AN IMPROVED SWITCHED DIVERSITY COMBINING USING FUZZY ADAPTIVE CONTROL

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ABSTRACT

Diversity combining techniques, due to their extreme effectiveness in counteracting fading effects in wireless environment, have been extensively studied in recent years [1, 2, 8]. However, most of developed diversity combining schemes are not suitable for mobile units because of either a complicated analog circuitry required, such as with maximal-ratio combining, or a poor performance, such as with switched combining. In this paper, we propose an improved switched combining scheme using fuzzy adaptive control, namely, fuzzy adaptive switched diversity (FASD), which is intended to be applicable in a mobile unit. The fuzzy adaptive control is introduced to determine the threshold levels of the switched diversity combining in order to improve the combining performance in terms of both the diversity gain and BER (bit error rate). Specifically, with incorporating the statistics of mobile fading channels as well as a lot of computer simulations, we have achieved an effective system design of FASD which has significant improvement in the system performance of the switched combining while maintaining reasonable simplicity in implementation.

INTRODUCTION

It is well known that multipath fading is one of the main causes of performance degradation in a mobile radio system [1]. Not only can it be annoying but also disastrously harmful if we consider, for instance, its effects on data transmission. Fortunately, this is not an undefeatable enemy and, in fact, many techniques can be used to counteract its effects. A widely recognized technique for combating fading effects is the use of a diversity combiner [1, 2, 8], for which two or more radio links of a diversity channel are presumed to be statistically independent. However, most of developed combining schemes, such as *maximal-ratio combining*, *equal-gain combining* and *selective combining* [1], require very complicated analog circuitry and have hardly been used in practice, especially in mobile units. A promising cost-effective combining scheme is *switched diversity combining*, or *switched diversity*. Since the switched diversity combining needs only one receiver, it is less costly and may be used in mobile units. But the disadvantage is that its performance is greatly affected by threshold level, at which the switch is performed. Thereby, having much worse performance than those with multiple receivers [2]. In order to improve this scheme, it is desirable that the threshold level can be adapted dynamically in real time based on the present varying channel conditions. Unfortunately, there is quite limited work on developing such adaptive algorithms. This may be due to the fact that conventional approaches usually result in a very complicated threshold adaptation control, which, in turn, causes a drawback in the cost of improving the switched combining over other combining techniques [2].

The study of fuzzy logic control has been making rapid progress in recent years [3]. In particular, some researchers have introduced its application to the communication field. For example, [4] and [5] proposed new approaches to the equalization of non-linear channels using fuzzy adaptive filters. Likewise, [6] successfully introduced a fuzzy logic control technique for adaptive power control in a direct-sequence code-division multiple-access (DS/CDMA) cellular system. It can be expected that there will be more and more research work on the use of fuzzy system in wireless communications [6].

In this paper, we investigate the use of fuzzy logic control techniques in improving the switched diversity combining for a cellular system over the mobile fading radio channels. Specifically, the fuzzy logic control is used to provide an algorithm which converts the linguistic control strategy, which is based on characteristics of mobile radio channels, into the threshold-level control strategy for the switched diversity. By using the defuzzification, the fuzzy control decisions are converted to a crisp threshold control command which is used to adjust the threshold-level of the switched combining. Furthermore, to achieve an effective fuzzy switched threshold control, both statistic analysis of mobile channels and Monte Carlo simulations are used to refine the fuzzy IF-THEN rules. It is shown

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[1] It is noted that selective combining can be also classified as a switched combining. But it has the same major problem as maximal-ratio combining and equal-gain combining, that is the number of receivers required, one for each branch. Throughout this paper, for convenience, we refer the switched combining only to the case of threshold selection combining, for which only one receiver is required.

that the proposed FASD achieves significant improvement in the combining performance of the switched diversity while maintaining reasonable simplicity in implementation.

