CROSS-LAYER OPTIMIZATION PERFORMANCE OF SINGLE CELL MILLIMETER WAVE OFDM WIRELESS NETWORK UNDER RAIN FADING

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ABSTRACT

This paper presents cross-layer optimization implementation for millimeter wave OFDM network in the presence of rain fading. Cross-layer optimization is proposed to overcome the power inefficiency and complexity of conventional fading mitigation technique. The network is modeled as downlink multi-user single cell OFDM network. The rain fading data is generated based on Synthetic Storm Technique using rain rate data measured in Surabaya Area. To show the interest of cross-layer optimization, a combining optimization between physical and MAC layer using dynamic sub-carrier allocation and adaptive power allocation algorithm is demonstrated. The optimization objectives are the improvement of utility and fairness in heavily rain affected cell. The result shows an improvement of utility for multi-user OFDM network in term of total rate.

Keywords: OFDM, single cell multi-user, millimeter wave rain fading, SST, cross-layer design, JSPA..

1. INTRODUCTION

OFDM has been chosen as future platform to fulfill the need of very high bandwidth in broadband communication network. Wireless OFDM has proven his performance to combat inter-symbol-interference and operate in fading environment by using multi-carrier technique. In tropical region, in addition to noise and link attenuation, *rain fading* is becoming one of important constraint to the capacity of millimeter wave OFDM wireless system. That's why; there are many researches about characteristics of tropical rain fading. The knowledge of dynamic rain fading characteristic is necessary to develop fading mitigation technique (FMT) in the network air interface (Castanet, 2003) (Gremont, 2004) (Chu, 2005). In traditional FMT, fading is mitigated by a set of minimum required margin, filtering, power adaptation, MIMO and advanced coding in physical layer.

Beside FMT, some techniques and algorithms of resource allocation are also developed. They try to achieve an efficient and effective communication system beyond the limit of conventional FMT result. One of the most proposed approaches is *cross-layer design* (Corvino, 2008). This approach is carried-out by taking benefit from exchanging information of different protocol layers. The operation is held by knowing the physical layer channel state information (CSI) and upper layer information, such as *type of message* and *queuing state information* (QSI), (Song, 2005a). The design objective is then extended from maximizing user throughput to maximize the overall channel utilization and fairness of service between users.

While cross-layer is considered as a promising approach, the number of study on cross-layer approach in rain fading environment is still limited. Studies that try to combine the three aspects: OFDM, cross-layer, millimeter wave and rain fading channel are found in (Endroyono, 2008a) (Endroyono, 2008b). Some engineers said that the probability of rain fading events can be neglected in design. However, we know that in severe rain fading intensity, a deep fading will lead victim network to have a low capacity and utility. A conventional mitigation in rain fading is usually resulting in power utilization inefficiency and increasing the complexity (Song, 2005a).

This paper is then presented to fill the space and is organized as follow. Section 2 describes the millimeter wave channel model. In section 3, we present cross-layer model for a millimeter wave OFDM network considering rain fading. In section 4, we present an illustrational result and discussion related to the subject of interest. Finally, in section 5 we give a brief summary and future challenge of research.

2. MILLIMETER WAVE CHANNEL MODEL

In traditional transmission link budget, the received signal will depend on transmit power (P_T), system gain (G_T, G_R) and free-space-loss of link in function of frequency (f in MHz) and distance of transmitter-receiver (r in km). It is described by the following equation.

$$P_R = P_T + G_T + G_R - 20\log_{10}(f) - 20\log_{10}(r) - 62.4 \quad dBm \tag{1}$$

In tropical region, in addition to path loss of equation (1) and shadowing, rain fading will exist. As stated in (Endroyono, 2008a) and (Endroyono, 2008b), a rain event at 24 GHz, with 80 mm/hr rate could produce a conditional *excess loss* up to 50 dB/km, due to hydro-meteor effect. So, the rain fading should be considered in millimeter wave link.

