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Research Article

Adaptive Selection Combining Receiver over Time Varying Frequency Selective Fading Channel in Class-A Noise

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An adaptive selection combining (SC) scheme is proposed for time varying mobile communication channel in Class-A impulsive noise. The receiver adaptively selects a diversity branch out of the available branches and discards the others. This is performed by computing the maximum likelihood (ML) metric of each diversity branch and selects the branch with the maximum metric. The proposed adaptive SC scheme dynamically adjusts the threshold value according to the time variations of the channel. Equalization and data detection are performed after combining using maximum likelihood sequence estimation implemented by Viterbi algorithm (MLSE-VA). The minimum survivor technique is employed to reduce the complexity of the receiver.

1. Introduction

In wireless communication networks, fading phenomenon imposes serious limitations upon the system performance. Diversity techniques as means of achieving high capacity communication systems and combating fading effects have been the subject of interest for many years. The traditional diversity combining techniques include maximal ratio combining (MRC), equal gain combining (EGC), and selection combining (SC). MRC coherently combines all diversity branches after weighing each branch with the respective gain of the branch. EGC coherently combines all diversity branches after weighing each branch with equal gain. In SC only one diversity branch is used for data reception. The usual way of selecting this branch is to choose the branch with the largest instantaneous SNR.

Most literature in diversity is mainly limited to the conventional assumption of AWGN. AWGN realistically represents the thermal noise at the receiver but ignores the impulsive nature of atmospheric noise, electromagnetic interference, or man-made noise. Automatic ignition noise and power transmission lines are examples of impulsive noise sources encountered mainly in metropolitan areas [1]. One of the noise models that combines the Gaussian noise with a non-Gaussian impulsive noise is Class-A impulsive noise proposed by Middleton. Despite the practical and theoretical importance of the problem, only few results on diversity combining for Class-A noise are available in the literature [1–6]. In [1], the performance of a multirelay network with amplify-and-forward relaying over a flat Rayleigh fading channel in impulsive noise is considered. In [2], the performance of maximum ratio combining (MRC), equal gain combining (EGC), selection combining (SC), and postdetection combining under Class-A impulsive noise is analyzed. In [3], the bit error rate of diversity combining schemes for a single user communication system operating over flat Rayleigh fading channel subject to impulsive alpha-stable noise is derived. In [4], the authors study the asymptotic behavior of the bit error probability and the symbol error probability of quadratic diversity combining schemes such as MRC, differential EGC, and noncoherent combining in correlated Rician fading and non-Gaussian noise. In [5], the performance of postdetection combining over Rayleigh fading channel with impulsive noise is obtained and compared with the performance of MRC. In [6], optimum and suboptimum diversity combining schemes for coherent and differential M-ary phase shift keying impaired by Class-A impulsive noise over Rician fading channel are proposed.

From the previous discussion we observe that SC schemes are developed for slow flat fading channel. However, in practice, most wireless channels of the communication systems, such as mobile radio, are time varying frequency selective fading channels and it is shown that diversity can also lead to significant performance improvements for frequency selective fading channels [7]. Moreover, as mentioned previously, most studies in this area consider the interfering noise as Gaussian. However, in many cases, the transmission is additionally disturbed by man-made noise which is impulsive noise. In this paper, an adaptive SC receiver is proposed for time varying frequency selective fading channel in presence of Class-A impulsive noise. The selection of the branch is performed according to the time variations of the channel. Therefore, the proposed adaptive SC receiver is more suitable for mobile channels. Channel estimation is performed by sign algorithm which is more stable than LMS algorithm in presence of strong impulsiveness of the noise. The rest of the paper is organized as follows. In Section 2, the Class-A impulsive noise is presented. In Section 3, the proposed adaptive SC receiver is introduced. Section 4 provides the numerical results and the conclusions are given in Section 5.

2. System Model

In this section, the model of the frequency selective channel and the class-A impulsive noise is described.

2.1. Channel Model. The channel is characterized by L branches, each of which is time varying and has the same fading characteristics but is statistically independent of one another. For the lth branch, $l = 1, 2, \ldots, L$, the sampled received signal is given by

$$r_n^l = \sum_{q=0}^{Q-1} s_{n-q} h_{q,n}^l + n_n^l, \quad n = 1, 2, \ldots, N, \tag{1}$$

