T \cdot (G_S/\alpha) \cdot (G_B/\beta) \cdot \left(\frac{c}{4\pi f}\right)^2 \cdot \frac{1}{d^m} \quad (13)$$

where d is the distance between the interfering base and the subscriber, α and β are the subscriber-antenna and base-antenna gain ratios respectively. The gain ratio is defined as the ratio between the main lobe gain and the peak sidelobe gain. G_S and G_B is the subscriber-antenna gain (main-lobe gain) and base-antenna gain (main-lobe gain) respectively.

The average signal to interference ratio for each interference from base station i is:

$$(SIR)_i = 10\log S - 10\log I_i \quad (14)$$

where I_i could be either I_D , I_H , or I_L . If the shadowing is not considered, the SIR of the sum of the interferences is $SIR = 10\log S - 10\log \Sigma I_i$.

Figure 4 Dominant Interference in the Downlink of Sektored System
(angle A=38 degrees, angle B=11 degrees)

It is shown in Figure 4 that the dominant interference is from the interfering hub which is located behind the desired base station right in the beam direction of the subscriber antenna. Under the assumption of regular hexagon cells coverage, within the range of $B=11$ degrees in the beam direction, one may notice that there is only one interferer at distance $4r$ (r is the cell radius) from the subscriber at the corner of the cell. Even if the

beamwidth of the subscriber antenna is very small, this interference could not be avoided. Similarly, when the antenna beamwidth grows from 11 degrees (angle B) to 38 (angle A) degrees as shown in Figure 4, there are additional two interferers which are approximately $5.5r$ away and the power of interference within this range keeps constant. Such insensitivity of the received SIR to the beamwidth of antenna is not entirely realistic, because the buildings' reflections could introduce interference from outside of the beam range. Besides, the actual service coverage area is mapped with irregular cells and the hubs may not be located at the exact center of each cell, therefore there might be more than one interferers within the beam width of 11 degrees.

4.1.3 Moments Estimation of SIR with Consideration of Shadowing

As stated in section 4.1.1, the sum of interferences is approximately lognormal distributed. The main question, then, is how to estimate the mean and deviation of this new lognormal random variable. Here we use Schwartz and Yeh's approximation method [38]. Since our interest is the SIR of the corner subscriber rather than the interference itself, and SIR is also a lognormal random variable, the mean and deviation estimation is focused on SIR instead of the total interference.

Let us first focus on the moments estimation of two variables, then the multiple-interference could be easily solved.

Supposing there are two independent interfering signals with the corresponding two variables $L_1 = I_1/S$ and $L_2 = I_2/S$, where I_1 and I_2 represent the two interferences and S is the desired signal power, then it is assumed:

$$Y_1 = \ln L_1 \quad (15)$$

$$Y_2 = \ln L_2 \quad (16)$$

$$L = e^L = L_1 + L_2 \quad (17)$$

Therefore,

$$Z = \text{Ln}(e^{Y_1} + e^{Y_2}) \quad (18)$$

We define the ISR (interference to signal ratio) in log-scale of the sum of the two variables P_2 :

$$P_2 = 10 \log L = 10 \log(L_1 + L_2) = (10/\text{Ln}10)Z \quad (19)$$

Define the Gaussian random variable

$$\omega = Y_2 - Y_1 \quad (20)$$

$$m_\omega = m_{Y_2} - m_{Y_1} \quad (21)$$

and get

$$\sigma_\omega^2 = \sigma_{Y_2}^2 + \sigma_{Y_1}^2 \quad (22)$$

$$\begin{aligned} E(Z) &= E[\text{Ln}(e^{Y_1} + e^{Y_2})] \\ &= E\{\text{Ln}[e^{Y_1}(1 + e^{Y_2 - Y_1})]\} \\ &= E(Y_1) + E[\text{Ln}(1 + e^\omega)] \\ &= m_{Y_1} + G_1(\sigma_\omega, m_\omega) \end{aligned} \quad (23)$$

where m_{Y_1} and $\sigma_{Y_1}^2$ are the mean and variance of random variable Y_1 , m_{Y_2} and $\sigma_{Y_2}^2$ are the mean and variance of random variable Y_2 , and,

$$G_1(\sigma_\omega, m_\omega) = \int_{-\infty}^{\infty} f(\omega) \cdot \text{Ln}(1 + e^\omega) d\omega \quad (24)$$

$$f(\omega) = \frac{1}{\sqrt{2\pi}\sigma_\omega} \exp\left(-\frac{(\omega - m_\omega)^2}{2\sigma_\omega^2}\right) \quad (25)$$

then the mean of the log-scale P_2 is:

$$m_{P_2} = (E[P_2]) = (10/\text{Ln}10)E(Z) \quad (26)$$

To find the standard deviation of P_2 ,

$$\begin{aligned} E(Z^2) &= E[\text{Ln}^2(e^{Y_1} + e^{Y_2})] \\ &= E\{[Y_1 + \text{Ln}(1 + e^\omega)]^2\} \end{aligned}$$

$$= \sigma_{Y_1}^2 + m_{Y_1}^2 + E[2Y_1 \text{Ln}(1 + e^{\omega})] + E[\text{Ln}^2(1 + e^{\omega})] \quad (27)$$

Following Yeh's method [38],

$$\begin{aligned} \sigma_Z^2 &= E(Z^2) - m_Z^2 \\ &= \sigma_{Y_1}^2 - G_1^2(\sigma_{\omega}, m_{\omega}) - 2\rho^2 G_3(\sigma_{\omega}, m_{\omega}) + G_2(\sigma_{\omega}, m_{\omega}) \end{aligned} \quad (28)$$

where

$$\begin{aligned} G_1(\sigma_{\omega}, m_{\omega}) &= \int_{-\infty}^{\infty} f(\omega) \cdot \text{Ln}(1 + e^{\omega}) d\omega \\ G_2(\sigma_{\omega}, m_{\omega}) &= \int_{-\infty}^{\infty} f(\omega) \cdot \text{Ln}^2(1 + e^{\omega}) d\omega \\ G_3(\sigma_{\omega}, m_{\omega}) &= \sigma_{\omega}^2 \int_{-\infty}^{\infty} f(\omega) / e^{\omega} (1 + e^{\omega}) d\omega \end{aligned} \quad (29)$$

then the deviation of the log-scale P_2 is:

$$\sigma_{P_2} = (10/\text{Ln}10) \cdot \sigma_Z \quad (30)$$

The above formulae are developed to compute the exact mean and variance for the power sum with two components.

$$P_2 = 10\log(L_1 + L_2) \quad (31)$$

As discussed before, the sum of the two log-normal variables P_2 is still approximately a log-normal variable with the mean m_{P_2} and the deviation σ_{P_2} . Then the sum of three variables can be considered as:

$$P_3 = 10\log(L_1 + L_2 + L_3) = 10\log(10^{(P_2/10)} + L_3) \quad (32)$$

and compute the mean and deviation is computed using the derived formulae. In this manner, iteration is conducted until the required moments of P_k are obtained,

$$P_k = 10\log(L_1 + L_2 + \dots + L_k) \quad (33)$$

where $L_i = I_i/S$, P_k is the total ISR in log-scale, then the mean and variance of SIR are:

$$\begin{aligned} m_{SIR} &= -m_{P_k} \\ \sigma_{SIR} &= -\sigma_{P_k} \end{aligned} \quad (34)$$

In our interference estimation for the corner subscriber, about 30 interfering base stations within the nearest three tiers are being considered, thus iteration number k is taken as 30.

4.2 Outage Probability and Error Probability

The reception performance which depends on the criteria of SNR ratio could be expressed in terms of outage probability which is the probability of unsatisfactory reception. Different modulations require different SNR thresholds by given a limit of bit error probability. e.g. uncoded 4QAM requires a minimum SNR of 10 dB to obtain an bit error probability (BER) to be less than 10^{-3} . With a proper error control coding employed, the BER could drop to less than 10^{-8} .

There are two basic methods to estimate the outage probability of the system. First, we could estimate the deviation and the mean of the lognormal random variable S/I in log-scale, and then calculate the outage probability based on its Gaussian distribution in log-scale (method A).

$$m_{db} = E(10\log S/I) \quad (35)$$

$$\sigma_{db} = \sqrt{\text{Var}(10\log S/I)} \quad (36)$$

$$P_1 = \frac{1}{\sqrt{2\pi}\sigma_{db}} \int_{-\infty}^{\gamma} \exp\left(-\frac{(x - m_{db})^2}{2\sigma_{db}^2}\right) dx \quad (37)$$

where m_{db} and σ_{db} are the mean and variance of $(S/I)_{db}$ and the estimation is described in section 4.1.3, I is the sum of total interference, P_1 is the outage probability and γ is the system signal-to-interference threshold for a specific modulation for a given bit error probability.

