An Adaptive Modulation in Millimeter-Wave Communication System for Tropical Region

Suwadi[1], Gamantyo Hendrantoro[2] and Wirawan[3]
Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember Surabaya
Kampus ITS Sukolilo, Surabaya 60111, Phone/Fax. +62 31 5947302/5931237
e-mail : suwadi@ee.its.ac.id[1]; gamantyo@ee.its.ac.id[2], wirawan@its.ac.id[3]

Abstrak

Redaman hujan merupakan faktor propagasi yang dominan yang mempengaruhi outage dan efisiensi spektrum dari sistem komunikasi gelombang milimeter yang bekerja pada frekuensi 30 GHz. Modulasi adaptif diusulkan untuk meningkatkan kinerja sistem tersebut yaitu outage dan efisiensi spektrum. Makalah ini menjelaskan prosedur analitik untuk evaluasi outage dan efisiensi spektrum dari sistem tersebut di Indonesia, yang mempunyai curah hujan tinggi. Sebagai validasi, hasil analitik dibandingkan dengan hasil simulasi. Hasil penelitian menunjukkan bahwa modulasi adaptif dapat memperbaiki outage dan efisiensi spektrum sistem secara signifikan, khususnya untuk link dengan jarak jauh.

***Kata kunci**: efisiensi spectrum, gelombang millimeter, modulasi adaptif, redaman hujan*

Abstract

The dominant propagation factor affecting the outage and the spectral efficiency of millimeter-wave communication systems operating at frequencies 30 GHz is rain attenuation. An adaptive modulation is proposed to improve the outage and spectral efficiency performance of the system. This paper presents an analytical procedure for the evaluation of the outage and spectral efficiency of the system in Indonesia with heavy rain rate. By comparing analytic and simulation a validation was conducted. The results show that adaptive modulation can significantly improve the outage and the spectral efficiency performance of the system, for links with long distance.

***Keywords**: adaptive modulation, millimeter-wave, rain attenuation, spectral efficiency*

1. Introduction

The demand for broadband communication for high quality multimedia transmission is driving the use of higher radio frequency spectrum. Local multipoint distribution service (LMDS) [1] is a line of sight (LoS) point-to-multipoint broadband fixed wireless access system (BFWA) operating at millimeter-wave frequency. It is designed to deliver telecommunication and broadcast services (multimedia, video, internet, etc) from a central transmitter to individual subscriber within its cell size. The frequency bands allocated by ITU R and CEPT are usually above 20 GHz. In this band, rain attenuation is the most influential propagation factor to determine the system outage probability [2]. In such tropical countries as Indonesia very high rainfall intensities might cause significant attenuation in millimeter-wave communication system [3], [4].

Adaptive power control has been shown to work well as a 30/20 GHz rain fade countermeasure in satellite systems [5]. The cell-site diversity technique has also been proposed in order to reduce the outage time by utilizing the spatial variations of rain [6], [7]. However, these techniques are mainly concerned with the improvement of outage performance, but not the spectral efficiency. On the other hand, adaptive modulation has been shown to improve outage and spectral efficiency performances of communication systems in Rayleigh distributed channel for a target bit error probability [8], [9]. In the sequel, the discussion will be started with the system model, clear sky signal to noise ratio, rain attenuation, including formulation of outage probability and average spectral efficiency, and follow it up with numerical results and discussions.

2. Proposed Adaptive Modulation

In this paper, adaptive modulation technique is used to improve the outage and spectral efficiency of LoS millimeter-wave communication system in the presence of tropical rain attenuation, as shown in Figure 2. The system uses various modulation levels, i.e. 4, 16 and 64QAM, to appropriate channel condition that is affected by rain attenuation A. In clear sky conditions, the channel is only affected by Gaussian noise with power spectral density N (W/Hz). The system uses 64-QAM so that it has maximum spectral efficiency of 6 bps/Hz and outage probability less than 0.01%.