This paper is organized as follows. Section II briefs the mobile channel statistics along with the principle of diversity combining. In Section III, we propose an improved switched diversity combining scheme using fuzzy adaptive control. Section IV demonstrates some sample simulation results. Section V gives a brief discussion on the system implementation. Conclusions are given in Section VI.

MOBILE CHANNEL STATISTICS AND DIVERSITY COMBINING

We begin with a brief description of a mobile channel model. It is well known that the received signal through a digital mobile channel is affected by two types of fading. One is the long-term fading, which is due to shadowing and path loss; Another is the short-term fading, which is due to multipath propagation. The former results in very slow channel varying, which usually can be compensated by enhancing transmission power and/or AGC (Automatic Gain Control) in the receiver, or by handoff. The latter, however, often results in very fast channel varying, which significantly challenges the counteraction of its effects. Hence, being the interest of this paper. Generally, the short-term fading can be modeled as a Rayleigh-distributed envelope with Doppler spread [1, 2]. An example of the typical Rayleigh fading envelope is depicted in Fig. 1, where the instantaneous fading signal α (amplitude) is subject to the following Rayleigh distribution

$$f_R(\alpha) = \frac{\alpha}{\rho^2} \, exp\left(\frac{-\alpha^2}{2\rho^2}\right) \tag{1}$$

where ρ^2 denotes the expectation of α^2.

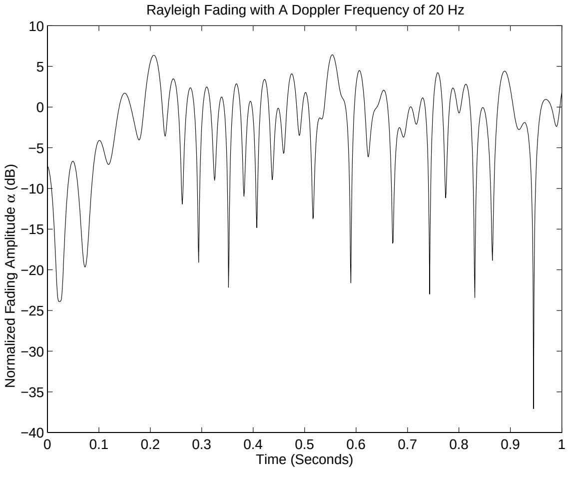

Figure 1. Rayleigh fading envelope with a Doppler spread of 20 Hz.

It is observed from Fig. 1 that random deep fades, in which α has very low values (say, less than -20 dB), occurs corresponding to a Doppler frequency. In such case, any methodology for enhancing signal strength will simultaneously get the noise emphasis. Instead, methodologies for *fading avoidance* are extremely preferable, of which a widely recognized technique for combating the fading effects is to deploy a diversity combiner [8]. In principle, diversity combining relies on the fact that independent signals have a low probability of experiencing deep fades at the same time instant.

There are basically four diversity combining methods, *maximal-ratio combining*, *equal-gain combining*, *selective combining* and *switched combining*. The first three methods require multiple receivers, one for each branch. A schematic diagram of the selective combining is shown in Fig. 2, where "Rx" represents a receiver. As for maximal-ratio combining and equal-gain combining, ever more complicated analog circuitries are required due to co-phasing. Thereby, having hardly been used in practice, especially in mobile units [2].

