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A PROPAGATION STUDY OF THE 28 GHZ LMDS SYSTEM PERFORMANCE WITH M-QAM MODULATIONS UNDER RAIN FADING

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Abstract—In this paper, rain statistics of 10 years record in Taiwan area was used to investigate the transmission performance of the Ka-band LMDS system with QAM modulation. Emphasis was placed to investigate the effects of rain fading under M-QAM modulation schemes. It is found that for LMDS cellular network, M-QAM modulation is difficult to provide an effective and reliable high speed transmission for the case of 6 km radius of cell coverage unless the frequency and polarization diversities are applied; otherwise, the cell coverage of service should be shrunk.

1. INTRODUCTION

LMDS [1] is a line of sight (LOS), point-to-multipoint concept wireless access system operating at Ka-band microwave frequency. The over 1 GHz bandwidth of LMDS which is allocated by FCC to provide envisions throughputs as fast as 1.5 Gbps downstream, with upstream rates as high as 200 Mbps [1]. Despite of its ultra-wide bandwidth capacity, fading due to rain has long been recognized as a major limitation to reliable communication system (satellite to earth or terrestrial links) operating at higher frequency such as LMDS. Therefore, understanding of rain effects is essential to system design to warrant a margin of signal-to-noise ratio or carrier-to-noise ratio to order to maintain a minimum outage that users most concern. Extensive research has been carried out in the past and substantial understanding has been gained to improve and assist the system

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performance. For satellite links, the outstanding work was done for NASA ACTS propagation experimental campaign [2, 3]. Excellent reference may be found in a book by Crane [4]. A number of rain attenuation experiments with OLYMPUS, ITALSAT satellites that gathered valuable data sets were reported. Continuous efforts are being conducted due to the fact that in part rain attenuation is complex in spatial-temporal pattern and in part because of new communication systems with new modulations, coding, antenna, etc., being developed and put into operation.

The complex hydro-geological settings and yet environmentally sensitive of Taiwan island poses great challenge for terrestrial links operating at Ka-band and up. The yearly cumulative rain rate is over 2000 mm at flat areas and over 3000 mm at the mountain areas. In [5], we reported LMDS performance through rain using QPSK modulation. It was shown that using 2 frequencies and 2 polarizations QPSK modulation LMDS with 20 interference cells in Taiwan rainy season. In this paper, we want to further investigate how the rain affects the LMDS system performance using various QAM (Quadrature Amplitude Modulation) modulation schemes. Although, M-QAM has the same bit packing as M-PSK, the spectral efficiency of M-QAM is more attractive than M-PSK modulation [6, 7] and has higher signal-to-noise ratio for the same BER [9]. A detail discussion the system aspects of M-QAM and a comparison of channel capacity between ideal M-QAM and M-PSK can be found in [7]. However, when we come to practical use, M-QAM modulation is more sensitive to environment interference which included rain (natural) and cellular (artificial) effects [7]. Therefore, it is necessary and of interest to analyze the rain fading effects on LMDS system performance with M-QAM modulation. Considering the fact that increase M value signal space distance will shrink and thus increase the system complexity, this study limited the value of M to 64. Of course, higher M of 256 or even 512 QAM can be evaluated following the same procedure if so desired. In addition, the rain distribution from a two-year measurement was used. In particular, the rain drop size distribution was recorded and analyzed to establish the rain fall model by modifying Crane model [4].

This paper is organized as follow. A system and cell configuration of 28 GHz LMDS for our analysis is briefly described in the next section. Section 3 gives the rain model for Taiwan areas from a two-year contiguous measurement. System performance, the main body, was detailed and discussed in Section 4. Finally, conclusions were drawn from this study.

2. AN EXPERIMENTAL LMDS SYSTEM

2.1. LMDS System and Cell Planning

In this study, a LMDS at 28.35 GHz system including base station wireless equipments (BTS) and customer premises equipments (CPE) was used to perform the system analysis [5]. For ease of reference, Table 1 lists key parameters along with link budget given in the last column. Because the high directivity antenna was used in the upstream, only the downstream clutter interference needs to be considered. The antenna patterns of BTS sector antenna and CPE Cassegrain antenna were given in [5]. These patterns were thoroughly integrated into the analysis of the intercellular interference sources to best reflect the real world situation. As for modulation scheme, QAM with coherent detection were used for analysis. Each modulation scheme has different key parameters, i.e., code rate, SNR and spectrum efficiency, etc. Higher order modulation scheme has higher bandwidth efficiency to guarantee a specific BER which will be set to threshold of 10^{-6} in this study. For higher M, although higher spectral efficiency is obtained, QAM suffers from nonlinear distortion. It is noted that for higher order QAM, both service range and sensitivity were reduced in LMDS system. Hence, in this study, we keep M up to 64.