On the other hand, we can estimate the outage probability in its linear scale (method B). Given the deviation of the desired signal σ_s and deviation of the total interfer-

ence σ_i , and the average of signal to interference ratio $\bar{S}/\bar{I}$ in linear scale, the outage probability P_1 could be also derived by [35]:

$$P_1 = P(s - i < \Upsilon) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-\Upsilon} \exp(-z^2/2) dz \quad (38)$$

where Υ is the system signal-to-interference threshold for a specific modulation.

$$v = \frac{\bar{s} - \bar{i} - \Upsilon}{\sqrt{\sigma_s^2 + \sigma_i^2}} \quad (39)$$

$s = 10 \log S$ and $i = \log I$ with σ_s and σ_i are the deviations of s and i (Note: s and i are in linear scale).

$$\bar{s} - \bar{i} = 10 \log(\bar{S}/\bar{I}) - (\sigma_s^2 - \sigma_i^2)(\ln 10)/20 \quad (40)$$

where, $10 \log(\bar{S}/\bar{I}) = m_{db}$, and the estimation of m_{db} is described in section 4.1.2. Given the same condition, estimations through method A and method B should approach the same result. Here, method A is used for convenience.

The mean and standard deviation of S and I (in linear scale) could be transferred to the mean and deviation of s and i (in log-scale) by [35]:

$$\bar{s} = e^{(\ln 10/10)^2 \sigma_s^2 / 2} e^{(\ln 10/10) \bar{s}} \quad (41)$$

$$\bar{i} = e^{(\ln 10/10)^2 \sigma_i^2 / 2} e^{(\ln 10/10) \bar{i}} \quad (42)$$

$$\sigma_s^2 = \left[e^{(\ln 10/10)^2 \sigma_s^2} - 1 \right] e^{(\bar{s} \ln 10)/5} e^{(\ln 10/10)^2 \sigma_s^2} \quad (43)$$

$$\sigma_i^2 = \left[e^{(\ln 10/10)^2 \sigma_i^2} - 1 \right] e^{(\bar{i} \ln 10)/5} e^{(\ln 10/10)^2 \sigma_i^2} \quad (44)$$

It is confirmed by Cox[35] that by given $\sigma_s = \sigma_i$, the mean of I_i/S in linear scale $[10 \log(\bar{S}/\bar{I})]$ is the same as the mean of ISR_i in log-scale $[(ISR)_{db}]$, because:

$$\overline{(ISR)_{db}} = 10 \log(\bar{S}/\bar{I}) - (\sigma_s^2 - \sigma_i^2)(\ln 10)/20 \quad (45)$$

when σ_s and σ_i are equally 10 dB, then $\overline{(ISR)}_{db} = 10\log(\bar{S}/\bar{I})$. Thus the estimation result of $10\log(\bar{S}/\bar{I})$ in linear scale could be applied in the probability calculation in method A directly to substitute m_{db} in log scale. If σ_s and σ_i are not equal, then the average of the lognormal variable I/S estimated in section 4.1.2 will be quite different from the mean of the Gaussian variable $\overline{(ISR)}_{db}$.

Figure 5 shows that even though the average signal to interference ratio $\bar{S}/\bar{I}$ is much higher than the threshold required, the outage probability is still large in comparison with the general system bit error probability of 10^{-3} due to the large scale variation of shadowing. However, if we take a look at the corner subscriber in Figure 6, we can find there are three base stations with distance of r (r is the radius of the cell) to the subscriber. The subscriber could chose either of them by switching its antenna beams to point to the selected base station. Thus the three hubs have equal independent probabilities to service the corner subscriber through different channels. Fluctuations on the signals and interferences should be independent, hence the overall outage probability of the three nearest base stations P_{1e} is the third power of the outage probability of one base station, i.e. $P_{1e} = P_1^3$ while $P_1 = P(s-i < 1)$. The subscriber could further select another three hubs which are $2r$ away from the subscriber and the six hubs in the third tier (with equal distances of $2.6r$ to the subscriber) if the nearest three hubs could not provide good quality of service (Figure 6). The overall outage probabilities for each tier of base stations are: $P_{2e} = P_2^3$ and $P_{3e} = P_3^3$ while P_{3e} is shrunk to the third power of P_3 instead of the sixth (Figure 6) because of the dependent situation of inter base stations.

Figure 5 Outage Probability of One base station in 3-sectored System
 $m=3$, beam $<11^\circ$ QAM: SIR threshold=9.8dB for $P_e < 0.001$ (include shadowing)

Figure 6 Selective Site Diversity in Wireless LMCS System

4.3 Estimation Results and Performance Analysis

We first calculate the average of each $ISR = I_i/S$ as described in section 4.1.2 without consideration of shadowing and transfer it into dB units. In the further estimation including the shadowing effect, we assume the variances of $10\log I_i$ and $10\log S$ are 10db, thus the variance of $10\log(I_i/S) = 10\log I_i - 10\log S$ is $10\sqrt{2}$ dB, then we estimate the mean and deviation of the total signal-to-interference ratio in log-scale SIR_{db} , (described in section 4.1.3) where

$$SIR_{db} = 10\log S - 10\log \sum I_i = -10\log \Sigma(I_i/S) \quad (46)$$

As SIR_{db} follows a Gaussian distribution, the outage probability of the corner subscriber could be derived from method A in section 4.2.

4.3.1 Considerations on Hub-antennas

Following section 4.1.2, the interference of the corner subscriber from each base station I_i is calculated, and the total interference is estimated by summing the I_i . The SIR comparison of the omni and the sector system is shown in Figure 7. The SIR of the omni system is quite low when using subscriber-antennas of low gain. Even though the gain ratio of the subscriber antennas is increased to 20 dB, the SIR estimated with the consideration of the large scale variation is still as low as 0 dB for omni hub antennas as shown in Figure 7. This result makes it clear that omni cells with isotropic antennas at the base stations may not be suitable for radio system with frequency reuse of 1. Hence, each cell must be sectorized to reduce the interference. The SIR could be expected to be increased at least 5 dB when the cells are split into three 120-degree sectors, and it could be further improved when increasing the number of sectors of each cell. However, with highly directional antennas employed at the subscriber, too many sectors with relatively small beams at the base station will introduce more sensitivity to pointing errors. System design with 120-degree sectors may be one of the possible selections for the LMCS system architecture.

Figure 7 Average SIR with Consideration of Shadowing
 $m=3$, beam $< 11^\circ$ (include shadowing with deviation=10db for each individual interference)

Figure 8 Standard Deviation of SIR in 3-sectored System
 $m=3$, beam $< 11^\circ$ (include shadowing with deviation=10db for each individual interference)

The later estimation and analysis are based on this 120°-sector-cell assumption for the basic LMCS architecture with narrow-beam antenna used at the fixed subscriber site (Figure3). In the later section, 90° sectors are also considered in LOS system.

4.3.2 Mean and Standard deviation of SIR

The moments estimation of SIR is under the assumption of 10 dB deviation for interference from the main lobe of hub antenna to the subscriber high beam, i.e. I_D . The other interferences are $I_H = I_D/\alpha$ and $I_L = I_D/\beta/\alpha$, where α is subscriber-antenna gain ratio and β is hub-antenna gain ratio. α and β could be treated as constant in the interference log-normal random process. Therefore the deviation of I_H and I_L are the same as that of I_D , and the deviation of each individual interference received is 10 dB. The antenna gain ratio has no effect on the standard deviation estimations.

As indicated in Figure 7 and Figure 8, the average SIR has approximately linear increase versus subscriber-antenna gain ratio, and the SIR also increases as the base-antenna gain ratio increases. As the gain ratio increases, the antenna reduces its sidelobe, and thus attenuates co-channel interference. It is shown that the average SIR of the omni-system is significantly lower than that of the sectored system. With the same condition of 20 dB hub antenna gain ratio and 15 dB subscriber-antenna gain ratio, the omni-system has a SIR about 10 dB lower than the 120°-sector system. This confirms the sector system selection.

The deviation of SIR of the sectored LMCS system is 6-8 dB (see Figure 8) if each individual interference has a standard deviation of 10 dB. As the subscriber-antenna gain ratio increases, the deviation of SIR increases slowly, but will not exceed the deviation of individual $(ISR_i)_{dB} = 10\log(\bar{I}_i/3)$ which is $10\sqrt{2}$ dB. This is because the variance of the sum of interference is affected by two parameters: not only the mean of each individual interferences, but also the variance of those interferences. The decrease in the power of individual interferences leads to an increase in the deviation of the total interference. As the

subscriber-antenna gain ratio increases, the interferences are reduced and the deviation of the total interference increases.

4.3.3 System Performance Analysis

The regular cell coverage of LMCS system shown in Figure 3 indicates that the most significant interference I_D is coming from the base station sitting right behind the servicing hub. As seen in Figure 7, this interference from the main lobe of the base antenna in the beam direction of the subscriber at the corner of the cell limits the SIR to below 15 dB and decreases the system performance significantly, while the sum of the other interferences I_H and I_L which are received by the sidelobe of the subscriber-antenna could decrease SIR at most 2 dB when the subscriber-antenna gain ratio is 15 dB. Because of such a dominant interference I_D , the outage probability of the corner subscriber is relatively large (Figure 9) and it could be noticed that this is not the worse case. The subscriber located at the edge of the cell suffers more interference than the corner one with S/I ratio as low as 14dB (without shadowing). Its outage probability is 55% for the nearest servicing base station. Even with the diversity consideration of the nearest 6 possible servicing base stations shown in Figure 6 at page 38, the overall outage probability is still 17%. This result indicates that in the wireless LMCS system with full frequency reuse in each cell, though high antenna gain ratio could significantly mitigate co-channel interference, there is still a relatively high outage for the subscribers located far from the cell center. In practice, this would likely be alleviated to some extent by tilting hub antenna beams slightly downward and by obstructions to distant interfering signals caused by buildings, trees, etc.