2.1 Wireless Link Model in Rain Fading

Figure 1, gives an example of the CDF of rain attenuation statistic in rainy season (conditional) and full year statistic. It shows the reason that some designers exclude the rain fading from the calculation to simplify the design. It is clear that there is a low percentage of rain fading to exceed certain limit. However, in a very high bit rate broadband system, an outage of 1% of time will cause a very important impact. A small outage will result in very high number of packet loss or decreasing the utility.

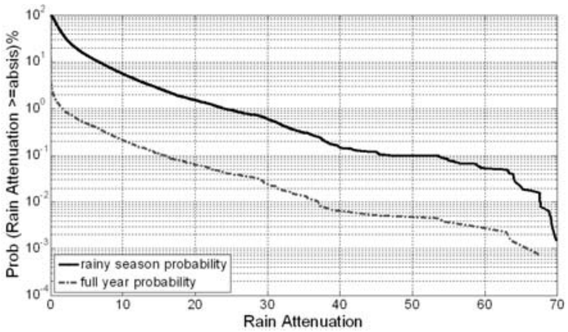

Figure 1. Example of Rain Fade CDF

To simulate rain fading effect, a single cell wireless link consisting of *Base Transceiver Station* (BTS) and multi-user terminals is proposed. User terminals are distributed randomly around the BTS. The rain fading is generated based on a model called *Synthetic Storm Technique, SST* (Kanellopoulos, 1986) (Castanet, 2003) (Fontan, 2005). In SST model, the rain attenuation $A_i(k)$ of a link segment ΔL_n is not measured directly from site. The attenuation series is generated based on the sampling rain intensity (rain rate data, R), the assumption of rain velocity, rain direction (relative angle to the rain direction for segment number, $i = 1,2,3...n$), relative distance, and ITU's coefficients a,b in frequency 30 GHz; as following equation:

$$A_i(k) = \sum_{n=0}^{N} aR^{b}_{(k-n)} * \Delta L_n \qquad (2)$$

The relation between rain cell, rain direction and link direction is shown in Figure 2.

In our case, rain rate data was gathered from multiple measurement sites in ITS Surabaya that the detail is presented by (Mahmudah, 2008). As illustrated in Figure 3, each link in cell will experience different fade intensity due to their position and respective distance. The graphs show similar statistic trends, but they have different probability in higher attenuation due to rain fading correlation factor. Correlation factor and differential gain will be important to be considered in the cross-layer approach.

In general, SST attenuation model is enough to present an effect of moving rain in a cell. However, two other parameters of rain fading *(fade duration* and *fade slope)* are also important in the cross-layer design of a millimeter wave. Parameters of power control, adaptive modulation and advanced coding should be designed to adapt the value of fade slope and fade duration.

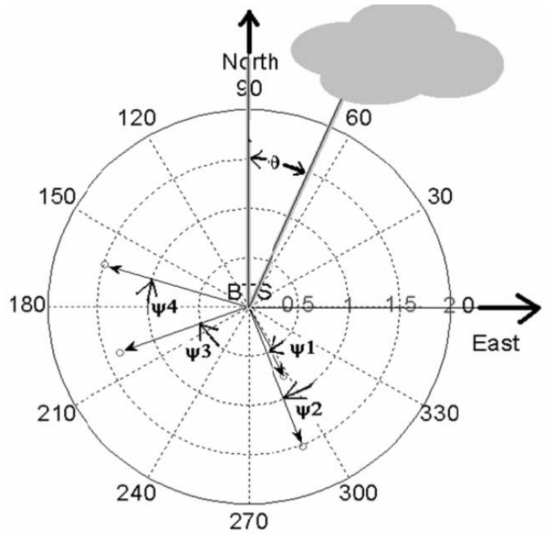

Figure 2. Cell Structure in SST Model

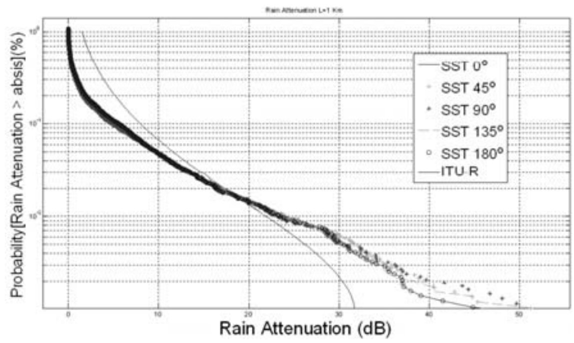

Figure 3. Link Attenuation Statistic Based on SST

3. CROSS-LAYER MODEL FOR OFDM NETWORK IN RAIN FADING

In this section, a simple cross-layer optimization for OFDM wireless network is presented.