3. RAIN STATISTICS IN TAIWAN

Taiwan is an island located around 24° N, 120° E covering the boundary of tropical and subtropical zones. Figure 3 shows yearly rain statistics for 4 large cities from north to south for 12 years from 1989–2000 records. For rain measurement, two kinds of rain gauge were used to record and compared to each other: the tipping bucket rain gauge with 0.1 mm sensitivity and optical rain gauge with 0.001 mm sensitivity sampling at every 5 seconds. It is well known that rain rate in hourly basis from annual observation is not suitable for fading margin estimation of telecommunication system [7, 8]. It is necessary at this point to convert a long-term hourly data to short-term minutely measurements. To do so, we follow the procedure proposed in [9] by introducing a conversion factor (CF)

$$CF = \frac{R(mm/min)}{R(mm/hr)}$$

where $R(mm/min)$ and $R(mm/hr)$ represent the rain rate cumulative distribution on minutely and hourly basis, respectively. By regress fitting, we obtain a CF for Taiwan area:

$$CF = 0.69\left(R^{0.12}\right)\exp\left[1.51R^{0.02}\right] \tag{1}$$

Accordingly, the Crane model [4] for attenuation was modified as

$$A(R,D) = \begin{cases} aR^b\left[\dfrac{e^{ubd}-1}{ub}\right], & (0 \le D \le d) \\ aR^b\left[\dfrac{e^{ubd}-1}{ub} - \dfrac{B^b e^{cbd}}{cb} + \dfrac{B^b e^{cbD}}{cb}\right], & (0 \le D \le 22.5\,\text{km}) \end{cases} \tag{2}$$

where A is rain attenuation in dB as function of rain rate R and operating distance D, and all the coefficients are given below.

$$\begin{aligned} u &= \ln\left[Be^{cd}\right]/d \\ B &= 2.3R^{-0.17} \\ c &= 0.026 - 0.03\ln(R) \\ d &= 3.8 - 0.6\ln(R)\,\text{km} \end{aligned} \tag{3}$$

Noted that in (2) the parameters a and b are locally tuned to fit the measurements as $a = 0.048$, $b = 1.192$.

4. PERFORMANCE ANALYSIS OF LMDS UNDER RAIN FADING

For LMDS, frequency planning involves, as for other mobile cellular systems, many aspects and processes and all aims at maximizing the spectrum utilization. It is determined at least by such issues as spectrum availability, frequency plan, modulation format, and C/I requirements [1]. Here we explored the last issue, C/I, under rain fading. Exhausted investigation of all frequency plans [11–15] is prohibited due to space limitation. Instead we presented two plans: dual frequency-dual polarization and four frequency-dual polarization. Impacts of the rains associated with both signal attenuation and inter-cell interference will be analyzed and reported in the following.

It is well known that the rain attenuation A can be modeled as log-normal distribution [8, 9]

$$P_A(\xi) = \begin{cases} \dfrac{1}{\xi\sigma\sqrt{2\pi}}\exp\left[-\dfrac{(\ln\xi-\mu)^2}{2\sigma^2}\right], & \xi < 0 \\ 0, & \xi \ge 0 \end{cases} \tag{4}$$

where the mean (μ) and standard deviation (σ) will be discussed in the next section. The channel capacity, C/B (bps/Hz), is random in nature due to propagation fading. It is this random variability of the channel capacity that deteriorates the system performance. Therefore, one may want to determine the probability density function (PDF) and cumulative distribution function (CDF) of the channel capacity for given S/N which is given by

$$\left(\frac{S}{N}\right) = \left(\frac{S}{N}\right)_0 - A \qquad \text{(dBW)} \tag{5}$$

where $\left(\frac{S}{N}\right)_0$ is the signal-to-noise ratio (in dB) for clear conditions and A is the total rain attenuation for the data link. It follows that the CDF of channel capacity can be expressed in terms of S/N in the presence of rain fading as [8]

$$\begin{aligned} F_{C/B}(y) &= Prob\left\{\frac{C}{B} \geq y\right\} = Prob\left\{\frac{S}{N} \leq \gamma\right\} \\ &= Prob\left\{A \geq \left(\frac{S}{N}\right)_0 - \gamma\right\} \\ &= F_A^C\left[\left(\frac{S}{N}\right)_0 - \gamma\right] \end{aligned} \tag{6}$$

with $\gamma = 10\log(2^y - 1)$

From (6) it is recognized that the CDF of channel capacity is related to the complementary CDF of rain attenuation A and thus the CDF of channel capacity can be simply written as

$$F_{C/B}(x) = \int_x^\infty P_A(\xi)d\xi = Q\left(\frac{\ln x - \mu}{\sigma}\right) \tag{7}$$

where $x = \left(\frac{S}{N}\right)_0 - 10\log(2^y - 1)$; $Q(g) \equiv \int_x^\infty \frac{1}{\sqrt{2\pi}} e^{-t^2/2} dt$.