Figure 9 Outage Probability of 3-sectored System with Site Diversity
 $m=3$, beam $<11^\circ$ QAM: $g=9.8\text{db}$ for $P_e < 0.001$ (include shadowing)

Gs	Beamwidth θ							
	0°	2°	4°	6°	8°	11°	13°	15°
15 db	9.8	9.8	9.8	9.8	9.8	9.0	9.0	9.0
20 db	13.5	13.5	13.5	13.5	13.5	12.1	12.1	12.1
23 db	15	15	15	15	15	13.3	13.3	13.3

TABLE 2 Average SIR Received at the Corner Subscriber (db)
 G_s = antenna gain ratio, θ = antenna beamwidth, with no shadowing

The estimation results without considering shadowing in TABLE 2 show that the average SIR is not too sensitive to the beamwidth of the subscriber-antenna. The SIR keeps constant until the beamwidth increases over 11 degrees. On the other hand, even though the beamwidth of the subscriber antenna is quite narrow, the dominant interference I_D can not be avoided and limits the outage probability of each individual base station. The measurement conducted in Calgary [8] indicates that more than 95% of the locations

within the service coverage area receive no significant multipath signals by using highly directional antenna at the subscriber. With such strong confirmation, the above SIR estimation is derived based on the assumption of no multipath fading. However, if the beamwidth of the subscriber-antenna is wider, more multipath reflections will get into the beam of the antenna and could not be neglected. Thus the beamwidth of the directional antenna should be a very sensitive parameter for the SIR reception and the corresponding outage.

TABLE 2 shows the relationships between the SIR and the hub antenna, and also the effects of the subscriber antenna on the received signal. The SIR varies 6 dB as the subscriber antenna gain ratio (high gain/low gain) ranges between 15dB to 23db. It seems that there are diminishing returns in SIR when the gain ratio of subscriber-antenna and the gain ratio of the hub-antenna increase beyond a certain point.

In conclusion, the signal to interference ratio and the system performance are heavily related to the three parameters of antenna: subscriber-antenna beamwidth, subscriber-antenna gain ratio, and hub-antenna gain ratio.

The above interference estimation is based on the assumption of a cellular layout with identical hexagon cells, but in a practical service area, the cells are not so regular and the hub may not be located at the exactly center of the cell, so some of the subscribers along the edge of the cell do not suffer the dominant interference I_D due to the irregular locations of the hubs. In some of the cases, the subscriber could avoid this dominant interference by switching its antenna to the directions to other hubs.

It is worth to point out that small changes in path loss exponent m could significantly increase or decrease the SIR of the system and change the system performance greatly. In built-up environments, the presence of buildings along the direct path between a transmitter and receiver would lead to an increase in path loss. If the propagation exponent m is increased from 3 to 3.5, the SIR could increase 3 dB.

4.3.4 The Effect of Standard Deviation of Shadowing

The assumption of 10 dB deviation of each interference is fairly typical for the omni-system with isotropic antennas at both the transmitter and the receiver within a heavy user density area [35]. In the wireless LMCS system, as the hub-antenna and subscriber-antenna are non-isotropic sector or directional antennas, and services may be provided in undeveloped areas with low to moderate building densities, 10 dB might be too large for the variance consideration of the interference process. We change the value of the deviation of each interference σ and reestimate the moments of SIR and outage probability, and find that the mean of SIR decreases proportionally with σ (Figure 10). Inspection of the reestimation of outage probability of the corner subscriber in Figure 11 shows that the system performance is very sensitive to the value of σ . e.g., for an antenna gain ratio of 20 dB, when σ is 10 dB, the outage probability P_1^3 obtained (by allowing the subscriber to choose the hub giving the minimum SIR) is as high as 20%. As the value of σ decreases to 6 dB, the outage probability is decreased to about 2%. This confirms our previous discussion that the system performance is heavily related to the beamwidth of subscriber-antenna and the different propagation environments due to the different large scale variations. It could be expected that the decrease of the beamwidth of subscriber-antenna could result in the decrease of the deviation of total interference, and thus bring the significant improvement in the system performance.

Figure 10 Effect of Standard Deviation of Shadowing on the average SIR of a 3-sectored LMCS System

Figure 11 Effect of Standard Deviation of Shadowing on Outage Probability of a 3-sectored system with Selective Diversity

4.4 Problem Issues and Discussion

From the estimation results, it is clear that the outage probability of each base station is quite high due to the severe interference with a frequency reuse factor of one. Even if the shadowing deviation σ is reduced to 6 dB, P_1 is still larger than 10%, and the overall outage $P_e = P_1^3$ with macrodiversity is quite sensitive to the deviation σ (where P_e is the overall outage of nearby three base stations).

By assuming that the fluctuations on the signals and interferences for each possible servicing hubs are independent processes, the overall outage probability of the system could be estimated by multiplying the outage probabilities of each base stations [35]. e.g., in wireless LMCS system as shown in Figure 6, there are three closest hubs near the corner subscriber, the outage probability P_1 of each of these hubs is assumed to be equal. Note that there are some other base stations near the subscriber which can also be the candidates to provide communication links. If the outage probability of each of these hubs is P_2 , then the overall outage probability of the system can be calculated by $P_e = P_1^3 P_2^3$.

Given $P_1 = 0.6$ and $P_2 = 0.5$, the overall outage $P_e = P_1^3 P_2^3 = 0.027$ which is good enough for telephony. Actually, equal probability of each base station to service the subscriber is not valid because of their different distances to the subscriber, and the independence of the base stations need to be carefully considered. Thus in the system with high outage probability of each base station, the system probability could not be calculated by simply multiplying the outage probabilities of multiple hubs. The system error probability should be greater than $P_e = P_1^3 P_2^3 = 0.027$ in the above example.

The above analysis is conducted based on the assumption that the desired signal and each individual interference are independent with others. It can be observed from Figure 5 that the dominant interference is in the exact direction of the desired link, therefore, they must have some correlation and are not purely independent. The actual system performance with accounting the correlation of these lognormal variables must be higher than the analytical results as shown here.

The system outage probability is derived based on the SNR threshold given the bit error probability of 10^{-3} for a specific uncoded modulation. This is good enough for the services of telephony and facsimile[10]. For data and HDTV service, the bit error rate performance requirement is as stringent as 10^{-7} or even 10^{-9} . One of the solutions to mitigate the co-channel interference is to combine the techniques of polarization reuse and frequency interleaving if the system allocated bandwidth is sufficient. In the LMCS system, frequency interleaving is not practical due to the limited frequency resource. A proper coding scheme could help to detect and correct some of the bit errors by retransmission. As a trade off, its bandwidth efficiency will be lower. It is expected that the system performance of 10^{-7} could be achieved by use of additional coding and diversity mechanisms.

Further research is needed to find a proper coding approach for this outdoor broadband wireless system with requirement of high quality of transmission.

Chapter 5

SIMULATIONS OF LMCS INTERFERENCE AND OUTAGE

The concept of LMCS (or LMDS) system and its important applications of directional antennas have been presented in Chapter 2. In Chapter 3 a general consideration on the radio propagation environment of LMCS was discussed. After the performance analysis on the corner subscriber of LMCS in Chapter 4, we are going to have a close look of the overall system performance through simulations in this section.

In this chapter, we are going to present two system models which are based on two scenarios, NLOS (non line-of-sight) and LOS (line-of-sight) respectively. The objective of these simulations is to investigate the changes in system outage probability and interference characteristics which are related to a number of system parameters. These parameters include several issues of directional subscriber-antennas and some characteristics of the propagation environment. The effects on performance improvement by power control and site diversity are also being considered in our simulations. The systems are assumed to be heavily loaded, thus each channel is active at all times.

5.1 Simulations on NLOS Model

5.1.1 NLOS System Model

There are a lot of arguments on the LOS availability within the whole system coverage area. The measurement results in Brooklyn [7] demonstrate a high blocking probability of 74% at subscriber-antenna height of 4 m and 32% at 11.3 m. Another measurement [8] reports that only 17% locations could rely on reflectors to achieve LOS transmissions. These measurements indicate that LOS system may not be able to provide full coverage.

Accordingly, NLOS system performance will be investigated by simulations. The total allocated system bandwidth is assumed to be reused in each cell, with directional antennas at fixed-location subscribers, and omnidirectional or sectorized antennas at hubs.

Each cell is 5 km in radius and is assumed to be overlapped with adjacent cells (This is simulated by providing higher transmitting power than the cell coverage required. Since we are mainly concerned here with interference rather than noise, the choice of cell radius is not critical).

As introduced in Chapter 2, the LMCS system is operating at radio frequency of 28 GHz with separated frequencies allocated for uplink and downlink. Therefore, we can assume there is no interference between the uplink and the downlink. The multiple access format is assumed to be TDMA and the system is designed to reuse the allocated frequency in each cell.

A 36-hub-model with coverage of 3600 km² has been simulated for both uplink and downlink (Figure 12). Users are randomly placed throughout the region with a certain user density. Here we assume the channels are fully utilized at all times within each cell to investigate the system performance under the condition of heavy user density. Thus there is exactly one interferer in every cell (except for LOS system). As our simulation interest is on the system outage probability instead of system capacity and a high channel activity is assumed, the procedure of call set up and hand off is not included in the simulations. Simulations are focused on the SINR reception of each subscriber with random location rather than a specific call at random time with different duration.