3.1 Cross-layer Model

Figure 4 gives a generic model of cross-layer approach for a down-link single cell multi-user wireless OFDM. The optimization idea is similar to the proposition of (Song, 2005a) (Song, 2005b). The optimization is performed by *Resource Allocation Algorithm* block; in combining the information from physical layer and lower part of MAC layer. The contribution of study is to show that cross-layer approach is an effective method to optimize the network in a rain fading environment.

The operation of resource allocation is depends on channel condition of users (the Channel Status Information, CSI) and fairness information. CSI is necessary to maximize the available capacity (throughput). The fairness information (or priority) is necessary to prevent bad users from zero utility condition.

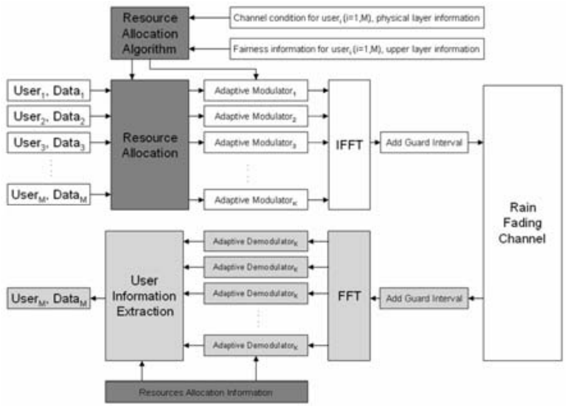

Figure 4. Cross-layer Model in OFDM System

3.2 Cross-layer Optimization Parameters

The optimization keys of optimization are the number of user involved in optimization, number of orthogonal sub- Carrier of OFDM, bandwidth per sub-carrier, CSI and performance. Parameters used in the paper are listed in Table 1.

Tabel 1. System Design Parameters

Notation	*Parameter concerned*
M, i	Total number of user, user index
K, k	Total number of Sub-carrier, sub-carrier index
W, Δf	Total bandwidth and bandwidth of each sub-carrier, $\Delta f = W/K$
$H_i[k], H_i[\Delta f]$	Channel gain of user *i* for sub-carrier *k* or for each sub-carrier bandwidth.
$N_i[k], N_i[\Delta f]$,	Noise power of user *i* for sub-carrier *k* or for each sub-carrier bandwidth.
$\rho_i[k]$	Channel condition of user *i* for sub-carrier *k*, related to SNR_{rain}
P, $p[k]$, $p(\Delta f)$	Total power and transmit power on sub-carrier *k*
$C, c_i[k]$	Capacity, achievable transmission rate (bps/Hz) per of user *i* sub-carrier *k*
r, r_i	Total rate and data rate of user *i*
D_i	Set of allocated sub-carrier to user *i*
$U_i(r_i)$	Utility function related to achievable rate of user r_i

To focus the optimization problem, we assume that each user always have information in their buffer to be transmitted via an optimized channel, having the following Shannon's capacity formula.

$$C = W \log_2(1 + SNR) \quad bps \tag{3}$$

In our case, the formulation will be normalized to achievable rate of user i with power P,

$$c_i^P \cong C/W, \quad bps/Hz \tag{4}$$

In regard of multi-carrier system, the equation (4) could be rewritten as $c_i^P(\Delta f)$ related to the transmission power $p(\Delta f)$, the channel condition $|H_i(\Delta f)|$, and SNR-gap β for required BER, with $\beta = 1/5/(-\ln(5BER))$.

$$c_i^P(\Delta f) = \log_2\left(1 + \frac{\beta . p(\Delta f)|H_i(\Delta f)|^2}{N_i(\Delta f)}\right) \quad \frac{bps}{Hz} \tag{5}$$