where Q is the channel memory length (the ISI length), N is the number of symbols, n_n^l are independent and identically distributed (i.i.d) complex valued zero mean white class-A impulsive noise samples of the lth channel, $\{s_n\}$ is the sampled transmitted sequence with alphabet size M and autocorrelation $R_x = \sigma_x^2 I$, and $h_{q,n}^l$ is the discrete time varying parameters of the lth channel. The channel time varying parameters $h_{q,n}^l$ are usually modeled as Gaussian random process. However, a more precise description of the time variations of the channel coefficients can be provided for the multipath channels, which have small number of reflectors. For example, for constant vehicle velocity, the mobile radio channel is almost periodically varying when the multipath delays change linearly with time due to the carrier modulation inherent in the transmitted signal [8]. Its time varying parameters can be expressed as a combination of exponentials whose frequency depends on the carrier frequency and the vehicle speed. We consider the channels, whose time varying parameters $h_{q,n}^l$ can be approximated by a linear combination of a finite number of basis sequences $b_{v,n}$ [8], [9, page 383]:

$$h_{q,n}^l = \sum_{v=1}^{V} \theta_{vq}^l f_{v,n}, \tag{2}$$

where θ_{vq}^l are nonrandom expansion coefficients. For mobile radio channels, these basis sequences are expressed as $f_{v,n} = \exp\{j\alpha_v n\}$, where α_v are some known frequencies [8].

2.2. Class-A Impulsive Noise Model. Class-A impulsive noise model of Middleton is a generalized model of the Gaussian noise combined with a non-Gaussian impulsive noise. In this model, a frequency component of the impulsive noise is constrained within the bandwidth of the receiver. The class-A impulsive noise for complex channel has a probability density function (pdf), $f(n)$, given by [10]

$$f(n) = \sum_{m=0}^{\infty} \frac{e^{-A} A^m}{m! 2\pi\sigma_m^2} \exp\left(-\frac{|n|^2}{2\sigma_m^2}\right), \tag{3}$$

where the parameter A is called the impulsive index: it is the product of the received average number of impulses per unit time and the duration of an impulse. This parameter defines the impulsiveness of the noise. For small A, the noise becomes more impulsive; that is, $f(n)$ exhibits large impulsive "tails" and for larger A, the statistical characteristics of the class-A impulsive noise approach those of Gaussian noise. The variances σ_m^2 are related to the physical parameters and are given by

$$\sigma_m^2 = \sigma_n^2 \frac{(m/A) + \Gamma}{1 + \Gamma}, \quad m = 0, 1, 2, \ldots, \tag{4}$$

where the parameter σ_n^2 defines the mean variance of the class-A impulsive noise. The model of the white class-A noise combines the presence of an additive man-made noise component with variance σ_I^2 and a white Gaussian noise component with variance σ_G^2. The parameter Γ in (4) is the ratio of the mean power of the Gaussian noise component to the non-Gaussian impulsive noise component. The white Gaussian noise component is presented in the class-A noise model to describe the influence of thermal noise which is naturally present in the real physical receiver. Note that $f(n)$ consists of an infinite weighted sum of zero mean Gaussian densities with decreasing weights and increasing variances. An approximation to the model in (3) can be obtained by limiting the sum to the first three terms only which are found to be sufficient to give excellent approximation to the noise probability density functions [10].

3. The Proposed Adaptive SC Receiver

3.1. Selection of Diversity Branch. In this subsection, the method of selection of the best diversity branch is described. By substitution of (2) into (1), r_n^l can be expressed as

$$r_n^l = \sum_{q=0}^{Q-1} \sum_{v=1}^{V} \theta_{vq}^l s_{n-l} f_{v,n} + n_n^l. \tag{5}$$

Let us define the following vectors:

$$\boldsymbol{\theta}_q^l = \left[\theta_{1q}^l, \theta_{2q}^l, \ldots, \theta_{Vq}^l\right]^T,$$
$$\mathbf{x}_{q,n} = \left[f_{1,n}s_{n-q} \;\; f_{2,n}s_{n-q} \;\; \cdots \;\; f_{V,n}s_{n-q}\right]^T. \tag{6}$$

Let the parameters $\boldsymbol{\theta}_q^l$ be assembled into the $(V \times Q) \times 1$ unknown vector $\boldsymbol{\Theta}^l$:

$$\boldsymbol{\Theta}^l = \left[\boldsymbol{\theta}_0^{l\,T} \;\; \boldsymbol{\theta}_1^{l\,T} \;\; \cdots \;\; \boldsymbol{\theta}_{Q-1}^{l^T}\right]^T \tag{7}$$

and also

$$\mathbf{x}_n = \left[\mathbf{x}_{0,n}^T \;\; \mathbf{x}_{1,n}^T \;\; \cdots \;\; \mathbf{x}_{Q-1,n}^T\right]^T, \tag{8}$$

where the superscript T denotes matrix transposition. Note that the vector $\boldsymbol{\Theta}$ collects the unknown channel parameters from all paths and it is called the channel parameters vector (CPV). Using the previous definitions, we can rewrite (5) in the following representation:

$$r_n^l = \mathbf{x}_n^T \boldsymbol{\Theta}^l + n_n^l. \tag{9}$$

Let $\mathbf{r}^l = [r_1^l, r_2^l, \ldots, r_N^l]^T$ and $\mathbf{s} = [s_1, s_2, \ldots, s_N]^T$ denote N-symbols of the noisy received signal and the transmitted signal, respectively. Since the observation noise is assumed to be class-A impulsive noise, then the probability density function (pdf) of the received signal vector $\mathbf{r}^l$, conditioned on the vectors $\mathbf{s}$ and $\boldsymbol{\Theta}^l$, can be written as

$$p\left(\mathbf{r}^l \mid \mathbf{s}, \boldsymbol{\Theta}^l\right) = \prod_{n=1}^{N}\left(\sum_{m=0}^{\infty} \frac{e^{-A}A^m}{m!2\pi\sigma_m^2} \exp\left\{\frac{-1}{2\sigma_m^2}\left|r_n^l - \mathbf{x}_n^T\boldsymbol{\Theta}^l\right|^2\right\}\right). \tag{10}$$

For equiprobable messages, the ML metric of the received signal from the lth diversity branch can be written as

$$\gamma_n^l = \sum_{n=1}^{N} \ln\left(\sum_{m=0}^{\infty} \frac{e^{-A}A^m}{m!2\pi\sigma_m^2} \exp\left\{\frac{-1}{2\sigma_m^2}\left|r_n^l - \mathbf{x}_n^T\boldsymbol{\Theta}^l\right|^2\right\}\right). \tag{11}$$

Evaluating γ_n^l has a great difficulty because it requires evaluation of an infinite sum, which is not possible. A simplification can be performed under the condition that the impulsive index A is sufficiently small. In this case, the infinite sum in (1) can be approximated by the maximum value of its first three terms [10]. According to this approximation the pdf of the class-A impulsive noise becomes

$$f(n) = \max_{m=0,1,2}\left[\frac{e^{-A}A^m}{m!2\pi\sigma_m^2} \exp\left(-\frac{|n|^2}{2\sigma_m^2}\right)\right]. \tag{12}$$

Using this approximated pdf, γ_n^l can be written as

$$\gamma_n^l = \sum_{n=1}^{N} \max_{m=0,1,2}\left\{\ln\left(\frac{e^{-A}A^m}{m!2\pi\sigma_m^2}\right) - \frac{1}{2\sigma_m^2}\left|r_n^l - \mathbf{x}_n^T\boldsymbol{\Theta}^l\right|^2\right\}. \tag{13}$$

The selection of the best diversity branch is performed by evaluating the ML metric γ_n^l for $l = 1, 2, \ldots, L$ and selecting the branch that has the maximum γ_n^l and turning off the rest of branches. The selected diversity branch is most probably ML diversity branch at that time. This branch is regarded as the most likely close to the signal samples at that time. Note that, since the channel is time varying, the values of γ_n^l are changed every n, and consequently, the best branch is updated every n corresponding to channel fading level. Therefore, the receiver selects the optimum ML branch dynamically every time according to the variation of the channel. The selection of the branch is optimum in the sense of maximizing the log-likelihood function.

Let $\widehat{\boldsymbol{\Theta}}_n^l$ denote the estimation of the CPV at time n, then, in order to evaluate γ_n^l, the CPV at time n, $\widehat{\boldsymbol{\Theta}}_n^l$, and the data vector $\mathbf{x}_n$ must be known. Therefore, at the start-up, a preamble sequence is transmitted and used to obtain $\widehat{\boldsymbol{\Theta}}_n^l$ and γ_n^l. After the start-up phase, the data sequence corresponding to the survivor with the maximum metric is used to update these values. The structure of the proposed adaptive SC receiver is discussed in detail in Section 3.3.

3.2. Data Detection and CPV Estimation. After selecting the strongest branch, data detection is performed using MLSE-VA. The trellis structure for this problem has M^Q states, and each state Δ_n, for the nth signaling interval, corresponds to one of the possible Q previous symbols so that $\Delta_n = (\widehat{s}_{n-1}, \widehat{s}_{n-2}, \ldots, \widehat{s}_{n-Q})$. For each state Δ_n, there are M transitions emerging from it and going to M different states $\Delta_{n+1} = (\widehat{s}_n, \widehat{s}_{n-1}, \ldots, \widehat{s}_{n-Q+1})$. Each transition corresponds to one of the M possible choices for the symbol $\widehat{s}_n$. In our problem, the trellis branch metric η_n that is associated with each transition from state Δ_n to state Δ_{n+1} in the Viterbi trellis is defined as