The simulation is performed in two dimensions, with a “flat-topped” beam pattern assumed for both sectorized and directional antennas (Figure 2), i.e., the gain in the main lobe is uniform, and the side lobe is simulated by assuming a certain uniform side lobe gain which is lower than the main lobe gain. In practice, this sidelobe gain represents the peak sidelobe gain, thus the assumption of uniform sidelobe gain is conservative, but simplifies our study. It is known that the main lobe gain of the directional antenna increases as the high beam of the antenna becomes sharper, but actually the sidelobe increases too. Therefore, the gain ratio which is the ratio between the main lobe gain and the maximum sidelobe gain has no enormous change with the beamwidth, thus it is assumed to be of fixed value in our simulations.

Figure 12 Simulated System Plan

A representative system performance criterion is the outage probability which is estimated based on cochannel interference and noise level. The outage probability is the probability that the signal to total interference ratio at the reception is less than a given threshold.

To evaluate the downlink channel performance, the signal to interference and noise ratio (SINR) is calculated for the user with random location in the central cell, while the interferences are from each hub of other adjacent cells and it is assumed the same channels in different cells are synchronous. For the uplink, the simulation is focussed on the hub of the central cell and the outage of this hub can be evaluated based on the calculations of its interferences from the subscribers randomly located in other cells.

Note that the interfering signal is between either the main lobe or sidelobe of the sectorized hub antenna and the high beam or sidelobe of the directional subscriber antenna, and the interference can be greatly attenuated when it is in the sidelobe. Therefore, both

the locations and the angles of directional antennas are under the consideration in our simulations.

The simulations focus on the applications of directional antennas at fixed subscriber of LMCS under a certain propagation environment, and some basic wireless techniques such as power control and site diversity are also investigated in this simulation. The factors which have been investigated are listed in TABLE 3.

Issues to be Simulated		Investigation Scope
Directional Subscriber Antenna	Beamwidth (θ)	$0^\circ - 10^\circ$
	Gain Ratio (Gs)	0 db - 30 db
base station Antenna	# of Sectors	Omni - 12 sectors
	Gain Ratio (Gb)	0 db - 30 db
Propagation Environment	Propagation Exponent (m)	2 - 4
	Standard Shadowing Deviation (σ)	0 db - 10 db
	Operating Frequency (Freq)	20 GHz - 60 GHz
Noise Consideration	Channel Bandwidth (BW)	0.03 MHz - 50 MHz
Investigated Techniques	Power Control (PC)	20 db or 5 db steps (for uplink only)
	Site Diversity	no limit for # of hubs (select the one with highest SIR)
SINR Reception Threshold	Given BER $< 10^{-3}$	10 db - 30 db

TABLE 3 Investigated Issues in NLOS Simulation

5.1.2 Propagation Signal Model and Link Budget

As discussed in Chapter 4, by using directional antennas with narrow beamwidths and high gain ratio at the fixed subscribers, most of multipaths due to reflections and dif-

fractions are nulled out by the sidelobe of directional antenna. This is confirmed by the measurement conducted by Allen & Associates in Calgary [8] that nearly 95% of locations has no significant second path signal received. Some simulations have also demonstrated that delay spread is only 10 ns or less at large distance reception within urban area [33] [39]. The valuable measurement results by Violette [40] shows that at radio frequency of 28 GHz with the application of highly directional antennas, narrow- and wide-band channels perform similarly due to their very small delay differences. Therefore, the effect of inter symbol interference (ISI) is assumed to be very small and is not considered in the scope of this simulation. Since most services provided by LMCS are broadband with high bit rate, the fast fading is relatively small [25], and it is also neglected in the simulations.

Path loss and the large scale fading are the two major issues included in our signal propagation model. The strengths of the cochannel interference and desired signal are calculated based on such a signal model, and the system outage is observed based on the comparison between the SINR received and a certain threshold.

In consideration of reflection of ground and diffractions from trees and buildings, the transmission space loss is larger than free space loss. However, since the cell size of LMCS system is relatively small with radius of 5 km, the propagation exponent should be smaller than 4. In this simulation, a typical propagation model with path loss exponent of 3 is simulated and a standard deviation of 10 dB is assumed for the lognormal shadowing.

If d_{ref} denotes the distance between the closest subscriber and the desired hub, then the received power of all subscribers with T-R separations greater than d_{ref} can be calculated based on the known received power at d_{ref} which is considered as a reference: [41]

$$S = P_{ref} \cdot \left(\frac{d_{ref}}{d} \right)^m \quad (47)$$

where S is the received power of the subscriber with distance of d ($d > d_{ref}$), m is the propagation exponent, P_{ref} is the received power at distance of d_{ref} and is calculated based on an assumption of free space propagation:

$$P_{ref} = P_T \cdot G_T \cdot G_R \cdot \left(\frac{c}{4\pi f}\right)^2 \cdot \left(\frac{1}{d_{ref}}\right)^2 \quad (48)$$

where P_T is the transmitting power, $c = 3 \times 10^8$ m/sec, f is the radio frequency in Hz, G_T and G_R are gains of antennas. For directional antenna (or sectored antenna), the gain could be either the main lobe gain or the sidelobe gain, and the ratio between the gains of the main lobe and the maximum sidelobe is called the *gain ratio*. The distance between the nearest subscriber and the desired hub d_{ref} is assumed to be 20 m in our simulations and analysis.

For LMCS systems operating at millimeter wave radio frequency of 28 GHz, path attenuation is larger than that of lower frequencies such as 900 MHz and thus the required transmitting power is relatively high. In consideration of power consumption, small cells are preferable in LMCS system design [39]. In this simulation, we assume the cell radius is 5 km.

The link budget of the NLOS system for an scenario of 5 km cell radius is shown in TABLE 4. It is also assumed the weather is clear, thus the rain loss margin is not included.

In the case of NLOS system with propagation exponent of 3, there is about 157 dB space loss at the edge of a cell as calculated in Equation (47) and Equation (48). If the transmitting power is 0 dbw, given an antenna gain of 15 dB for hub antenna, and 36 dB for directional subscriber antenna, the received power at the edge of the cell is -106 dbw. Fade margin is not included in this link budget calculations since the application of site diversity has greatly reduced the effect of fading.

The thermal noise power is -127 dbw for a typical 50 MHz channel and the noise figure is assumed to be 8 dB. Therefore, the carrier to noise ratio (N/C) at the edge of the cell is 13 dB for a 50 MHz stream.

In terms of uplink with a 2 Mb/s per user, the noise floor is relatively low and C/N ratio of 17 dB can be achieved at the receiver.

Transmitter		Hub (downlink)	subscriber (uplink)
Modulation	Units	4QAM	4QAM
Bandwidth	MHz	50	2
Transmitter Power	dbw	0	-10
Power Control	db	No	20
Transmitter Antenna Gain	dbi	15	36
EIRP (clear sky)	dbw	15	26
Edge of Single Cell	km	5	5
Space Loss at Edge of Coverage (assuming $m=3$)	db	157	157
Receiver Antenna Gain	dbi	36	15
Received Power at the Edge of Coverage	dbw	-106	-116
Receiver Noise Figure	db	8	8
Noise Floor	dbw	-127	-141
C/N at Edge of Coverage (clear sky)	db	13	17

TABLE 4 Link Budget of NLOS system

There are a number of factors that can be engineered into the system to extend the area of reliable coverage. e.g., the system outage can be improved by increasing transmitter power, increasing the antenna gain, decreasing the cell size or reducing the noise figure. The transmitting power is limited at the subscriber due to the considerations of power consumption and safety, and the noise level is a function of channel bandwidth which will be described in section 5.1.3. Therefore, when the transmitting power is relatively low, reducing the antenna beamwidth to maintain a high antenna gain may be a practical and an effective solution to improve system performance.

5.1.3 Signal to Interference and Noise Ratio (SINR)

The system outage is evaluated based on the reception of signal to interference and noise ratio (SINR). The received power calculation of the desired signal and cochannel interference are discussed in Chapter 4 and section 5.1.2, while the receiver thermal noise assumed here as an additive white Gaussian noise (AWGN) is given by [42]

$$N_{RX} = 10\log(K \cdot T) + 10\log(BW_{IF}) \quad (49)$$

where N_{RX} is the thermal noise, K is the Boltzman's constant (1.374×10^{-23} joule/K), T is the environment temperature ($290^0 K$), and BW_{IF} is the receiver IF bandwidth in Hz.

The SINR threshold is related to the given modulation scheme and a certain required error rate. For a modulation scheme of 4QAM with coherent detection (no coding), given a bit error rate (BER) of 10^{-3} , the corresponding SINR threshold is about 10 dB. Note that some broadband services such as HDTV require very low error rate with higher threshold. Here we take the BER of 10^{-3} as an example to investigate the system outage over this level. Actually, with a proper error control coding, there can be an effective gain in SINR of 6 - 10 dB, i.e., the bit error rate should be 10^{-8} to 10^{-9} given the same threshold of 10 dB as the case of no coding with 10^{-3} BER. The other threshold settings in a scope of 10 - 30 dB are also investigated in the simulations.