To start with cross-layer approach, the signal power, margin and SNR in the link budget are assumed to be enough to fulfill BER and throughput requirement in clear sky condition. So, we just consider the *rain fading impact* to the system. The SNR under rain (SNR_{rain}) is therefore the SNR in clear sky (in *decibel*) minus the attenuation by rain captured from channel gain in rain.

$$SNR_{rain} = SNR_{clear} - A_{rain} \quad (dB) \tag{6}$$

In Figure 5 we can see the example of temporal variation of SNR in rain with $SNR_{clear} = 30 dB$. Figure 6 shows that conditionally probability of having $SNR_{rain} \le 20 dB$ is more than 4%. It is clear that an adaptation is required.

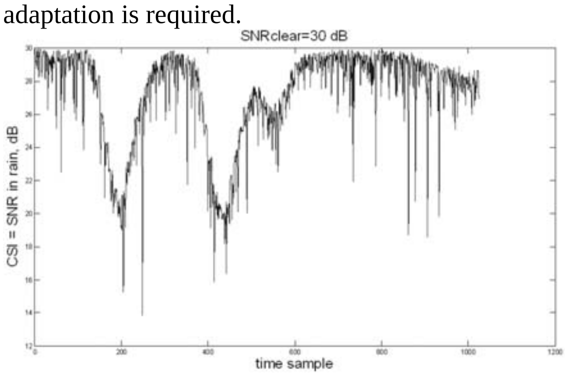

Figure 5. CSI in Rain Fade, with SNR_{clear}=*30 dB*

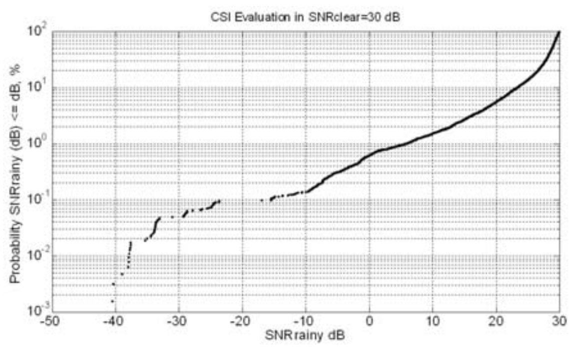

Figure 6. CDF of SNR_{rainy}, with SNR_{clear}=*30 dB*

So, equation (5) can be written by knowing the SNR target SNR_{clear} and the condition of rain fading A_{rain}.

$$c_i^P(\Delta f) = \log_2\left(1 + \frac{\beta . SNR_{clear}}{A_{rain}}\right) \quad \frac{bps}{Hz} \tag{7}$$

$$c_i^P(\Delta f) = \log_2(1 + \beta . CSI) \quad \frac{bps}{Hz} \tag{8}$$

The CSI in equation (8) is assumed always available in BTS. In discrete form, the CSI is the sample of link status $\rho_i[k]$ at a known power $p[k]$ and noise density $N_i[k]$.

$$\rho_i[k] = \frac{|H_i[k]|^2}{N_i[k]} \quad (9)$$

Therefore,

$$c_i^P[k] = \log_2(1+\beta.p[k].\rho_i[k]) \quad bps/Hz \quad (10)$$

From equation (10), the optimization will then depend on required BER (β), power allocated $p[k]$ and number of allocated sub-carriers based on $\rho_i[k]$.

In our case, we have two cross-layer allocation adaptation: dynamic Sub-carrier Allocation (DSA) and Adaptive Power Allocation (APA). The two adaptation are based on a selection of an optimum set of carrier D_i and power $p[k]$ to optimize the available rate r_i and maximize the utility $U(.)$ of each user, $i \in M$.

$$r_i = \sum_{k \in D_i} c_i^P[k].\Delta f \quad (11)$$

$$\max_{D_i, p[k]} \sum_{i \in M} U_i(r_i) \quad (12)$$

In utility based optimization, the value of utility should always be bigger than zero. The possibility to maximize number of sub-carrier in regard of CSI for multiple users $M > 0$ should follow the fairness criteria in equation (12) used by (Song, 2005a) (Song, 2005b).

$$U(r) = 0.16 + 0.8\ln(r - 0.3) \quad (13)$$

The maximum utility will be achieved in condition that $U(r) = r = throughput$ in physical layer maximizing utility $U_i(r_i)$ means improving the *Fairness* in cross-layer approach.