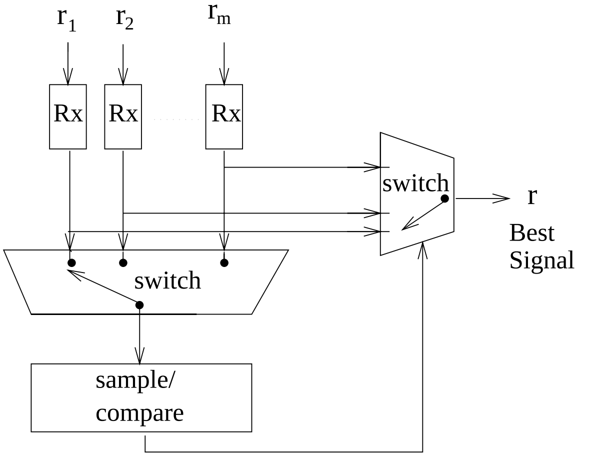

Figure 2. A schematic diagram of pure selective combining

The switched diversity combining, however, is a promising cost-effective combining scheme, which needs only one receiver and is thus less costly and may be used in mobile units. Fig. 3 shows the overall schematics of an m-branch (r_1, r_2, ... r_m) switched diversity, where, again, "Rx" represents a receiver. In such case the received signals are scanned in a sequential order, and the first signal with a power level above a certain threshold is selected. While above the threshold, the selected signal remains at the combiner's output; otherwise, a scanning process is switched to another branch. Moreover, we consider the case of switch-and-stay threshold selection in this paper in order for a simple implementation. Such switch process is further illustrated in Fig. 4, while the case of two-branch switched diversity is considered. We assume two independent fading signals, R_1 (solid line) and R_2 (dashed line) coming from two antennas, which are shown in Fig.4 (a). Suppose the receiver firstly receives R_1, it will keep receiving until R_1 goes below the predetermined threshold. When R_1 is detected below the threshold, the receiver switches to R_2, no matter what the current signal level of R_2 is. After R_2 becomes below the threshold, the receiver switches to R_1, and so on. As a result, the received signal is obtained as shown in Fig. 4 (b).

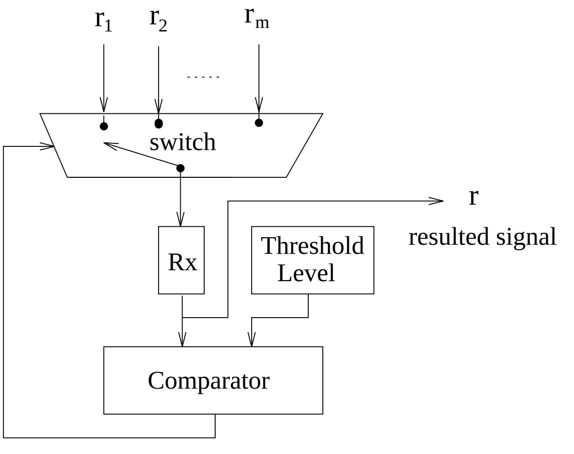

Figure 3. Switched diversity with threshold selection

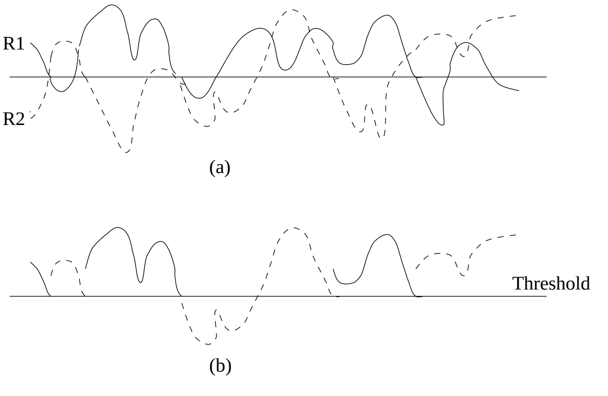

Figure 4. Illustration of switched diversity: (a) two independent fading signals, R1 and R2; (b) resultant signal using switch-and-stay threshold selection

It is noted that the threshold may be either fixed or variable. Setting its level is a task involving the knowledge of the mean signal strength in the geographical area. Consequently, the fixed approach may work well within the region for which the fixed threshold was found to be appropriate. On the other hand, if conditions change, this approach can give bad results. The distribution of the SNR (Signal-to-Noise Ratio) resulted from switched diversity with different threshold levels is shown in Fig. 5. Clearly, the performance of the switched diversity is greatly affected by threshold level. If the threshold is low, high diversity gain can be achieved only in the region with low SNR, but very little gain in the region with high SNR. Likewise, if the threshold is high, high diversity gain can be achieved only in the region with high SNR, but very little gain in the region with low SNR. Accordingly, to improve this scheme, it is desirable that the threshold level can be adapted dynamically in real time based on the present received signal level.