5.1.4 Site Diversity and Power Control

In the outdoor wireless LMCS system design, each cell is overlapped heavily with adjacent cells to provide full coverage and site diversity. Such macrodiversity is simulated by allowing the subscriber to select the best (in terms of SINR) available hub to obtain the best communication link.

Power control is also investigated for the reverse link, but it may not be used in the downlink, because many downlink services use common channels to broadcast television or other public information to all of subscribers with random locations in the coverage area.

It is assumed that the radio is capable of switching its power level between two coarse settings: normal power and low power with 20 dB steps. The low power setting is used in the transmitter as long as the SINR reception at the receiver exceeds the required threshold.

5.2 Simulations on LOS Model

In section 5.1, we have already described the simulations on LMCS based on NLOS transmissions. However in most of LMCS system designs such as TI (Texas Instrument) and CellularVision [3], LOS is assumed for desired link transmissions to achieve high SINR. The results of the propagation measurement at 28 GHz in Brighton Beach, Brooklyn [7] indicate that strong signals were only received at locations where a LOS path was available. In some suburban area without many high buildings, LOS could be available in a large percentage of locations, and such a system could support good quality of services in comparison to NLOS (non line of sight) systems.

5.2.1 LOS System Model

A LOS system scenario with 4 sectors in each cell has been simulated for both uplink and downlink (Figure 13). The system attempts to reuse the total allocated bandwidth in each sector of the cell through the use of highly directional antennas and polarization reuse in adjacent sectors. Perfect orthogonal polarization transmissions which can reduce interference from adjacent sectors are used in this simulation. At the uplink, power control with steps of 5dB has been executed.

In the simulation of LOS scenario, cochannel interference is assumed to be NLOS with propagation exponent of 3 and standard shadowing deviation of 10 dB. The desired signal transmission of LOS has no shadowing, and its propagation is assumed to be similar to a free space transmission with exponent of 2 [43]. Due to the short wavelength at 28 GHz, the break point, as an result of ground reflection, is much beyond 10,000 ft rather than in the interval of observation [44]. Therefore, break point is neglected in this simulation.

Figure 13 Wireless LMCS system of LOS
(H for horizontal, V for vertical)

5.2.2 Propagation Signal Model and Link Budget

As shown in TABLE 5, in LOS system with cell radius of 5 km, the power decay at the edge of the cell which is about 136 dB is smaller than that of NLOS scenario. For the downlink budget with transmitting power of 0 dbw, given the same antenna patterns as those of NLOS, i.e., 15 dB gain for hub antenna, 36 dB for directional subscriber antenna, the EIRP (effective isotropic radiated power) after the hub transmitting antenna is 15 dbw, and the received power at the edge of the cell (after the receiving subscriber antenna) is -85 dbw. For a 50 MHz stream with a noise level of -127 dbw and 8 dB noise figure at the receiver, the C/N ratio at the edge of coverage is 34 dB for downlink and 38 dB for uplink 2 Mb/s channel correspondingly.

Transmitter		Hub (downlink)	subscriber (uplink)
Modulation	Units	4QAM	4QAM
Bandwidth	MHz	50	2
Transmitter Power	dbw	0	-10
Power Control	db	No	5
Transmitter Antenna Gain	dbi	15	36
EIRP (clear sky)	dbw	15	26
Edge of Single Cell	km	5	5
Space Loss at Edge of Coverage (assuming $m=2$)	db	136	136
Receiver Antenna Gain	dbi	36	15
Received Power at the Edge of Coverage(rain)	dbw	-85	-95
Receiver Noise Figure	db	8	8
Noise Floor	dbw	-127	-141
C/N at Edge of Coverage (rain)	db	34	38

TABLE 5 Link Budget of LOS System

Note that unlike NLOS, the power control for the uplink of LOS system has very small power variation steps. It is for the purpose of reducing the dominant interference from the subscriber in the opposite sector. We will discuss that in more details in the next chapter.

Chapter 6

SIMULATION RESULTS OF LMCS SYSTEM

The main objective of this chapter is to investigate the significant effects of directional antenna on the performance improvement of LMCS system and verify the preliminary system design with frequency reuse of one. The effects of propagation parameters and the employment of macrodiversity and power control are also being discussed. Both LOS (line of sight) and NLOS (non-line of sight) are investigated in this chapter, and the characteristics of the cochannel interference for these two scenarios are compared.

6.1 Simulation Results of NLOS System

The system designs for NLOS and LOS scenarios are different. For NLOS system, the allocated frequencies are reused in each cell, but different sectors of the same cell have different frequencies. If LOS transmission is assumed to be available for desired links, the NLOS cochannel interference is relatively small comparing to the LOS desired signal. Therefore the system could be designed to reuse the allocated frequencies at each sector of the cells with polarization reused in adjacent sectors of the same cell. Simulation results for NLOS scenario are discussed in this section, while LOS system performance will be presented in the next section.

6.1.1 Performance Improvement by Directional Antenna

6.1.1.1 Effect of Antenna Beamwidth

Since the simulation results present quite similar outages for both uplink and downlink, the results of uplink are taken as an example of the system performance and are discussed for the NLOS model in the present and subsequent sessions.

The simulation results shown in Figure 14 indicate that with a fixed gain ratio of 25db, the system outage probability for a 10 dB SINR threshold is decreased significantly

as the subscriber-antenna beamwidth decreases. Highly directional antennas are not only helpful to avoid most interference, but also can provide very high gain for the reception of desired signal. As the main lobe beamwidth reduces from 10° to 2° , the outage probability drops from 18% to 6% for a 3-sectored system (different frequencies are used in the three separated sectors of each cell).

The results in Figure 14 also indicate that using a sectored antenna at the hub could improve system performance significantly. When using 2° narrowbeam antennas at subscribers, a 3-sectored system can achieve outage probability at least one order of magnitude lower than that of an omni system with isotropic antennas at base stations. However, when the cell is further sectorized to 6 sectors, the system outage does not drop much. In fact, if we use directive antennas at both the hub and the subscriber, there will be an increase of pointing errors. Therefore, a 6- or more- sectored antenna is not recommended at the hub in LMCS system.

Considering the inferior performance of the omni system (20% outage at beamwidth of 2 degrees shown in Figure 14) and the significant improvement by using a 120-degree antenna at the base station, it is preferable to use 3-sectored antenna at the base station. An omni system may not be practical due to its large outage. The above simulation results confirms our original analysis in section 2. These sectored antenna results are for sectored cells in which there is no more than one interference from each cell. Results in which each sector has full frequency reuse are reported in section 6.2 for LOS simulations.

Figure 14 Effect of Antenna Beamwidth on System Outage

$m = 3$, $\sigma = 10$ db, $G_s = G_b = 25$ db, Freq = 28 GHz, BW = 6 MHz, no diversity, no PC.

6.1.1.2 Effect of Antenna Gain Ratio

The gain ratio between the main lobe and the maximum side lobe of the antenna is an important parameter for antenna design. The simulation results in Figure 15 show that the system performance could be dramatically improved when using a directional antenna of high gain ratio at the subscriber. The outage probability is decreasing as the gain ratio increases, and when the gain ratio is over 20db, the simulation result illustrates a lower sensitivity compared to that of the small gain ratio, and finally the system performance approaches a certain non-zero level (Figure 15). Such a non-zero outage limit is partly due to the effect of white Gaussian noise, but a key contribution is the dominant interference received from the main beam of directional subscriber-antenna if the subscriber is located in the so called critical area where the interference is in the exact direction of the desired link (Figure 1 in page 7). In such a case, the interference can not be avoided by just increasing antenna gain ratio or even reducing the beamwidth of the subscriber-antenna. The subscriber may have to use a reflector (if available) or select another hub to set up a

new transmission link. Such site diversity has also been simulated and the results will be discussed later.

Similarly, as the gain ratio of the hub antenna increases, the outage probability is also decreased as shown in Figure 16. When the gain ratio is 0 dB, the hub antenna is omnidirectional. As the gain ratio increases, the side lobe is getting smaller and there is significant improvement in the performance of sectorized systems. There is also a non-zero outage limit for a sectorized hub-antenna for the similar reason as the subscriber-antenna. The outage limit level of a 3-sectorized antenna is higher than that of a 6-sectorized antenna due to the different beamwidths.

Comparing Figure 15 and Figure 16, it is shown that the system performance is more sensitive to the gain ratio of the directional subscriber antenna than that of the sectorized hub antenna. This is because most of interferences are from the sidelobe of the directional subscriber antenna and they are attenuated when the sidelobe of the antenna is reduced as the gain ratio increases, while for a typical 3-sectorized antenna, about 30% of the interferences are in the main lobe and are not affected by changing the antenna gain ratio. Thus the hub-antenna's gain ratio is a less sensitive parameter than that of subscriber-antenna.