Next, the complementary CDF of BER for M-QAM modulation [6] may be written as

$$F_{BER}^C(x) = Q\left(\frac{\ln\left[\left(\frac{S}{N}\right)_0 - \delta\right] - \mu}{\sigma}\right) \tag{8}$$

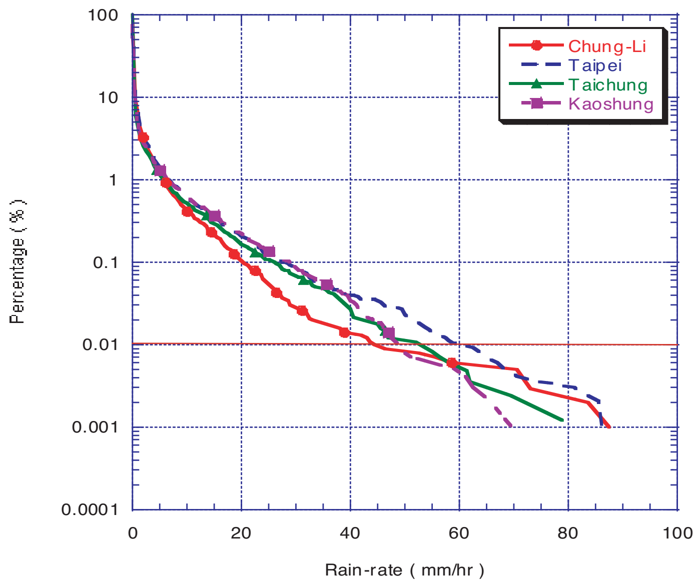

Figure 1. Compare with 4 cities time exceeded cumulative rainrate of 12 years hourly integration from north to south in Taiwan.

where

$$\delta = 10\log_{10}\left\{\left[\frac{erfc^{-1}\left(P_b \times \log_2 M\right)}{2\left(1-\frac{1}{\sqrt{M}}\right)}\right]^2\right\}, \quad (9)$$

$$P_b = 2\left(1-\frac{1}{\sqrt{M}}\right)\frac{erfc\left(\sqrt{\frac{S}{N}}\right)}{\log_2 M}. \quad (10)$$

Since the rain attenuation can be described by the log-normal distribution law, it is now necessary to determine its mean and standard deviation which can be obtained from the linear relation

$$\frac{\ln A - \mu}{\delta} = Q^{-1}(P) = \alpha \ln A + \beta \quad (11)$$

where the slope α and intercept β for this line may be found by means of linear regression from N measured data sets

$$\left(\ln A_i, Q^{-1}(P_i)\right); \qquad i = 1, 2, \ldots, N \tag{12}$$

$$P_i = Prob\{A \geq A_i\}; \qquad i = 1, 2, \ldots, N \tag{13}$$

Knowing that the rainfall intensity R (mm/h) represents the value exceeded a particular percentage of the year, it is easy to obtain the rain attenuation data for A and P; a relationship whereby A will be exceeded for P% of an average year. Here we simply need P and A data pairs from a 2 years of accumulated rain rate data measured in mm per minute. It turns out that we could find:

$$\mu = -\frac{\beta}{\alpha}, \qquad \sigma = \frac{1}{\alpha} \tag{14}$$

Once μ and σ are determined, we can calculate the CDF of channel capacity and BER for various signal-to-noise ratio (S/N) values in single cellular environment. For multi-cellular environment, we follow the same steps to determine the CDF of channel capacity. Note that the interference level is sum of interference from other cells and channel noise.

4.1. Two Frequency-Dual Polarization (2F2P)

Figure 2 shows the cell plan with 4 sectors, each sector pertained to 4 channels (two frequencies and two polarizations-horizontal and vertical polarized) for downlink. In this case, each coverage radius of reuse channel was 5 times of cell radius. For a given M-QAM modulation scheme, the system BER and C/B are a function of S/I (signal-to-interference) in the presence of rain fading as well as possible inter-cell

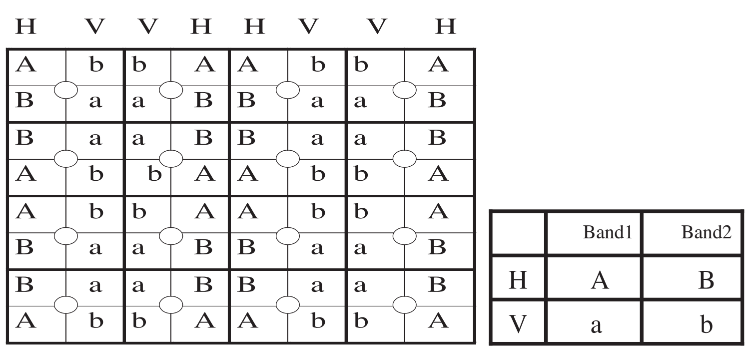

Figure 2. Two-frequency and dual polarization cell plan.

Table 1. Parameters formula and calculations for LMDS system.