Unfortunately, there is a quite limited work which develops algorithms to improve the switched diversity. In fact, any complicated adaptation algorithms will cause a drawback in the cost of improving the switched combining over other combining techniques. In this paper, we use a fuzzy adaptive threshold control (FATC) to improve the switched diversity, resulting in a FASD. Our goal is to make the performance of the improved switched diversity approach that of pure selective combining as close as possible[2] while maintaining reasonable simplicity in implementation.

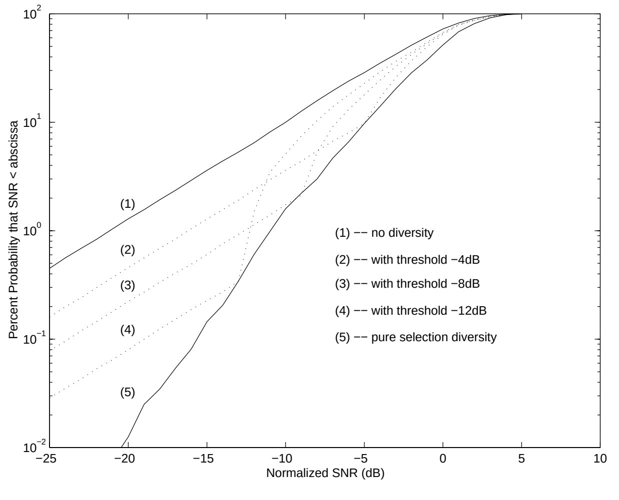

Figure 5. Distribution of the SNR resulted from switched diversity with different threshold levels (computer simulation)

AN IMPROVED SWITCHED COMBINING WITH FATC

Basically, a FATC comprises four principal components: a fuzzification interface, a fuzzy rule base, an inference engine, and a defuzzification interface [3]. The fuzzification interface intends to convert the input values, such as the current channel state (signal strength), the channel state variation, and the current threshold, into some linguistic values, i.e., fuzzy sets. The fuzzy rule base, which comprises a knowledge of the specific application and the attendant control goals, is used to define linguistic control rules and fuzzy number manipulation in a

[2] In theory, the performance of switched diversity should not outperform over that of pure selective combining [2].

FATC. Likewise, the inference engine is a decision-making logic mechanism of a FATC. It has the capability of simulating mobile radio channel based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic. Finally, the defuzzification interface converts fuzzy control decisions into crisp nonfuzzy threshold adaptation control signals, which are applied to adjust the threshold level of the switched diversity. Specifically, the schematic of the proposed switched diversity with FATC, i.e., FASD, is given in Fig. 6. It is noted that the "Mean Estimation" in Fig. 6, which is used to predict the average received signal power, is also a very important element such that FATC can always work with a normalized signal power. In this paper, nevertheless, we shall concentrate on the design of FATC, which is the key innovation in the FASD.

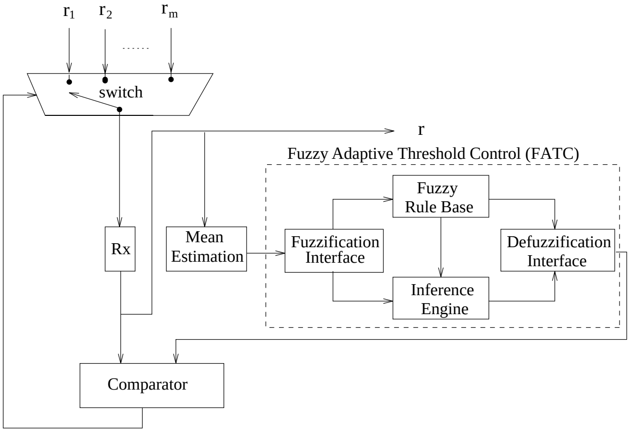

Figure 6. Fuzzy adaptive threshold switched diversity (FASD)