Figure 15 Effect of Directional Antenna Gain Ratio on System Performance

$\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_b = 25$ db, Freq = 28 GHz, BW = 6 MHz, $\delta = 10$ db, no diversity, no PC

Figure 16 Effect of Hub Antenna Gain Ratio on System Performance

$\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_s = 25$ db, Freq = 28 GHz, BW = 6 MHz, $\delta = 10$ db, no diversity, no PC

6.1.2 Performance Sensitivity to the Propagation Environment

6.1.2.1 Sensitivity to Path Loss Exponent

The effects of path loss exponent is also investigated in this simulation and Figure 17 shows the system performance as a function of propagation exponent for both omni and sectored antennas. It is indicated from Figure 17 that a small propagation exponent yields a huge increase in the outage probability, e.g., under the same condition of no power control and no site diversity, a 3-sectored system could achieve an outage of 14% at propagation exponent of 3, while at exponent of 2, the system performance is much worse with an outage of 26%. This is because the outside cell interference is less attenuated by the small propagation exponent. From this point of view, high buildings and heavy foliage may have positive effects on system performance by effectively reducing the outside cell interference. Of course at the same time, it is also becoming difficult to support desired links with good receptions due to the significant attenuations from buildings and foliage.

Figure 17 Propagation Exponent on System Outage

$\theta = 3^\circ$, $G_s = G_b = 25\text{db}$, $\sigma = 10\text{ db}$, Freq = 28 GHz, BW = 6 MHz, no PC, no diversity

From the link budget calculations of NLOS and LOS shown in TABLE 4 and TABLE 5, we can see that in order to support the same cell coverage, the required transmitting power for NLOS scenario with exponent of 3 is much higher than that of LOS with exponent of 2. Considering that the power consumption at the subscriber is limited, small cells are normally designed for the areas with large path loss exponent. For those areas with less buildings and trees, the cell size could be relatively large. In the consideration of multipath and delay spread in large distance of transmission, the cell radius is recommended to be no more than 5 km in the LMCS system.

Figure 17 shows that the performance beyond exponent 3.4 degrades sharply. This is due to the heavy attenuation of the larger exponent which results in low signal strength received in the desired link. Note that the value of the propagation exponent for the lowest system outage is at 3.4 rather than 3, this is because the transmitting power is designed to be greater than cell coverage in our system in order to support cells overlapping and macrodiversity. The huge performance improvement by macrodiversity will be discussed in section 6.1.3.

6.1.2.2 Standard Deviation of Lognormal Shadowing

The drastic effect of lognormal shadowing standard deviation on system performance is illustrated in Figure 18. The system outage decreases from 17% to 4% as the standard deviation drops from 10 dB to 6 dB (no diversity).

By using highly directional subscriber antennas to reduce most of interference, the system performance of LMCS system is enhanced significantly as shown in our simulation results. But on the other hand, the high directivity of the antenna results in high sensitivity to the propagation environment. Local buildings can degrade system performance by reflection and scattering, and could even block the desired links. In order to provide good quality of service and full coverage in a downtown area with heavy shadowing effect, smaller cells may be designed with a careful arrangement of reflectors or repeaters to set up a new line-of-sight link in case of blocking. There are a lot of arguments on the require-

ment of LOS for LMDS, but the measurement results in Brooklyn [3] [7] indicate a high blocking probability of 74% at a subscriber-antenna height of 4 meters, and the measurements by Allen & associated in Calgary [8] reports that only 17% locations could rely on reflectors. Furthermore, too many reflectors may bring interferences to other receivers, and the economic cost of repeaters should also be carefully considered.

Figure 18 Standard Deviation of Lognormal Shadowing on System Outage

$\theta = 3^\circ$, $m = 3$, $G_s = G_b = 25\text{db}$, $\text{Freq} = 28\text{ GHz}$, $\text{BW} = 6\text{ MHz}$, no PC, no diversity

6.1.3 Cells Overlapping and Selective Macrodiversity

In the consideration of the unreliable radio links, the Cellular Fixed Broadband Access System is designed to be a cellular system with heavily overlapping cells, in order to allow the subscriber to be able to choose the best reception from one of several nearby hubs. The simulation has performed this site macrodiversity and the results in Figure 19 (solid lines) demonstrate a significant improvement on system performance by employing selective macrodiversity. By adding the selective diversity, the system performance shows a three fold improvement at the lognormal standard deviation of 10db.

Comparing with our previous analytical results estimated for the corner subscriber with a permission to select desired link from the nearby three hubs, the simulation results demonstrate a smaller performance improvement by diversity than the analytical one which predicts a power of 3 enhancement. Note that the simulation is conducted on the uplink of a subscriber which is randomly located within a cell, thus the subscriber may not be able to have multiple choice of desired links when it is located outside of the overlapping areas. Therefore, not all of the simulated subscribers could benefit from site diversity as the corner subscriber in the original analysis. The analytical result is conducted based on the assumption by Cox [35] in which the transmission links from different base stations are always independent. In practice, even for the three nearby base stations there are still some correlations, therefore the actual outage improvement by diversity is not as much as the theoretical analysis.

By using macrodiversity with heavily overlapping cells, the LMCS system can be significantly enhanced not only on the outage rate, but also on the service coverage. Doug Gray from HP presented an 20% coverage improvement in his analytical results when using 4 hubs instead of 1 base station in a typical suburban area [45].

Figure 19 Standard Deviation of Lognormal Shadowing on System Outage
 $\theta = 3^\circ$, $m = 3$, $G_s = G_b = 25\text{db}$, $\text{Freq} = 28\text{ GHz}$, $\text{BW} = 6\text{ MHz}$, no PC.

6.1.4 Power Control

It is known that the near-far problem in cellular systems has a significant effect on the system outage due to the high interference, and using power control can reduce the negative effect of this problem. A coarse transmitter power control at the uplink is also included as an objective in this simulation study. The subscriber is capable of switching its output power level between two settings: normal and low power with 20 dB difference between them. The low power setting is used at the transmitter when the SINR (signal to interference and noise ratio) at the receiver exceeds the required SINR threshold by over 20 dB. The power control is simulated at the subscriber only, and it may not be included for forward broadcasting link in the system design.

The simulation results in Figure 20 (solid line) predict a significant performance improvement for both omni and sectored systems by using coarse power control. e.g. with directional antenna of 2 degrees at the subscriber, the outage probability of a 3-sectored system could achieve 2 to 3 fold outage improvement. Power control efficiently limits the interference by reducing the power of the interfering subscriber. When the desired subscriber is near the base station, the reduction of the transmitting power does not increase the probability of outage due to the power control algorithm which is based on both SINR and power received.

The system performance enhancement by power control does not change much with the beamwidth of directional antenna, but it is very sensitive to the gain ratio between the high beam and the side lobe of the narrow-beam antenna as noted in Figure 21. The outage does not decrease much at low gain ratio due to the incomplete power control. In the wireless LMCS system with frequency heavily reused in each cell, unsatisfactory SINR reception is observed at most of subscriber locations and of course power control could not be executed at those users. From Figure 21, it is also shown that by using both power control and macrodiversity, the outage probability of the 3-sectored system (at hub antenna gain ratio of 20db) can be decreased by more than one order of magnitude from 20% to about

0.9%. The system performance could be expected to be even higher with channel utilization which is less than 100%.

Figure 20 Propagation Exponent and Power Control of 3-sectored System

$\theta = 3^\circ$, $G_s = G_b = 25\text{db}$, $\sigma = 10\text{ db}$, $\text{Freq} = 28\text{ GHz}$, $\text{BW} = 6\text{ MHz}$, no diversity

Figure 21 Effect of Power Control and Site Diversity in the 3-sectored System

$\theta = 3^\circ$, $m = 3$, $\sigma = 10\text{ db}$, $G_s = 25\text{db}$, $\text{Freq} = 28\text{ GHz}$, $\text{BW} = 6\text{ MHz}$

6.1.5 Sensitivity to the SINR Threshold

The SINR (signal to interference and noise ratio) threshold is related to the given modulation scheme and a certain required error rate. For a modulation scheme of 4QAM with coherent detection (no coding), given a bit error rate (BER) of 10^{-3} , the corresponding SINR threshold is about 10 dB.

We take this BER of 10^{-3} as a reference and investigate different modulation schemes in a range of 10dB to 35 dB. Note that the BER of 10^{-3} is good enough for telephony, but can not satisfy the service requirement of some broadband services such as HDTV with an error rate required to be lower than 10^{-9} . We assume with a proper error control coding, the SINR reception can achieve 6 - 10 dB improvement, i.e., the bit error rate could be 10^{-8} to 10^{-9} given the same threshold of 10 dB as the case of no coding.

The system outage is evaluated based on the comparison of the received SINR and the given threshold. The system outage probability as a function of required SINR threshold are generated for different scenarios (with or without diversity, with or without power control) as shown in Figure 22. It is noticed that the effects of site diversity, and power control on performance improvement are similar at low SINR threshold, but at high threshold, the system performance is more sensitive to the technique of diversity and the effect of power control is relatively small. The diversity links may have quite different signal receptions and results in huge outage decrease. However, power control is employed on every subscriber with an effect on other subscribers' reception, thus the received SINR could be improved by power control but it is normally not very high. Therefore, the effect of power control on system performance is limited at high SINR threshold.

Figure 22 SINR Threshold on System Outage

$\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_b = G_s = 25$ db, Freq = 28 GHz, BW = 6 MHz

From Figure 22 we can see that the system outage is quite sensitive to the value of SINR threshold. For an 3-sectored system with site diversity and power control employed, the outage probability drops from 20% at a threshold of 35dB to 0.6% at 10db. As we discussed in our original analysis in Chapter 4, with frequency reuse in each cell in LMCS system, the received SINR can not be very high. Therefore, there is a relatively large outage at high SINR threshold. As we know, high level modulations such as M-QAM ($M > 4$) require less bandwidth, but need higher transmitting power and stringent linearity of power amplifiers, and they are less tolerant to interference, phase noise and channel distortions. Therefore in some papers low level modulations with low SINR threshold is recommended in the LMCS systems [46] [47].