Parameter	Units	Formula	value
Transmit Power into Antenna	dBW	p_{tx}: Transmit Power per carrier	0
Transmit antenna gain	dBi	$G_t = G_{ant}$	20.15
Frequency	GHz	f: Transmit Frequency	28.35
Path length	Km	D: Hub-to-Subcriber Station Range	6
Field Margin	dB	L_{FM}: Antenna Mis-Alignment	-1.0
Free-Space Loss	dB	$FSL = 92.45 - 20 * \log(f) - 20 * \log(d)$	-137.06
Total Path Loss	dB	$L_{Tot} = FSL + L_{atm} + L_{FM} + L_{excess}$	-138.06
Receiver Antenna Gain	dBi	$G_r = G_{ant}$	34.96
Effective Bandwidth	MHz	B_{RF}: Receiver Noise Bandwidth	40
Receiver Noise Figure	dB	NF: Effective Noise Figure	5
Thermal Noise	dBW/MHz	$10 * \log(k * T_0)$	-143.86
System Loss	DB	$L_{sys} = G_t + L_{Tot} + G_r$	-82.95
Receive Signal Level	dBW	$RSL = P_{tx} + L_{sys}$	-82.95
Thermal Noise Power Spectral Density	dBW/MHz	$N_0 = 10 + \log(k * T_0) + NF$	-140.51
Carrier-to-Noise Ratio	dB	$C/N = RSL - N_0 - 10 + \log(B_{RF})$	39.90

interference. It gives the percentage of the time for which the specified BER and C/B will be exceeded under rain fading. The BER and C/B performance of LMDS at various service distances from $D = 1$ to 6 km at step of 1 km for 6 km cell coverage was presented. It is noticed that interferences come from both the rain fading and the inter-cell noise. Figure 3 shows the long term complementary CDF of BER in the presence of rain attenuation. Wherever possible, we indicated results for $M = 4$, 16 and 64. We can see that as the service distance increases, the probability that exceeds a specified BER increases drastically. For higher BER, the lower order modulation has slight change of excedence probability. Relaxation of BER to lower values would also lower the excedence probability and the system gained better transmission performance accordingly. It is thus reasonably expected that for higher BER tolerant (e.g., 10^{-3} for voice) system, it should have higher availability than, say, data transmission (BER $= 10^{-6}$) system. We also see that among these path length changes, the 64 QAM gets the worst results for the case under consideration. It is almost out of bounds right away when $D > 2$ km. Table 2–Table 4 list these numeric values for $M = 4$, 16, 64. Here again it clearly indicates the degradation of system performance as M gets higher.

Now, the long-term statistical analysis of channel capacity is in

Table 2. Excedence probability of BER with 4-QAM modulation in the presence of rain fading process versus path length with inter-cell interference.

	D=1km	D=2 km	D=3km	D=4km	D=5km	D=6km
BER= 10^{-7}	3.14e-3%	1.3333%	5.542%	86.86%	100%	100%
BER= 10^{-6}	2.2e-3%	0.2125%	4.864%	34.154%	100%	100%
BER= 10^{-5}	1.21e-3%	1.30e-2%	2.45%	12.928%	71.939%	100%
BER= 10^{-4}	6.57e-4%	7.37e-2%	1.178%	4.736%	21.985%	71.627%
BER= 10^{-3}	3.04E-4%	4.66e-2%	0.512%	1.499%	5.81%	17.043%
BER= 10^{-2}	9.89e-5%	3.74e-2%	0.177 %	0.296%	0.978%	2.499%

Table 3. Excedence probability of BER with 16-QAM modulation in the presence of rain attenuation fading process versus path length with inter-cell interference.

	D=1km	D=2km	D=3km	D=4km	D=5km	D=6km
BER= 10^{-7}	8.42%	100%	100%	100%	100%	100%
BER= 10^{-6}	2.75%	100%	100%	100%	100%	100%
BER= 10^{-5}	0.84%	100%	100%	100%	100%	100%
BER= 10^{-4}	0.23%	100%	100%	100%	100%	100%
BER= 10^{-3}	0.049%	14.2585%	100%	100%	100%	100%
BER= 10^{-2}	6.39e-3%	0.7257%	36.3711 %	100%	100%	100%

Table 4. Excedence probability of BER with 64-QAM modulation scheme in the presence of rain attenuation fading process versus path length with inter-cell interference.