As is well known, the choice of the fuzzy control rules has a substantial effect on the performance of a FATC. A close observation of Figs. 4 and 5 indicates that, if the threshold level is high, most likely the output signal of the switched diversity will keep low value for long time, which in turn implies that the overall system performance will be poor. In such case, the threshold level should be decreased. Likewise, if the threshold level is very low, it becomes more difficult to catch up a high level signal. Thereby, achieving very little gain especially in the region with high signal strength. Based on these observations, we basically consider four linguistic variables, S, ΔS, Th and ΔTh, which denote the present channel state, the variation of channel state (received signal level), the previous threshold level and the change of threshold level, respectively. The output control linguistic variable is ΔTh, while the other three variables are used as inputs. Note that this is a 3-input-one-output fuzzy logic control system. Furthermore, the universes of discourse for S, ΔS, Th and ΔTh are assumed to be

$$U_s = \{S \mid -30\ dB \le S \le 10\ dB\}, \qquad (2)$$

$$U_{\Delta s} = \{\Delta S \mid -10\ dB \le \Delta S \le 10\ dB\}, \qquad (3)$$

$$U_{Th} = \{Th \mid -30\ dB \leq Th \leq 10\ dB\}, \tag{4}$$

$$U_{\Delta Th} = \{\Delta Th \mid -10\ dB \leq \Delta Th \leq 10\ dB\}, \tag{5}$$

where, note that, the bounds of the universes of discourse are determined in terms of the fading statistics of typical wireless channels, such as the one shown in Figure 1. The associated fuzzy term sets are {L (Large), M (Medium), S (Small) } for *S* and *Th*, and {PL (Positive Large), PM (Positive Medium), PS (Positive Small), NL (Negative Large), NM (Negative Medium), NS (Negative Small)} for ΔS and ΔTh.

It is noted that there are 324 possible combinations of the above fuzzy terms which generate 324 fuzzy IF-THEN rules. If all the rules are used in constructing the fuzzy system, we will have a very complicated FATC design, which is in turn contradict to the goal of this paper. Fortunately, experiments show that there are very few IF-THEN rules which indeed dominate the performance of FATC. However, uncompleted use of the fuzzy IF-THEN rules may cause an ill-defined and unstable fuzzy system which is not desirable [3]. To solve this problem, we choose the Gaussian membership functions which cover the whole universes of discourse for each linguistic variables. As such, we design the associated membership functions as follows:

$$\mu_L(S) = e^{-(S-6)^2/16}; \tag{6}$$

$$\mu_M(S) = e^{-(S+2)^2/16}; \tag{7}$$

$$\mu_S(S) = e^{-(S+20)^2/16}; \tag{8}$$

$$\mu_L(Th) = e^{-(Th-10)^2/16}; \tag{9}$$

$$\mu_M(Th) = e^{-(Th+4)^2/16}; \tag{10}$$

$$\mu_S(Th) = e^{-(Th+22)^2/16}; \tag{11}$$

$$\mu_{PL}(\Delta S) = e^{-(\Delta S-10)^2/4}; \tag{12}$$

$$\mu_{NL}(\Delta S) = e^{-(\Delta S+10)^2/4}; \tag{13}$$

$$\mu_{PM}(\Delta S) = e^{-(\Delta S-5)^2/4}; \tag{14}$$

$$\mu_{NM}(\Delta S) = e^{-(\Delta S+5)^2/4}; \tag{15}$$

$$\mu_{PS}(\Delta S) = e^{-(\Delta S-2)^2/4}; \tag{16}$$

$$\mu_{NS}(\Delta S) = e^{-(\Delta S+2)^2/4}; \tag{17}$$

$$\mu_{PL}(\Delta Th) = e^{-(\Delta Th-8)^2/4}; \tag{18}$$

$$\mu_{NL}(\Delta Th) = e^{-(\Delta Th+8)^2/4}; \tag{19}$$

$$\mu_{PM}(\Delta Th) = e^{-(\Delta Th-4)^2/4}; \tag{20}$$

$$\mu_{NM}(\Delta Th) = e^{-(\Delta Th+4)^2/4}; \tag{21}$$

$$\mu_{PS}(\Delta Th) = e^{-(\Delta Th-1)^2/4}; \tag{22}$$

$$\mu_{NS}(\Delta Th) = e^{-(\Delta Th+1)^2/4}; \tag{23}$$

The task to select the most significant IF-THEN rules along with determining the parameters of the above membership functions is very hard. This is because the wireless channel is always varying, which implies that it is difficult to obtain some input-output pairs such that we can use some methods like *Gradient Descent Training* or *Recursive Least Squares* [3] to derive the required membership functions. In this paper, we use extensive experiments to verify the effects of different IF-THEN rules along with different parameters in membership functions. Eventually, we find that the following five IF-THEN rules, along with the attendant membership functions defined in (6) ~ (23), are shown to be dominant to the overall system performance of the FASD. They are:

If S is small, Th is large, ΔS is negative large, then ΔTh is negative large;
If S is small, Th is medium, ΔS is negative medium, then ΔTh is negative medium;
If S is medium, Th is large, ΔS is negative medium, then ΔTh is negative medium;
If S is medium, Th is small, then ΔTh is positive small;
If S is large, Th is small, then ΔTh is positive medium.

Using the center average defuzzifier and the product inference engine[3], we obtain a very simple fuzzy adaptive threshold control ΔTh_{fuzz}, which is given by

$$\Delta Th_{fuzz} = \frac{-8Y_1 - 4Y_2 - 4Y_3 + 4Y_4 + Y_5}{Y_1 + Y_2 + Y_3 + Y_4 + Y_5} \tag{24}$$

where $Y_1 = \mu_S(S)\cdot\mu_L(Th)\cdot\mu_{NL}(\Delta S)$, $Y_2 = \mu_S(S)\cdot\mu_M(Th)\cdot\mu_{NM}(\Delta S)$, $Y_3 = \mu_M(S)\cdot\mu_L(Th)\cdot\mu_{NM}(\Delta S)$, $Y_4 = \mu_L(S)\cdot\mu_S(Th)$, $Y_5 = \mu_M(S)\cdot\mu_S(Th)$. In next section, we will demonstrate its performance using some sample simulation results.

SIMULATIONS AND COMPARISON

To verify the effectiveness of the proposed FASD, numerical values of the SNR distribution and the bit error rates are calculated over a Doppler spread Rayleigh fading channel using Monte Carlo simulations. Throughout, the channel parameters are generated using Jakes' model [7]. The BPSK modulation scheme along with two-branch diversity is used, and two extreme cases of varying channels with Doppler spreads of 2 Hz and 80 Hz, which could correspond to slow and fast varying fading channels, respectively, are considered. Furthermore, it is assumed that the "Mean Estimation" in Fig. 6 is perfect[3]and the switching noise due to switch impulses can be eliminated by a blank-and-hold devise [2].

Fig. 7 compares the SNR distributions resulted from different combining techniques over a slow varying fading channel. Pure selective diversity, FASD and

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[3] This is reasonable especially for the downlink where usually no power control is used. As for the uplink case, the reception is performed in a base-station which can incorporate more complicated diversity schemes. As such, the developed technique in this paper is more suitable for mobile unit which extremely prefers a simple implementation.

the conventional switched diversity with different fixed threshold levels are compared. It is observed that the performance of proposed FASD approaches very well to that of pure selective diversity combining. This can be further evaluated by means of "diversity gain", which is in the sense that, under certain outage probability of SNR, how much signal enhancement is gained with respect to a non-diversity case. For instance, for the outage probability of 1%, the diversity gain is about 10 dB by using pure selection diversity, and is about 9.5 dB by using proposed FASD. As far as the overall performance is concerned, the FASD has much better performance than any conventional switched diversity with fixed threshold levels, and only causes about 0.5 dB degradation with respect to ideal selection diversity.