3.3 Dynamic Sub-carrier Allocation

Dynamic Sub-carrier Allocation *(DSA)* is carried-out by controlling the allocation of sub-carriers $k \in D_i$ based on CSI in a fixed transmitted power. The achievable capacity is the sum of each individual sub-carrier having bandwidth Δf ,

$$r_i = \sum_{k \in D_i} c_i^P[k]\Delta f \quad (14)$$

To show the advantage of DSA in rain fading, sorting search algorithm proposed by (Song, 2005b) is compared to fixed sub-carrier allocation (FSA). By attribution of sub-carrier index x_{ik} to user with best channel condition, the optimization formulation is then denoted by:

$$\frac{1}{M}\sum_{i=1}^{M} U_i(r_i) = \frac{1}{M}\sum_{i=1}^{M} U_i\left(\Delta f.\sum_{k \in K} c_i^P[k].x_{ik}\right) \quad (15)$$

3.4 Adaptive Power Allocation

Adaptive Power Allocation (APA) is performed by controlling transmitted power like in the conventional power control, but in multi-carrier basis. Optimization of available capacity and utility is carried out by compensating channel attenuation to achieve a suitable *SNR* in each sub-carrier. In this case, the BTS try to normalize sub-carrier power for required SNR value. Power optimization mechanism is based on the balancing of (marginal) utility target and *SNR* target as in conventional water filling. Optimization is carried-out by controlling the sub-carrier power $p[k]$ based on captured CSI. In this case, $p[k]$ in equation (9) will be varied and denoted by $p^*[k]$, with $p^*[k] \geq 0$ and normalization power constant $\lambda > 0$ and $k \in D_i$.

$$p^*[k] \xleftarrow{iteration} \left[\frac{U_i'(r_i)}{\lambda} - \frac{1}{\beta.\rho_i[k]}\right]^+ \quad (16)$$

One of super constrain is that the total power must not exceed the total power of total bandwidth *W*.

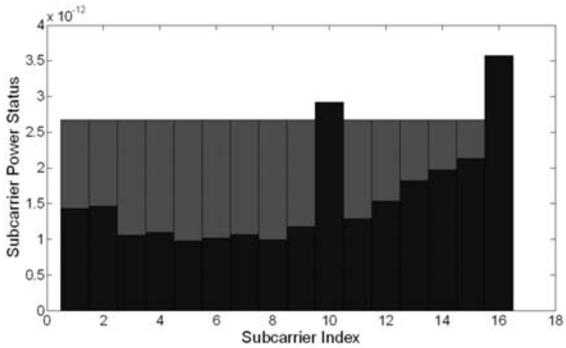

Figure 7. Water-filling used in APA

As proposed in (Song, 2005b), a combination of sequential linear approximation water filling algorithm and greedy power allocation algorithm is applied. The greedy approach is applied by allocating power in form of adaptive modulation $p[k] = f(b)$, to make the transmission of *b* (bps/Hz) possible by knowing the CSI and *SNR-gap*β.

$$f(b) = \frac{2^b - 1}{\beta.\rho[k]} \quad (17)$$

3.5 Joint Sub-carrier and Power Allocation

JSPA (joint DSA and APA algorithm) is a sequential combination between sub carrier allocation and power adaptation. The process is to find an optimal sub-carrier allocation of all potential users and to maximize data rate by appropriate power allocation. The result will depend on the affinity of sub carrier assignment process and step-size of power adaptation. FSA can be regarded as a static DSA.

4. RESULTS AND DISCUSSIONS

In this section, we will firstly present the interest of using cross-layer based on Shannon's formula and then present the result of cross-layer on single cell OFDM multi-user system with a 4 km cell diameter using SST generated rain fading. To show the advantage of JSPA, an evaluation between FSA and DSA, their joint with PA will be presented.