	D=1km	D=2km	D=3km	D=4km	D=5km	D=6km
BER= 10^{-7}	100%	100%	100%	100%	100%	100%
BER= 10^{-6}	100%	100%	100%	100%	100%	100%
BER= 10^{-5}	100%	100%	100%	100%	100%	100%
BER= 10^{-4}	100%	100%	100%	100%	100%	100%
BER= 10^{-3}	100%	100%	100%	100%	100%	100%
BER= 10^{-2}	97.52%	100%	100%	100%	100%	100%

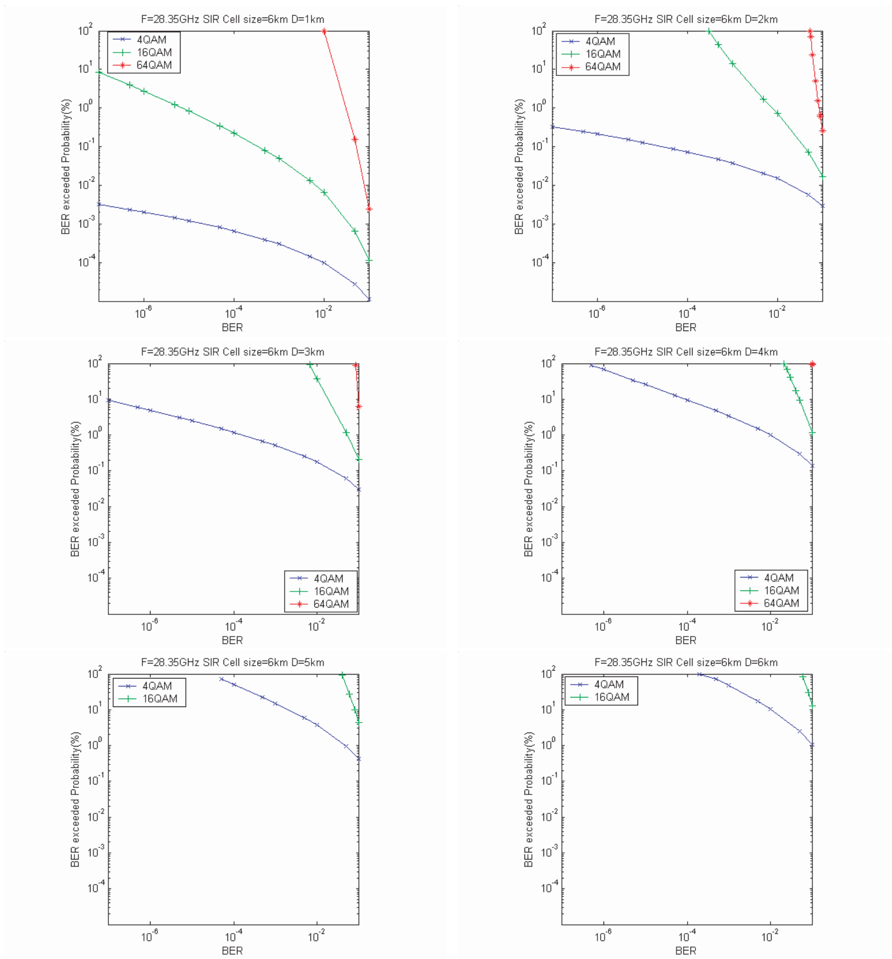

Figure 3. Excedence probability of BER in the presence of rain attenuation fading when $D = 1 \sim 6\,\text{km}$ by measurement model with presence of inter-cell interference (S/I). The cell size is set to 6 km.

order. Because the channel is subject to fading, its capacity varies with the changes in the propagation medium. One could say that the channel capacity inherits in one way stochastic properties of fading process. To consider the data downlink, again we set BER to 10^{-6}. Figure 4 displays the CDF of channel capacity at various service distances of different cell radius, where the thresholds of C/B at BER $= 10^{-6}$ for each modulation scheme were indicated. For the same link length, with increase of the cell size, the capacity is apparently