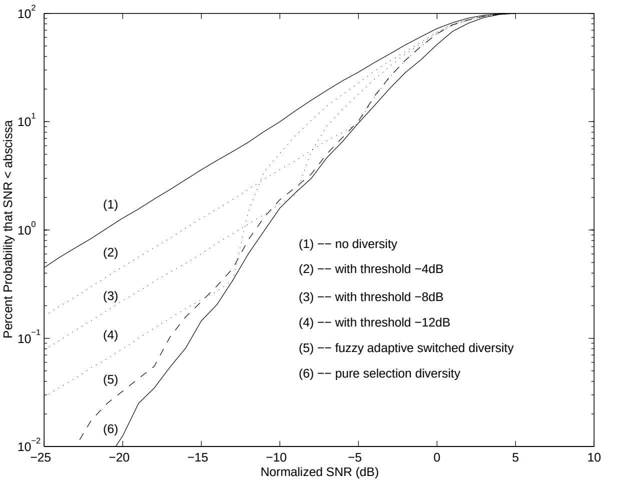

Figure 7. Comparison of resulted SNR distributions over a slow varying channel (Fd = 2 Hz) using FASD, conventional switched diversity with fixed threshold levels, and ideal selection diversity (computer simulation)

Fig. 8 compares the SNR distributions resulted from different combining techniques over a fast varying fading channel. In such case, the diversity gain achieved by the proposed FASD is less than that in case of Fig. 7, especially in the region with low values of SNR. This is because the fast varying fading introduces more difficulties for FASD to catch up the deep fades.[4] Nevertheless, such degradation due to fast varying fading is very minor in the region with not very small values of SNR. Thereby, implying that the proposed FASD is also applicable for the fast varying fading case.

Figs. 9 and 10 compare the BER versus average SNR under slow and fast varying fading channels, respectively, using pure selection diversity, FASD and conventional switched diversity with different fixed threshold levels. For the case of

[4] In fact, this can be further improved by including more IF-THEN rules if higher complexity is allowable.

slow fading, the improved performance of the proposed FASD with respect to the conventional switched diversity is significant. Even in the case of fast fading as shown in Fig. 10, this conclusion can be held as well. Hence, further confirming that the proposed switched combining with FATC can significantly improve the conventional switched diversity.

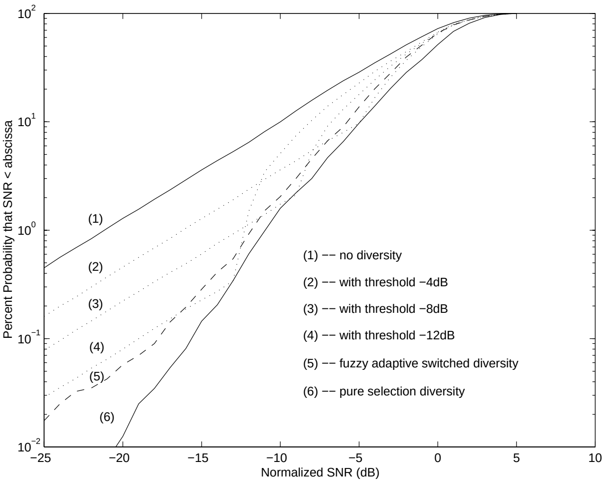

Figure 8. Comparison of resulted SNR distributions over a fast varying channel (Fd = 80 Hz) using FASD, conventional switched diversity with fixed threshold levels, and ideal selection diversity (computer simulation)