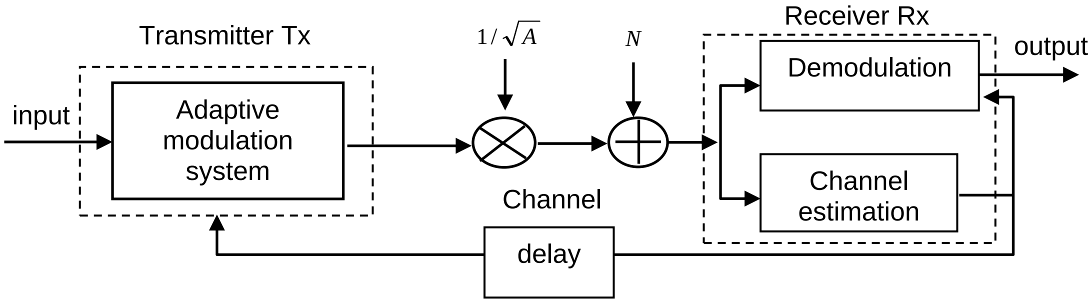

Figure2 Adaptive modulation system

In rain conditions, the channel is affected by rain attenuation which causes the received signal-to-noise ratio γ to decrease, so the system has to use lower modulation level, i.e. 16-QAM or 4-QAM. In this research, perfect channel estimation is assumed. The feedback path will be assumed that it does not introduce any errors. The availability of channel information at the transmitter allows it to adapt its transmission scheme relative to the variation channel. The effects of feedback delay are ignored since in reality this delay is very small with respect to the rate of variation of rain attenuation. Bit error probability P_b for an AWGN channel with MQAM modulation and ideal coherent phase detection is bounded by [9], [11]

$$P_b \leq 0.2\exp\left(\frac{-1.5\gamma}{M-1}\right) \qquad \text{for } M \geq 4 \tag{1}$$

The threshold signal-to-noise ratio for target P_b:

$$\gamma_{th} = \frac{(M-1)\ln(5P_b)}{-1.5} \tag{2}$$

with M denoting the modulation level. By using (2), thresholds of received signal-to-noise ratio γ_{th} can be obtained for each modulation level. Adaptation scenario for bit error probability 10^{-6} can be shown in Table 1.

Table 1. Adaptive M-QAM Scenario for Pb=10^{-6}

Region (j)	Modulation Mode	M_j	γ Interval (dB)
0	No transmission	0	γ < 13.876
1	4 QAM	4	13.876< γ < 20.866
2	16 QAM	16	20.866< γ < 27.098
3	64 QAM	64	γ > 27.098

3. Research Method

In this research, evaluation of the system performance uses simulation and analytical method.

3.1 Rain measurement

For rain measurement, instrument was used to record, i.e. disdrometer. It was placed at the campus of Institut Teknologi Sepuluh Nopember (ITS) Surabaya, Indonesia (7^o 13' S, 112^o 43' E) since 2007. Rain rate has been measured until now. It was used to record rain rate data and then stored in a personal computer (PC) through RS232 and data sampling at every 10 s. In this research, it uses rain rate measurement data for 2 years. The $R_{0.01}$ means that the rain rate at 0.01% of time in measured period that the rain-rate value is exceeded. Figure 1 shows that Surabaya Indonesia's $R_{0.01}$ is 140 mm/h, larger than that of non tropical area.