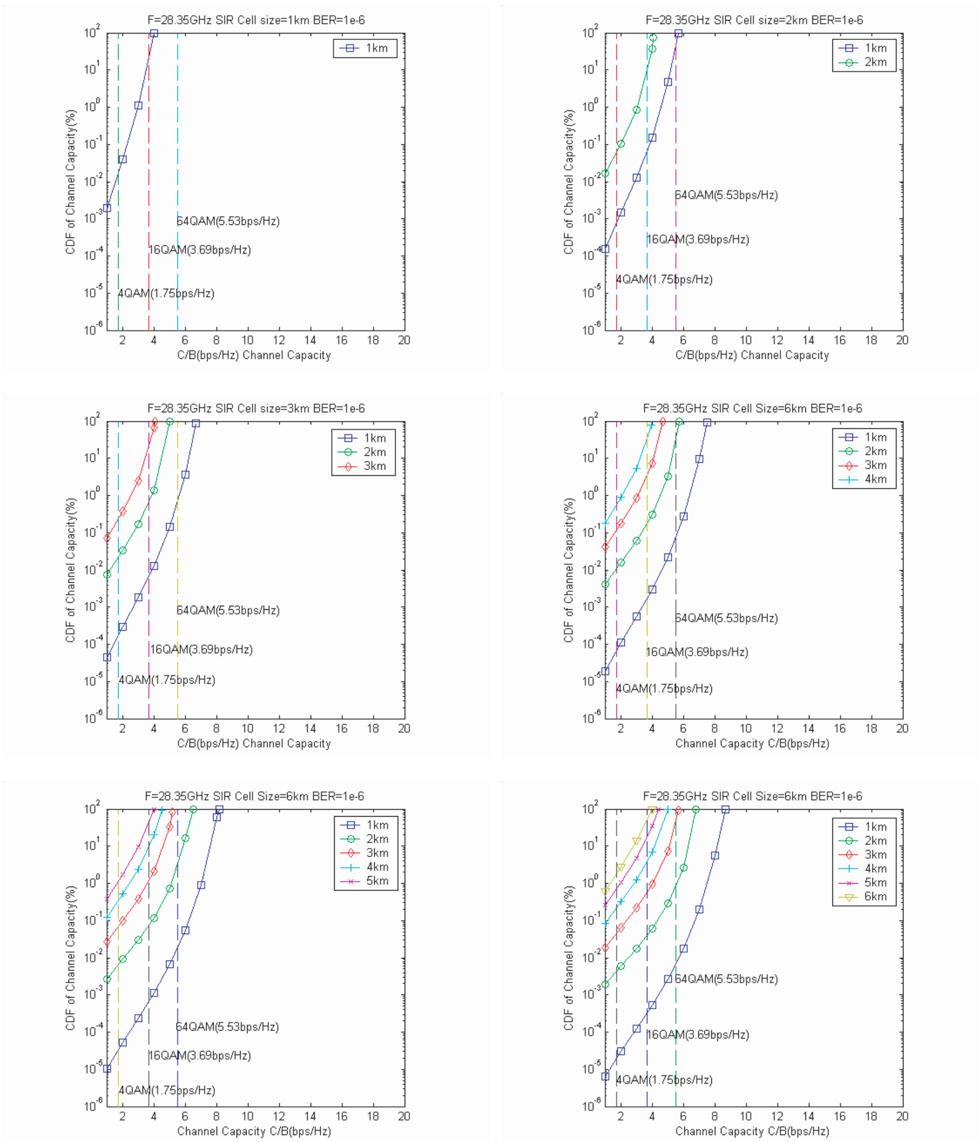

Figure 4. CDF of channel capacity in the presence of rain attenuation fading process versus path length ($D = 1 \sim 6\,\text{km}$) by measurement with inter-cell interference (S/I) using different cell size ($1 \sim 6\,\text{km}$).

Table 5. Excedence probability of BER with 4QAM modulation scheme in the presence of rain attenuation fading process versus path length by new cell planning with interference.

	D=1km	D=2km	D=3km	D=4km	D=5km	D=6km
BER=10^{-7}	3.83e-5%	7.3e-3%	8.17e-2%	0.427%	1.494%	4.047%
BER=10^{-6}	2.857e-5%	5.87e-3%	6.43e-2%	0.328%	1.121%	2.975%
BER=10^{-5}	2.051e-5%	4.56e-3%	4.88e-2%	0.242%	0.808%	2.1%
BER=10^{-4}	1.354e-5%	3.35e-3%	3.51e-2%	0.169%	0.549%	1.395%
BER=10^{-3}	7.868e-6%	2.26e-3%	2.30e-2%	0.107%	0.339%	0.839%
BER=10^{-2}	3.53e-6%	1.28e-3%	1.26e-2%	0.056%	0.171%	0.413%

Table 6. Excedence probability of BER with 16-QAM modulation scheme in the presence of rain attenuation fading process versus path length by 4F2P cell plan.

	D=1km	D=2km	D=3km	D=4km	D=5km	D=6km
BER=10^{-7}	2.18e-3%	0.238%	6.125%	94.456%	100%	100%
BER=10^{-6}	1.40e-3%	0.154%	3.275%	41.082%	100%	100%
BER=10^{-5}	8.39e-4%	0.095%	1.705%	16.49%	94.483%	100%
BER=10^{-4}	4.49e-4%	0.054%	0.836%	6.526%	34.019%	99.614%
BER=10^{-3}	1.99e-4%	0.027%	0.363%	2.361%	10.147%	33.135%
BER=10^{-2}	6.00e-5%	03e-2%	0.119 %	0.657%	2.3924%	6.729%

increased. Two more pronounced phenomena were observed. First, for higher order modulation, the capacity was rapidly reduced. Secondly, the link length poses significant impact on the capacity. One also sees that the curves of CDF of capacity were quite parallelized for various link lengths, no quick drop-off, and all closed to quasi-linear. One may reach that even for small cell size it seems hardly to avoid the interference.

At this point, we show that when M-QAM modulation scheme is used, all the service distances ($D = 1 \sim 6\,\mathrm{km}$) for downstream are hardly to link well with 6 km cell size using this cell plan, namely, two-frequency-dual-polarization configuration. In the following, we shall perform similar analysis but using four-frequency, dual-polarization cell plan.

Table 7. Excedence probability of BER with 64-QAM modulation scheme in the presence of rain attenuation fading process versus path length by 4F2P cell plan.