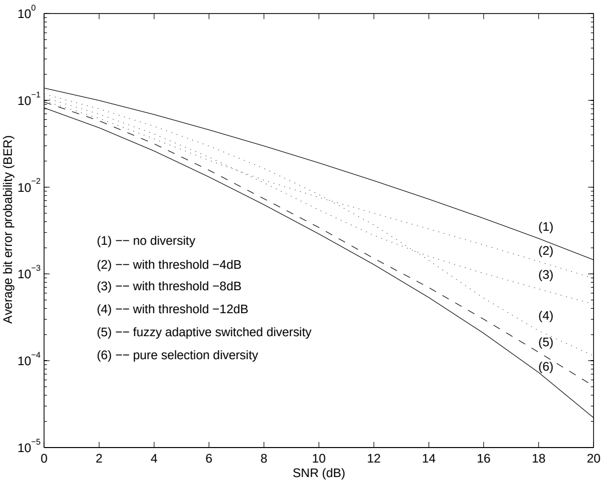

Figure 9. Comparison of BER in a slow Doppler spread Rayleigh fading channel using two-branch FASD, conventional switched diversity with fixed threshold levels, and ideal selective diversity (computer simulation)

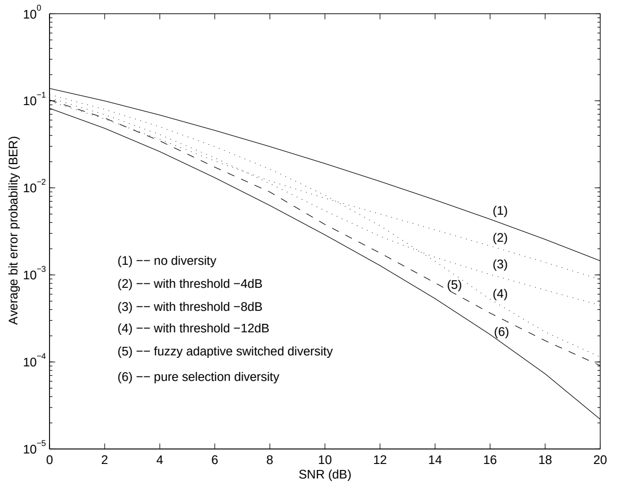

Figure 10. Comparison of BER in a fast Doppler spread Rayleigh fading channel using two-branch FASD, conventional switched diversity with fixed threshold levels, and ideal selective diversity (computer simulation)

FURTHER DISCUSSION

Throughout the design of FASD, its implementation complexity is a major concern. In section III, we have successfully minimized the number of IF-THEN rules so that the proposed FATC, which is a key element of the FASD, is practical. On the other hand, since our designed FATC has very simple form as shown in Eqn. (24), a cost-effective approach to simplify the implementation of the fuzzy control is to construct a set of look-up tables based on control rules and then to program it onto mask ROM chips. In other words, the calculations of fuzzification, fuzzy inference and centre average defuzzification can be performed on a ROM chip. This way, the proposed FASD has reasonable simplicity in implementation. Thereby, being competitive with other combining techniques, and thus an excellent candidate to be applicable in mobile units.

CONCLUSIONS

In this paper, we have successfully designed an effective fuzzy adaptive switched diversity (FASD), which is considered to be used in a mobile unit. In order for a simplified design of FATC, which is a key element of the FASD, a lot of efforts have been made to select the most significant fuzzy IF-THEN rules along with determining the parameters of associated membership functions. Eventually, we find that there are in fact only five dominant IF-THEN rules and the resulted fuzzy threshold control has a very simple form as shown in (24). Monte Carlo simulations show that the proposed FASD can achieve significant improvement in the system performance in terms of both the diversity gain and BER over both slow and fast fading channels. It is also noted that using the techniques developed in this paper, reasonable simplicity in implementation can be achieved as well.

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