4.1 Optimization Interest

Figure 8 gives us an illustration of sub-carrier number effect to the rate total in rain fading. The graphs show similar capacity trend, but the bigger number of sub-carrier will result in the bigger probability of having higher total available. It is appropriate with (Song, 2005a) (Song, 2005b) that the global optimal of system will normally be achieved if the number of user and the number of sub-carrier are large enough.

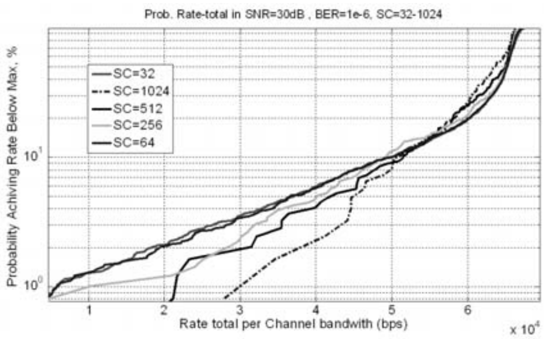

Figure 8. Rate Total with Different SC Number

Figure 9 shows us the effect of SNR value in a same rain fading statistic. With higher the SNR target, higher available capacity will be obtained.

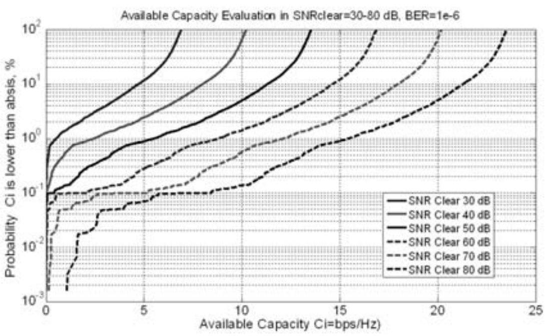

Figure 9. Available Capacity in different SNR

The available capacity of system in a fixed SNR with different BER requirement (SNR gab) is shown in Figure 10. When BER requirement increase, we need more margin to achieve the same capacity. So the available capacity will depend on the value of SNR gap.

From Figure 8, 9 and Figure 10, we conclude that the choice number of sub-carrier allocated to user, power, SNR_{clear} and required BER is important aspect in cross-layer approach to improve the utility of certain fairness requirement.

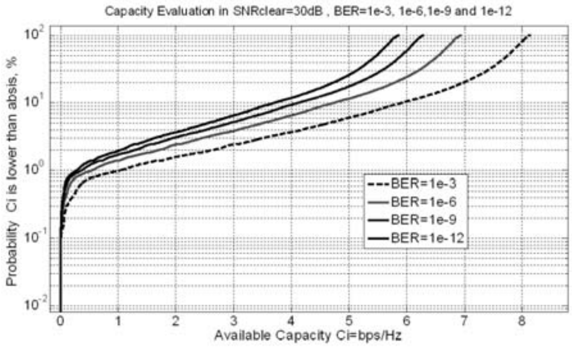

Figure 10. Available Capacity in Different BER Target

4.2 FSA and DSA in Rain Fading

In order to evaluate the interest of applying cross-layer approach using DSA algorithm, we use the CDF dynamic sub-carrier allocation using DSA in Figure 11. It gives a superior performance compared to conventional *Fixed Sub-carrier Allocation* (FSA) in term of channel capacity. An additional gain in FSA is less significant compared to the impact of additional gain in DSA.

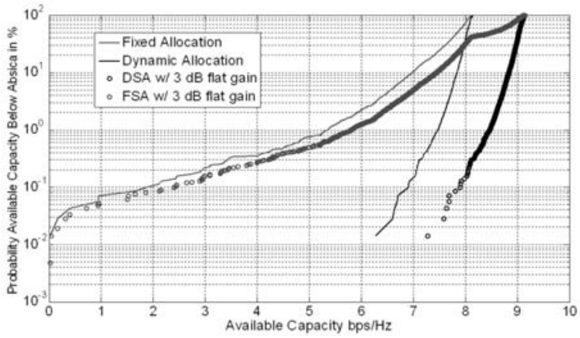

Figure 11. Comparison of FSA and DSA

4.3 APA and JSPA

Figure 12 shows the result of APA while operating in the same statistic of rain fading. This result is like the result of normal power control application.