	D=1km	D=2km	D=3km	D=4km	D=5km	D=6km
BER= 10^{-7}	14.84%	100%	100%	100%	100%	100%
BER= 10^{-6}	4.36%	100%	100%	100%	100%	100%
BER= 10^{-5}	1.19%	100%	100%	100%	100%	100%
BER= 10^{-4}	0.29%	100%	100%	100%	100%	100%
BER= 10^{-3}	5.50e-2%	19.91%	100%	100%	100%	100%
BER= 10^{-2}	5.71e-3%	67%	34.66%	100%	100%	100%

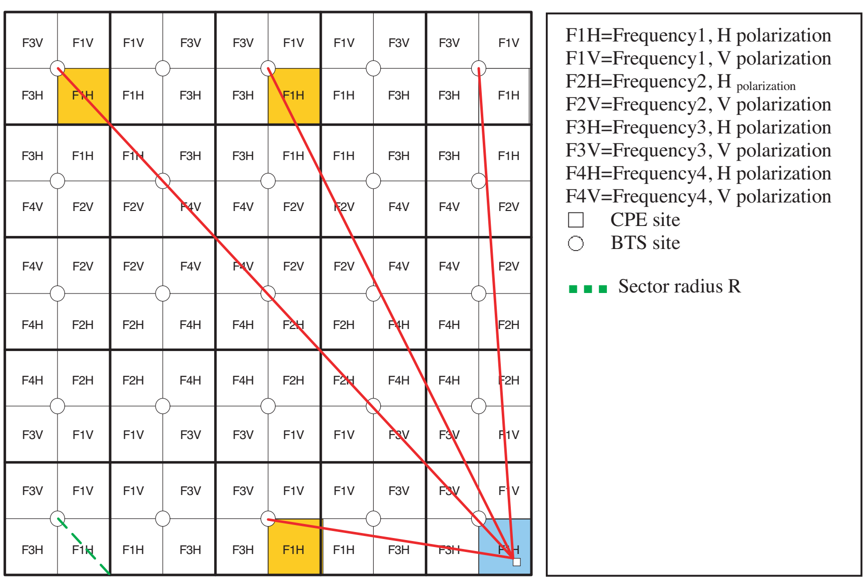

Figure 5. Four-frequency and dual polarization cell plan.

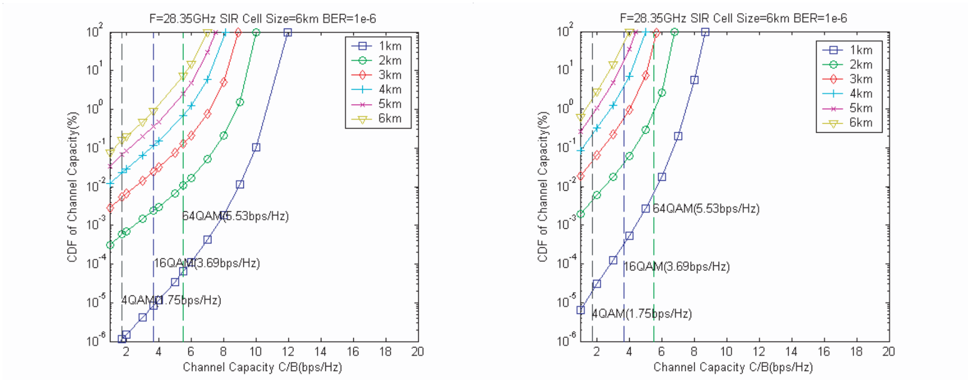

Figure 6. The comparison of channel capacity between two cell plans (left: 4F2P, right:2F2P) at various of distance with cell size of 6 km and BER= 10^{-6}.

4.2. Four Frequency-Dual Polarization (4F2P)

As presented above, the poor BER performance of M-QAM is due to the short path of the interference source. In order to improve the performance, we extend the distance between the BTS and interference sources. The new cell structure now uses 4 frequencies and 2 polarizations as sketched in Figure 5, where the main interference sources have four cells, instead of three sites in the configuration of two-frequency and dual polarization, with only one site closer to CPE than the others. Because the distance of the other three sites was now doubled, the S/I of downstream were increased. Comparing the signal-to-(noise + interference) between the two cell plans, i.e., 2F2P and 4F2P, it shows that about 5 dB gain can be obtained from this new cell plan. It may be mentioned at this point that this study is not intent to pursue exhaustive examination of every possible cell plans. Because of the shorter distance of interference source and narrow antenna beam width of CPE, the S/I is higher than that of 2F2P. Based on this cell plan, we analyzed the bit error rate (BER) performance and channel capacity of LMDS under the rain and cell interference environments. Figure 6 shows the channel capacity in comparison with the 2F2P cell plan at 6 km cell coverage. It is obvious that the capacity is now substantially increased. For example, for CDF smaller than 10^{-2}, the channel capacity increases from about 6 to 10 bps/Hz at link length of 1 km. Figure 7 plots the excedence probability of BER. Compared to Figure 4 we can see that the by configuring the cell structure, we may enhance the channel capacity by increasing the interference length.