6.1.6 Operating Frequency

The LMDS operating frequency proposed by FCC is at millimeter wave frequencies around 28 GHz. However, the frequencies of 40 GHz and 60 GHz are also considered in some countries. In this section, we are going to have a look on the simulation results of

radio frequency on a scope of 20 GHz to 60 GHz under the condition in which the transmitting power is 1 w for a LMCS system with cell radius of 5 km.

Figure 23 Operating Frequency on System Outage (no PC, no diversity)

$\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_b = G_s = 25$ db, $BW = 6$ MHz (with low power received)

The simulation results are presented in Figure 23 and it can be seen that the system performance is sensitive to the operating frequency. When using the same transmitting power, the outage probability of a 3-sectored system shown in Figure 23 almost decreases one fold from 60 GHz to 28 GHz. This is because the path loss is proportional to the carrier frequency, by comparing with the operations on 60 GHz, the transmissions at 28 GHz have smaller path loss and could achieve lower outage.

As we discussed before, the transmitting power is limited at the uplink due to the considerations of power consumption for the subscribers. With this limited transmitter power, 60 GHz is not suitable for the outdoor transmissions for a large cell system due to its huge propagation loss. If the system is designed with very small cells (e.g., the cell radius is less than 1 km), high frequencies such as 60 GHz or even higher are applicable due to the relatively small path loss of short distance.

6.1.7 Effect of Channel Bandwidth on Noise Level

The reception outage is affected by two factors: interference and noise level. In terms of noise, a typical white Gaussian noise which is a function of channel bandwidth and environmental temperature is assumed in our simulations. When the transmitting power is much higher than the required cell coverage (with heavily overlapping cells), the effect of Gaussian noise could be neglected. When the received signal is relatively small such as the subscriber at the edge of the cell coverage, the noise level should be taken into consideration.

The simulation on the noise level is based on low transmitting power and we investigate the channel bandwidth from narrowband to broadband of 50 MHz. The results shown in Figure 24 demonstrate that at low transmitting power, the reception outage is quite sensitive to the noise level which is a function of channel bandwidth. e.g., the reception outage of a broadband signal with bandwidth of 50 MHz is 2 fold higher than a narrowband signal with about 5 MHz bandwidth. This indicates that higher transmitting power is needed for the broadband services so as to enhance the system performance.

Figure 24 Channel Bandwidth on System Outage (no PC, no diversity)

$\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_b = G_s = 25$ db, Freq = 28 GHz (with low power received)

6.1.8 Uplink and Downlink performances

We have simulated both uplinks and downlinks of the NLOS scenario in this project and found the performances of the reverse channels are quite similar to that of the forward channels. The outage probabilities for both uplinks and downlinks of an typical 3-sectored system are shown in Figure 25.

Figure 25 Uplink and downlink Outages of a 36-hub NLOS model

$\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_b = 25$ db, $Freq = 28$ GHz, $BW = 6$ MHz, $\delta = 10$ db, no PC, no diversity

By now we have investigated the system performance of an 36-hub model which covers a large area through multiple small overlapping cells. In fact, in a residential area with low capacity requirement, the cell size can be relatively large and the whole servicing area may be supported by a small number of cells or even a single cell. In such a case, the outage probability can be much lower than that of a 36-hub scenario as we discussed above. Both simulation results of a 36-hub scenario and a 4-hub system model are shown in Figure 26.

Figure 26 System Outages of 4-hub model and 36-hub NLOS model

$\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_b = 25$ db, Freq = 28 GHz, BW = 6 MHz, $\delta = 10$ db, no PC

6.1.9 Summary of NLOS Results

As a conclusion from the above simulations of NLOS LMCS, a system design with full frequency reuse in each cell is verified to be possible when using highly directional fixed subscriber antennas with a high gain ratio. In the consideration of high quality services provision, a 3-sectored antenna is recommended to be used at each base station of the system instead of an isotropic one (4-sector antennas would likely give similar results by permitting alternation of horizontal and vertical polarization[45] [47]). The techniques of power control and selective site diversity are found to be powerful enhancements for the system. The system performance is not only heavily related to the characteristics of directional subscriber antennas such as beamwidth and gain ratio, but is also a function of factors of the propagation environment, e.g. propagation exponent, and standard deviation of lognormal shadowing. The analytical results in Chapter 4 indicate that some subscribers in the so called critical area may have quite high outage due to the dominant interference received in the direction of the desired links. In order to provide fair service and good cov-

erage, reflectors and repeaters are recommended to be used for these subscribers to set up new transmission links so as to avoid the dominant interference.

6.2 Simulation Results of LOS System

The above discussion is based on the NLOS scenario. In this section, we are going to investigate the system with LOS transmissions in the desired communication links. Due to the small attenuation on the desired signal which is LOS, the received SINR at the receiver is relatively high and this results in low outage. The simulation results indicate that under the same condition as the NLOS, i.e., both the subscriber antenna and the hub antenna have high gain ratios of 25db, and the SINR reception threshold is 10 dB, The LOS system has achieved a relatively good performance with an outage of 0.3%. However, as shown below, a good power control must be used at the uplink of LOS system, and the characteristics of the cochannel interferences for LOS system are quite different from the NLOS scenario.

6.2.1 Power Control at Uplink

It is noted in Figure 13 that the most dominant interference of the LOS system is from the opposite sector in the same cell. If we take a close look at the interference characteristics, we can find that the dominant interference for the downlink does not change with distance given a fixed value of hub antenna gain ratio G_b . The reason is that both the desired signal and the dominant interference are from different sectors of the same hub.

In uplink transmission, the interfering subscriber and the desired one have different distances to the desired hub, resulting in variation of SINR reception. When the interfering subscriber is near the hub but the desired subscriber is far away, outage may occur due to the low SINR reception.

Comparing the distributions of SINR receptions for both uplink and downlink in the LOS communication scenario, we can see that most of SINR receptions at the downlink subscribers are about 20db, while the uplink SINR tends to be lower as shown in Figure

27. Figure 27 shows the histogram results which are estimated through 500 samples of the received SINRs. It can be noted that the downlink SINR distribution is also different from that of the uplink. The uplink SINR is similar to a Gaussian distribution with large deviation, but for the down link, the received SINR has concentrated in the 20 - 30 dB range. This can be observed when the subscriber is close to the desired hub and has no large interference from outside of the cell except for a dominant interference from the opposite sector within the same cell.

In order to solve the near-far problems at the uplink, power control with steps of 5 dB is executed in the uplink to limit the SINR variation. Simulation results of CDP (cumulative distribution probability) shown in Figure 28 indicate that by using power control with 5 dB steps, the uplink received SINR is almost the same as that of downlink. In fact, when SINR threshold is low and the gain ratios of antennas are high enough, the uplink performance could achieve a similar low level of outage as the downlink (see Figure 29 and Figure 30).

Figure 27 SINR Distributions in LOS System

4 sectors in each cell, $\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_s = G_b = 25$ db, Freq = 28 GHz, BW = 6 MHz

Figure 28 CDP of SINR in Uplink of LOS system

4 sectors in each cell, $\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_s = G_b = 25$ db, Freq = 28 GHz, BW = 6 MHz

6.2.2 Sensitivity to the Gain Ratios

In our previous analysis of the NLOS scenario, we have investigated the effects of antenna gain ratio on the system outage, and found that the outage probability decreases proportionally as the gain ratio increases. In comparison of the hub antenna and the subscriber antenna, we can find that the NLOS system performance is more sensitive to the gain ratio of the subscriber antenna due to its high directivity.

By observing the simulation results of LOS scenario in Figure 29, we can notice that the system outage is quite sensitive to the hub antenna gain ratio and displays a nonlinear relationship with the hub gain ratio. The outage probability of the downlink has a significant decrease when the hub gain ratio is over 10 dB. This is because the most dominant interference of LOS system is from the opposite sector of the same cell, and when the gain ratio is less than 10 dB, the SINR reception should be less than the required threshold of 10 dB and could result in an huge outage rate.

Similarly, the outage probability of uplink has a great decrease when the hub antenna gain ratio is greater than 15 dB. The additional 5 dB required for the uplink hub antenna gain ratio is due to its power control step.

In comparison with the effects of hub antenna and subscriber antenna in TABLE 6, we find that unlike NLOS, the LOS system performance has more sensitivity to the hub antenna gain ratio. An outage of nearly 100% may occur when hub gain ratio is less than 10 dB, but for the subscriber antenna with relatively low gain ratio, the outage probability is just about 10% with an assumption that the outside cell interferences are NLOS with propagation exponent of 3. Note that in real propagation environment, the interference may not be always NLOS, and the LOS interference is not well included in our lognormal shadowing model with deviation of 10 dB. The outage probability at low subscriber gain ratio should be greater than our simulation results, but will be less than that of low hub gain ratio scenario.

Figure 29 Effect of Hub-Antenna Gain Ratio on LOS

4 sectors in each cell, $\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_s = 25$ db, Freq = 28 GHz, BW = 6 MHz.