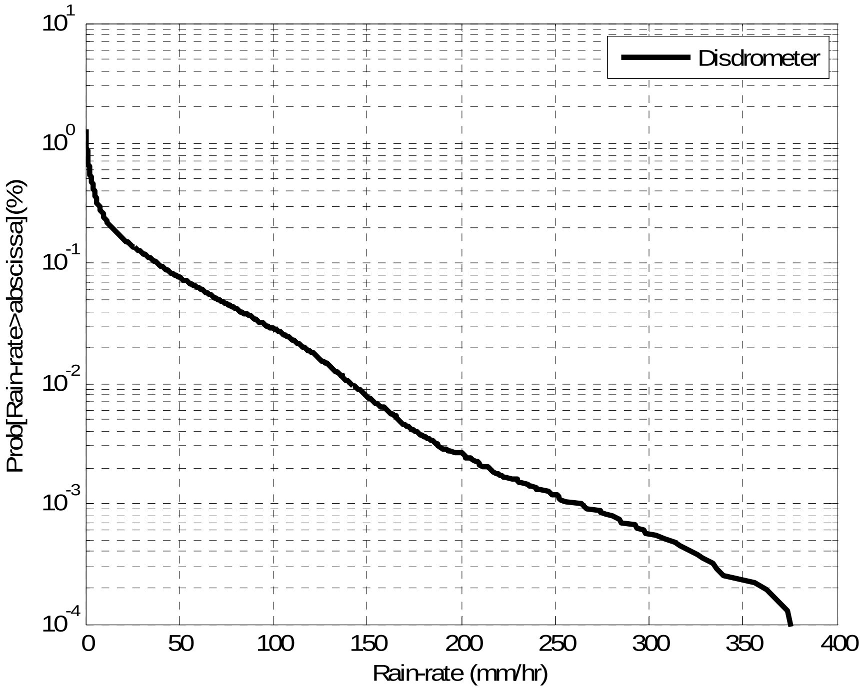

Figure 1 $CCDF_s$ of rain rate measurement result per year in Surabaya, Indonesia

In this paper, the use of adaptive modulation to improve the outage performance and average spectral efficiency is concentrated in millimeter-wave communication systems under the impact of tropical rain attenuation. To the best of the knowledge, this technique has never been studied for application in this condition. The technique will be explained in section 3.

In particular, analytical and simulation results of evaluation of outage probability and spectral efficiency in 30 GHz communication systems are presented. The simulation is done by applying the synthetic storm technique (SST) on rainfall intensity measurements in Surabaya, Indonesia and adopts ITU-R P.838-3 recommendation for calculating specific rain attenuation [10].

3.2 Clear Sky Signal to Noise Ratio

In this study, the key parameters of LMDS system used in ref. [12] are used. The transmitter and receiver antenna gains are 15 and 30 dBi, respectively. Accordingly, we compute signal to noise ratio clear sky condition for various transmitted powers and link lengths as shown in Table 2.

Table 2. Signal to Noise Ratio in Clear Sky Condition

Transmit Power (dBw)	Signal-to-noise ratio at clear sky condition γ_{cs} (dB)			
	1 km	2 km	3 km	4 km
-5	39.8	33.8	30.3	27.8
0	44.8	38.8	35.3	32.8
5	49.8	43.8	40.3	37.8

3.3 Rain Attenuation

In this research, the rain rate measurements recorded for 2 years in Surabaya ($7^0$13' S, $112^0$43' E), Indonesia are used. Rain rate statistic $R_{0.01}$ found from the measurement is 140 mm/h, larger than that of 100 mm/h suggested by ITU-R [9]. Rain attenuation was estimated by using synthetic storm technique (SST), which had been successfully tested for predicting long term statistics of fade duration [13]. Based on the rain attenuation estimates, it can be obtained mean μ and standard deviation σ of logarithm of rain attenuation of various link lengths as shown in Table 3. It is well known that rain attenuation value A (dB) is approximately log-normally distributed. Therefore, the overall long-term pdf of rain attenuation along the link has the form [12]:

$$P_A(a) = \begin{cases} \dfrac{1}{a\sigma\sqrt{2\pi}} \exp\left(-\dfrac{1}{2}\left[\dfrac{\ln a - \mu}{\sigma}\right]^2 \right), & a \geq 0 \\ 0, \quad a < 0 \end{cases} \tag{3}$$

and the CCDF:

$$P(A \geq a) = \int_a^{\infty} P_A(\lambda) d\lambda = Q\left(\frac{\ln(a) - \mu}{\sigma}\right) \tag{4}$$

where μ and σ are the mean and standard deviation of ln(A). It can be obtained analytically complementary cumulative distribution function (CCDF) of rain attenuation using (4). Figure 3 shows CCDFs of rain attenuation obtained using SST and analytically. The SST results can be approximated by the analytical at least for exceedance probabilities above 0.01%.

Table 3. Rain Attenuation Parameters of Mean and Standard Deviation

Rain attenuation parameters	1 km	2 km	3 km	4 km
μ	- 0.687	- 0.0255	0.347	0.603
σ	1.650	1.683	1.715	1.744