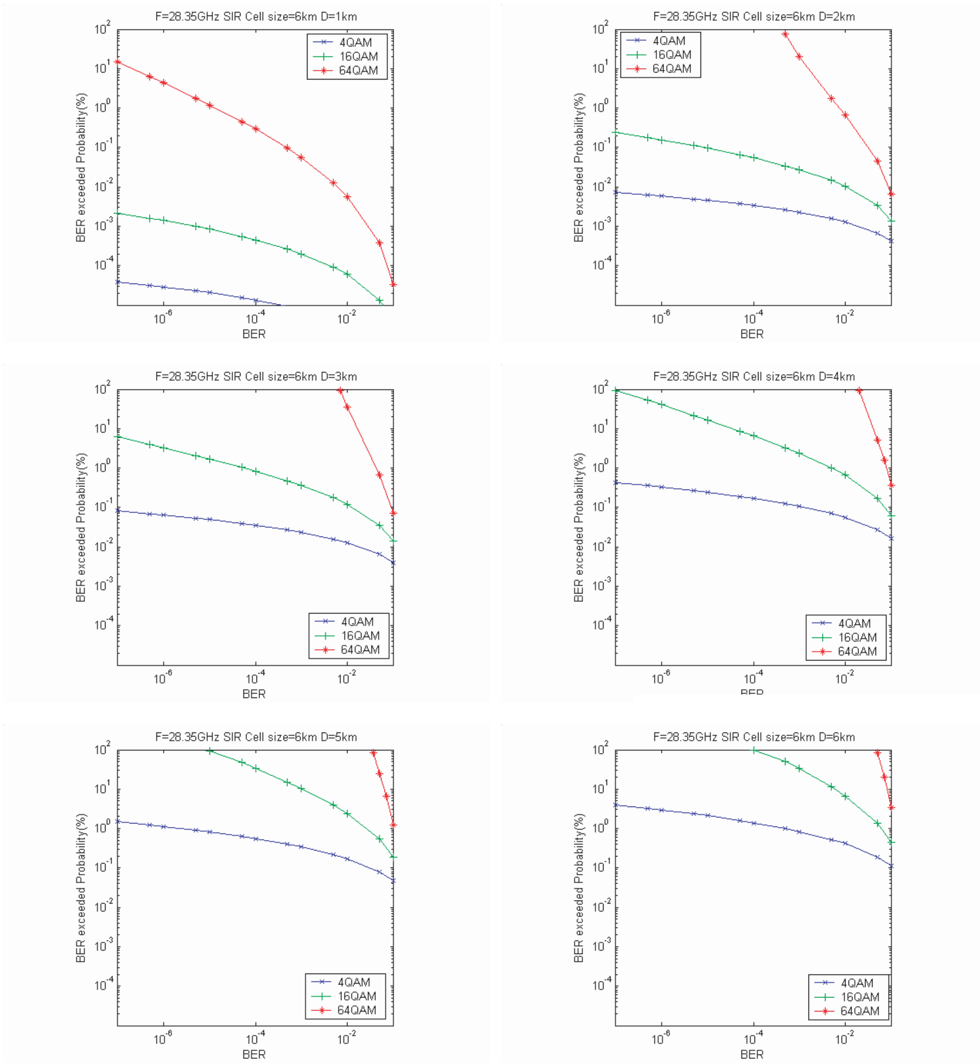

Figure 7. Excedence probability of BER in the presence of rain attenuation fading when $D = (1 \sim 6\,\text{km})$ and cell size $= 6\,\text{km}$ under 4F2P cell plan with inter-cell interference (S/I).

5. CONCLUSION

In this study, we used 12-year rain measurements data if Taiwan to conduct the long-term statistical channel performance of LMDS system operated at 28 GHz. Results indicated that the LMDS with M-QAM digital modulation, the service radius for data transmission should be less than 1 km with cellular interference in the 6 km cell coverage area under the rain fading. According to the performance analysis, it is suggested that the LMDS cellular network with M-QAM modulation was found to be hard to provide an effective and reliable high speed data transmission in 6 km large cell coverage radius in Taiwan's rain environment. To improve the performance, the cell plan may be configured by frequency and polarization diversity. It was found that the capacity of the LMDS using M-QAM was enhanced due to larger inter-cell interference link path. The BER and channel capacity can be improved by increasing the distance between BTS and interference sources. This can be done by deploying frequency and polarization diversity. As has been demonstrated, the 4F2P plan is superior to 2F2P plan where the interference path is shorter and hence poises higher interference level, further degrades the channel performance. Even with this improvement, we may conclude that for M-QAM modulation, the service range is quite limited considering the rain fading and inter-cell interference in terms of cost-effect.

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