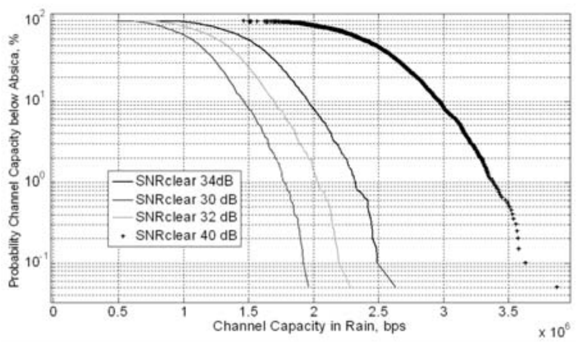

Figure 12. Comparison APA in Different SNR

Figure 13 shows the advantage of using joint cross-layer approach, when a combination of APA and other technique is carried-out. Combination of simple sub-carrier allocation in lower MAC layer and power allocation algorithm in PHY layer results in a global improvement in term of total utility. By exchanging information from two layers, the average utility of dynamic sub-carrier assignment and adaptive power allocation is extremely superior to fixed sub-carrier allocation in conventional system. We know that the probability to have maximum throughput may be diminished, but the probability of service for each user is higher. This result gives a better utility as predicted. It means that cross-layer system give us an opportunities to improve the network performance without sacrificing total power and more bandwidth.

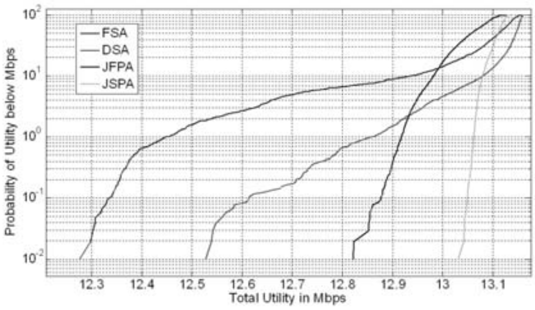

Figure 13. Utility Difference in Rain Fading

This study shows another example about the convergence of the approach, as shown in Figure 14. As the statistic of rain fading channel and the variation of user distance are random, each approach will give different temporal results. However, we can easily conclude that cross-layer (joint sub-carrier and power allocation) gives superior result to network utility. All graphs of JFPA and JSPA have high probability of the utility value. We (than) see another opportunity to improve the OFDM network capacity by implementing cross-layer design using *user diversity*, based on user independency related to *spatial- temporal* characteristic of rain channel.

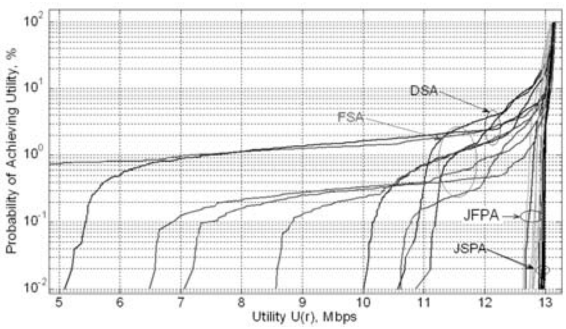

Figure 14. Trend of Utility in Rain Fading

5. CONCLUSION

In this paper, we consider the cross-layer optimization application for millimeter wave wireless network considering the presence of rain fading. To show the interest of cross-layer optimization, a combination of dynamic sub-carrier allocation algorithm and adaptive power allocation algorithm is demonstrated. The result of simulation shows that a very simple cross layer technique using Dynamic Sub-carrier Allocation (DSA), Adaptive Power Allocation (APA) in the form of JSPA can improve the performance of multi-user OFDM network in term of the utility based on fairness constraint. It shows that total throughput (available rate) has been improved while keeping an effective bandwidth and power. In the future, there will be possibility to take more benefit from spatial-temporal characteristic of rain fading in the form of space-time multi-user diversity in multi-cell multi-user OFDM network.

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