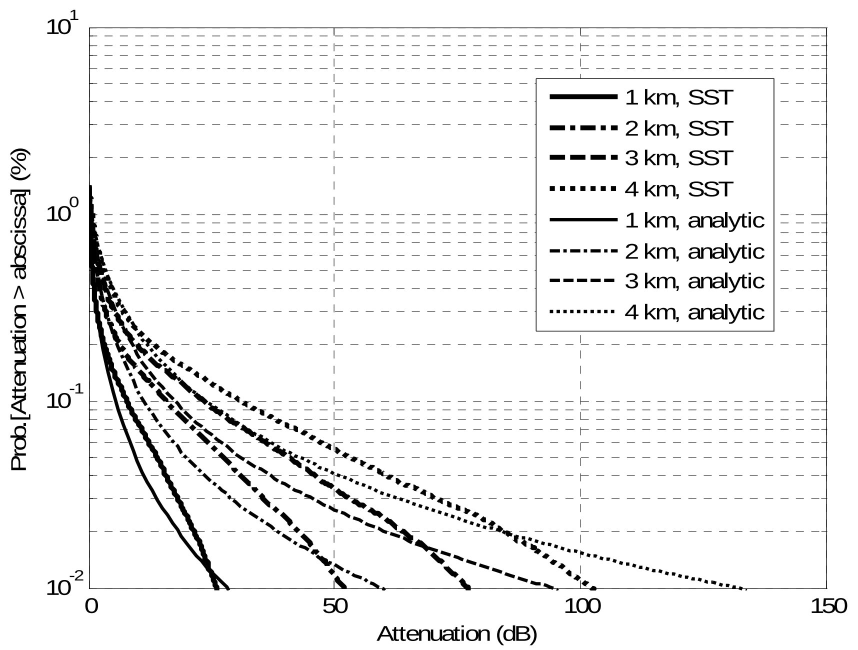

Figure 3 CCDFs of rain attenuation for single link with 1-4 km link lengths

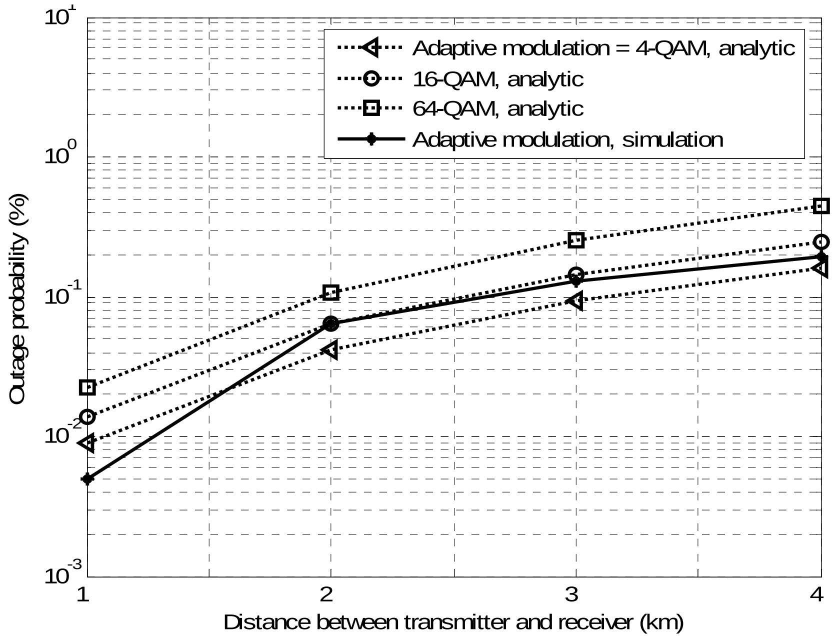

Figure 4 Outage probability of various link lengths with transmit power 0 dBw

3.4 Outage Probability

The outage probability is defined herein as the fraction of time where the signal-to-noise ratio γ falls below a specified threshold γ_{th} :

$$P_{out} = P(\gamma < \gamma_{th}) = P(\gamma_{cs} - A < \gamma_{th}) = P(A \geq \gamma_{cs} - \gamma_{th}) \tag{5}$$

where γ_{cs} and A respectively are signal-to-noise ratio (dB) in clear sky conditions and rain attenuation (dB). The final form of (5) can be computed using (4) with $a = \gamma_{cs} - \gamma_{th}$