Gain Ratio (dB)	System Outage probability with certain value of Gb (Gs=25 dB)		System Outage probability with certain value of Gs (Gb=25 dB)	
	uplink with PC	downlink	uplink with PC	downlink
5	100%	100%	6%	10%
10	90%	100%	4%	6%
15	1%	0.4%	1.2%	1.2%
20	0.7%	0.4%	0.8%	0.8%
25	0.4%	0.3%	0.4%	0.3%
30	0.4%	0.3%	0.4%	0.3%

TABLE 6 Effect Comparison of Antenna Gain Ratios

4 sectors in each cell, $\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, Freq = 28 GHz, BW = 6 MHz

(Gs is gain ratio of subscriber antenna, Gb is gain ratio of hub antenna, PC is power control)

6.2.3 Sensitivity to SINR Threshold

As noted in Figure 13, the most dominant interference of the LOS system is from the opposite sector in the same cell, while this interference is from the main lobe of the directional antenna of the interfering subscriber through a sidelobe of the hub-antenna. If the sidelobe of the sectored hub antenna is large, this dominant interference could not be attenuated much, and results in low SINR reception and high outage probability.

The simulation results in Figure 29 and Figure 30 indicate a very good performance with an outage of 0.3% for LOS system under the condition that both the subscriber antenna and the hub antenna have high gain ratios of 25db, and with the SINR reception threshold of 10 dB.

Figure 30 Effect of SINR threshold on LOS

4 sectors in each cell, $\theta = 3^\circ$, $m = 3$, $\sigma = 10$ db, $G_s = G_b = 25$ db, Freq = 28 GHz, BW = 6 MHz.

If the SINR threshold is high, or the gain ratios are not high enough, we can see that the outage of the uplink is much higher than that of the downlink. This is due to the variation of received SINR within the range of 5 dB which is the minimum power control step. Of course the power control step could be smaller to reduce such variation, but the trade off is that there are more recursions and complexity of power control. Note that in the uplink simulations it is assumed all subscribers are always transmitting. However, uplink interference will be considerably reduced with more realistic activity factors.

6.2.4 Propagation Environment Issues

In the simulation of LOS, the effect of the propagation environment has also been investigated. The simulation results in Figure 31 indicate that the system performance is very sensitive to the value of the propagation exponent m of interfering NLOS links. An outage of 30% at $m=2$ could be decreased to 0.3% at $m=3$, and less than 0.1% at $m=4$.

This high performance is due to the significant attenuation of interference at large exponents.

When the value of propagation exponent is large, the interferences from adjacent cells and adjacent sectors are greatly attenuated, but the dominant interference in the opposite sector of the same cell (Figure 13) can not be attenuated due to its LOS transmissions. The strength of this dominant interference in the uplink deviates proportionally to the distance variation, and results in relatively higher outage than in the downlink.

Figure 31 Propagation Exponent on LOS

4 sectors in each cell, $\theta = 3^\circ$, $G_s = G_b = 25\text{db}$, $\sigma = 10\text{ db}$, Freq = 28 GHz, BW = 6 MHz

The effect of standard deviation of lognormal shadowing on LOS system performance is shown in TABLE 7. It is observed that the system performance is not so sensitive to the shadowing deviation as to the propagation exponent. At large shadowing deviation of 12 dB, the system outage (e.g. for uplink) is 0.7% which is only 2 fold higher than that of 4 dB deviation. And the system outage has no significant change when the investigated standard deviation is in a scope of 0 - 10 dB. This is because the interfering signal with propagation exponent of 3 is heavily attenuated, and a positive deviation (due to reflections and other reasons) less than 10 dB has no enormous improvement on the

SINR reception. It can be noticed that the received signal strength of the LOS interference is much greater than that of the NLOS, and it is not well modeled by the lognormal shadowing with deviation of 10 dB. We simulate those special cases where there are many buildings and heavy foliage, thus interferers from outside of the cell with relatively large distances are normally NLOS with big attenuations by trees and obstructions.

standard deviation of shadowing (db)	System Outage probability	
	uplink with power control	downlink
0	0.3%	0.1%
2	0.3%	0.1%
4	0.3%	0.1%
6	0.3%	0.2%
8	0.3%	0.2%
10	0.4%	0.3%
12	0.7%	0.5%
14	1.1%	0.9%

TABLE 7 Standard Shadowing Deviation on LOS Outage
4 sectors in each cell, $\theta = 3^\circ$, $G_s = G_b = 25\text{db}$, $m = 3$, Freq = 28 GHz, BW = 6 MHz

In comparison of the uplink and downlink of LOS system, we can see that the system outage probability is relatively small at the downlink. This is because at the downlinks the transmitting powers are set at the same level, while at the uplinks there are some deviations on received signal strength due to the different distances at the desired link and the interference channel.

In short, high antenna gain ratios are needed in LOS system, especially at the hub antennas. Power control must be required at the uplink and high level modulation is not recommended in the system design due to its relatively high SINR requirement.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

A system design for LMCS with frequency reuse of one in each cell has been verified to be able to provide good performance with outage probability less than 1% by employing highly directional antennas at the subscribers' locations. Both scenarios of NLOS and LOS have been investigated and it is found that the system design based on LOS transmissions can provide four times greater capacity and lower outage than the NLOS model.

It is found that highly directional antennas at the subscribers in fixed locations can provide large improvements in system performance for both uplink and downlink and could support system design of frequency reuse of one in LMCS systems. The simulation results demonstrate that the overall outage can be significantly decreased by decreasing the beamwidth and/or increasing the gain ratio of the directional antenna (section 6.1.1). A highly directional antenna with small sidelobe can null out interference outside of the mainlobe and therefore improve system performance prominently.

The simulation results in Chapter 6 show that lower outage can be achieved when using a sectored antenna at the hub instead of an omni antenna. By using a 4-sectored antenna at the hub and polarization reuse in adjacent sectors of the same cell, the system performance can be improved significantly (section 6.2).

The LMCS system performance is affected by the path loss exponent and the deviation of lognormal shadowing (section 6.1.2 and section 6.2.4). A large value of propagation exponent can attenuate interference from outside of the cell, but will also increase the blocking probability of the desired links. To improve the transmission performance, the cells may be heavily overlapped and the user may be allowed to select the best communication link among the nearby hubs. Simulation results indicate that the outage probability

could be decreased one order of magnitude by employing site diversity in this way (section 6.1.3).

The near-far problem is severe in LMCS systems due to their full frequency reuse in each cell or sector. Power control executed at the uplink of LMCS system can result in two to three fold improvement in system outage (section 6.1.4).

Simulation results also show that with power control and selective macrodiversity employed, using directional antennas with beamwidth of 3° and gain ratio of 25db at the subscribers results in an outage of 0.9% for the NLOS system. If LOS is assumed available for desired links, an outage of 0.3% could be achieved with a 90° sectorized antenna at the hub and polarization reused in adjacent sectors of each cell (section 6.2).

In a LOS system, the downlink is relatively easy to maintain, but the uplink performance is quite related to the provision of good power control. The most dominant interference of a LOS system is from the opposite sector within the same cell, and a high-gain-ratio hub antenna is very important for the LOS system design (section 6.2.2).

As SINR reception threshold increases, the outage increases proportionally. In order to provide a good quality of service, a low level modulation scheme is preferable for LMCS system design with frequency reuse in each sector of each cell (section 6.1.5). However, the high capacity provided by high level modulation schemes is still attractive and high level modulation could be applicable once we reduce the frequency reuse and modify the system design.

7.2 Recommendations for Future Research

At various points in the discussion of results, questions have been raised which could not be answered by our simulation and analytical informations.

In this thesis, our investigations are based on a two-dimensional system model and we find there is a dominant interference coming into the mainlobe of the directional subscriber antenna. However, as the beamwidth of the directional antenna is limited in three

dimensions, some subscribers which are located near the hub can avoid the interferences from adjacent cells by tilting their antenna angles slightly upward. (Figure 32) Therefore, the performance of a practical system may be even better than what have been derived from our two-dimensional simulations. Three-dimension investigations are needed for future research.

Figure 32 Directional subscriber antenna with up-tilted angle in microcell system

In this thesis, a flat-topped antenna pattern is assumed for directional antenna with a small uniform sidelobe. Actually, a directional antenna may have more than one sidelobe with different levels. Such non-flat-topped pattern is not suitable to be used in statistical simulations. A new analytical method of ray tracing may be helpful to investigate the effect of the practical directional antenna.

It is assumed that there is no multipath or significant fast fading due to the applications of directional antennas with sharp beamwidths. But some people argue that there

might be still some multipath and unneglected delay spread in some critical areas even though highly directional antennas are employed. Some necessary propagation measurements will be completed by CRC at the beginning of 1997 and detailed research on the effects of multipath is needed.

The simulation of LOS system is conducted based on the assumption of ideal polarization transmissions which isolate the adjacent sectors completely. Actually, this is not practical and further investigation need to be conducted based on a more realistic assumption of polarization reuse.

Though low level modulation is recommended for the LMCS system in this thesis due to its robustness to interference, we cannot neglect the significant advantage of bandwidth efficiency of those high level modulation schemes such as 64 QAM. Further research on efficient coding solutions may help to reduce interference and provide the possibility of high level modulations in LMCS systems.

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