3.5 Average Spectral Efficiency

In variable-rate modulation the data rate R[γ] is varied according to the signal to noise ratio γ. This can be done by fixing the symbol rate R_s=1/T_s of the modulation and using multiple modulation schemes, or by fixing the modulation (e.g. 4QAM) and changing the symbol rate. In contrast, changing the modulation type with a fixed symbol rate is fairly easy, and these techniques are used in current systems [9]. When a discrete set of modulation types is used each value of γ must be mapped into one of the possible modulation schemes. This is often done to maintain the bit error probability of each scheme below a given value. To maintain the target P_b the modulation level M and constant power are adjusted. The average spectral efficiency for this discrete rate policy is just the sum of the data rates associated with each of the regions multiplied by the probability that γ falls in the region. The average spectral efficiency can be calculated by:

$$E[C] = \sum_{j=1}^{M_{j\max}-1} \log_2(M_j) \int_{\gamma_i}^{\gamma_{j+1}} p(\gamma) d\gamma \tag{6}$$

where C and $p(\gamma)$ are respectively spectral efficiency in bps/Hz and probability density function of signal-to-noise ratio in the presence of rain attenuation:

$$p(\gamma)=\begin{cases}\dfrac{1}{(\gamma_{cs}-\gamma)\sigma\sqrt{2\pi}}\exp\left[-\dfrac{\left(\ln(\gamma_{cs}-\gamma)-\mu\right)^2}{2\sigma^2}\right] & ;\gamma\le\gamma_{cs}\\ 0 & ;\gamma<\gamma_{cs}\end{cases} \quad (7)$$

The threshold signal to noise ratio γ_{th} for adaptive modulation system is 13.876 dB for P_b=10^{-6}. The analytically outage probability for various modulation modes with transmitted power 0 dBw is obtained as shown in Figure 4. Adaptive modulation and fixed 4-QAM have the least outage probability, if they are compared with fixed 16-QAM and 64-QAM.

4. Results and Discussion

It is defined herein outage probability improvement as outage probability of fixed 64-QAM divided by that of adaptive modulation. Figure 5 shows that outage probability can improve more than 200% for various link lengths and transmitted powers, when adaptive modulation is used. Outage performance can improve significantly at long distance with low transmit power, e.g., at 4 km link with transmit power -5dBW. In this case, the clear sky signal-to-noise ratio γ_{cs} is slightly higher than γ_{th} of adaptive modulation. Furthermore, as far as outage performance is concerned, adaptive modulation mode with low transmitted power seems to be more suitable.

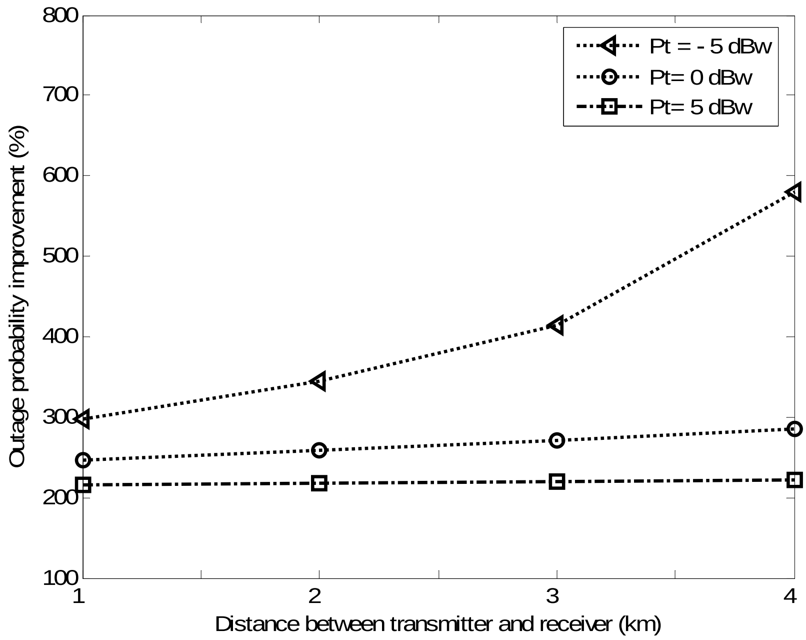

Figure 5 Outage probability improvements of various link lengths for several transmitted powers

Figure 6 shows analytical average spectral efficiency of various modulation modes for several link lengths and simulation result for adaptive modulation. The agreement between the analytical and simulation results seems to be quite good and indicative of the validation of the proposed procedure. Adaptive modulation system has shown the biggest average spectral efficiency among various modulation modes.

Here it is defined that the average spectral efficiency improvement as average spectral efficiency of adaptive modulation divided by that of fixed 64-QAM. Figure 7 shows improvement of average spectral efficiency for several link lengths and transmitted powers. Adaptive modulation can improve more than 200% average spectral efficiency for low power and long distance. In this case, if average spectral efficiency is concerned, adaptive modulation with low power on long distance links shows the biggest efficiency improvement.

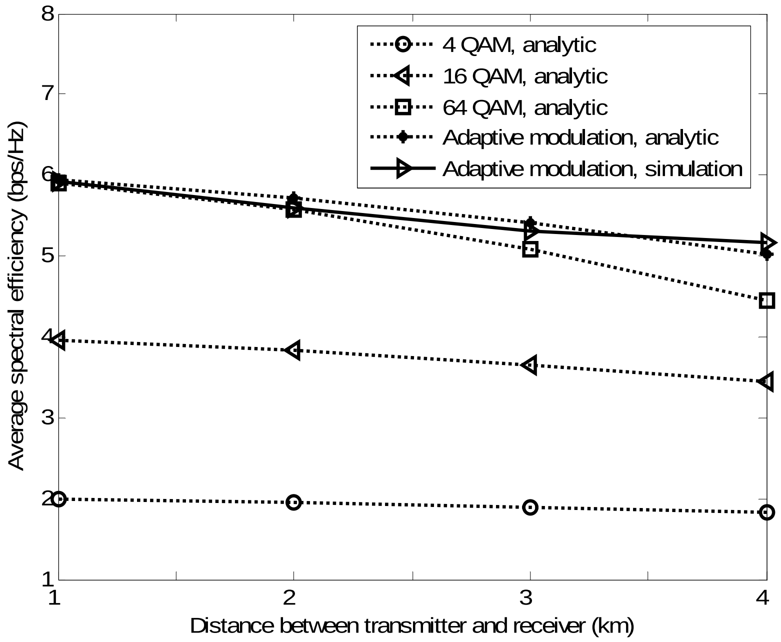

Figure 6 Average spectral efficiency of single link for P_b=10^{-6}

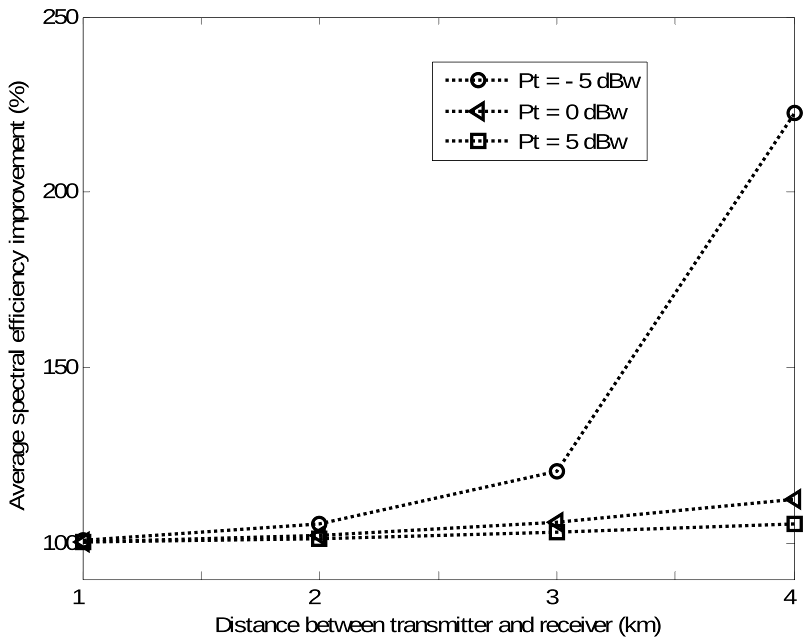

Figure 7 Average spectral efficiency improvement of various transmitted powers

5. Conclusions

Evaluation of the outage and average spectral efficiency of adaptive modulation system has been discussed. The results have been compared to those of SST simulation based on tropical rain rate measurements in Indonesia. The agreement between theoretical prediction and simulation appears to be good. Outage performance and average spectral efficiency can be improved by adaptive modulation system for long links when low transmit power is used. This suggest that adaptive modulation might be beneficial in such millimeter-wave radio networks to maintain high-quality service to subscribers located quite far from the base station, e.g., at the cell border. For these subscribers the received power is relatively low, which makes their reception quality more vulnerable to rain attenuation.

Acknowledgement

The reported work was supported by Directorate General of Higher Education (DGHE), Ministry of National Education, Republic of Indonesia.

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