$$\eta\left(\Delta_n, \widehat{s}_n\right) = \max_{m=0,1,2}\left\{\ln\left(\frac{e^{-A}A^m}{m!2\pi\sigma_m^2}\right) - \frac{1}{2\sigma_m^2}\left|r_n^l - \mathbf{x}_n^T\widehat{\boldsymbol{\Theta}}_n^l\right|^2\right\}, \tag{14}$$

and the trellis path metric is given by

$$E = \sum_{n=1}^{N} \max_{m=0,1,2}\left\{\ln\left(\frac{e^{-A}A^m}{m!2\pi\sigma_m^2}\right) - \frac{1}{2\sigma_m^2}\left|r_n^l - \mathbf{x}_n^T\widehat{\boldsymbol{\Theta}}_n^l\right|^2\right\}. \tag{15}$$

The sign algorithm is used to estimate $\boldsymbol{\Theta}^l$ and uses the sequence estimated from VA. The decision delay inherent in the VA, that is necessary to obtain reliable data estimates, causes performance degradation in the adaptive channel estimation algorithm. To overcome this problem and to reduce the complexity of the algorithm, we use minimum survivor processing technique [8], in which one channel coefficients estimate is performed per time step n for all states in the trellis instead of one estimate per survivor path. This estimate is performed using the data sequence associated with survivor path which has the lowest metric among all survivors. This procedure reduces the complexity of the algorithm. The realization of this procedure requires only the comparison of all survivor metrics at every time step. The sequence with the lowest metric is used to estimate the CPV at the new time step and then update the branch metric given by (15).

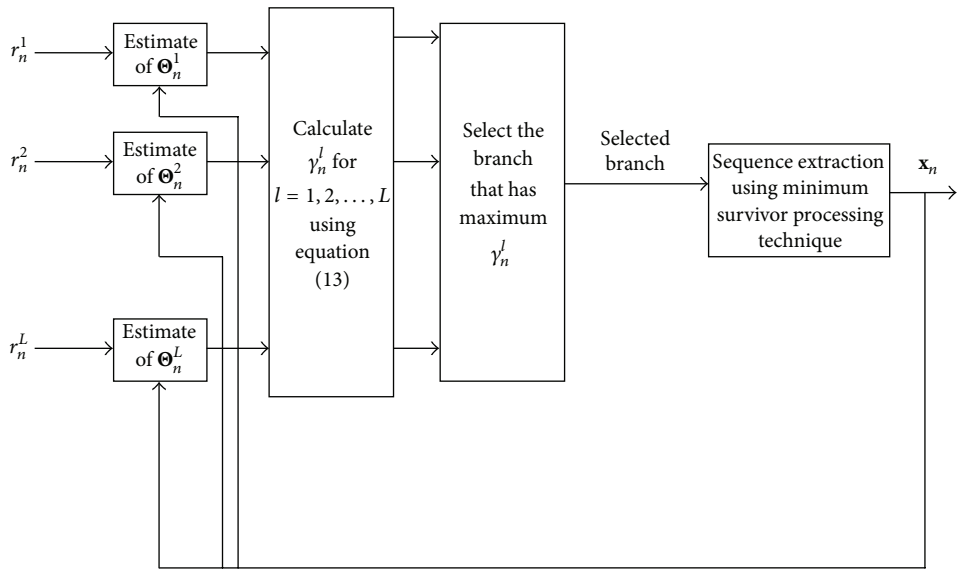

Figure 1: Structure of the proposed SC diversity receiver for the frequency selective fading channel.

It is important to observe that the true CPV is time invariant, so the task of the adaptive estimation algorithm is to converge to the CPV as opposed to tracking them as in the case of time varying coefficients. The estimation of CPV can be performed using the least mean square (LMS) algorithm. Occasionally, the LMS algorithm becomes unstable when the noise impulsiveness becomes stronger. This is because the LMS is based on a squared error function which is sensitive to strong impulsive samples [10]. A more robust alternative to the LMS algorithm, when the noise becomes more impulsive, is the sign algorithm (SA). The iterations of this algorithm are given as

$$\widehat{\mathbf{\Theta}}_{n+1}^{l} = \widehat{\mathbf{\Theta}}_{n}^{l} + \mu \mathbf{x}_n^l \operatorname{sign}\left(e_n^l\right), \tag{16}$$

where $e_n^{*l} = [r_n^l - \mathbf{x}_n^{l^T} \widehat{\mathbf{\Theta}}_n^l]^*$ is the estimation error conjugate at time step n. This algorithm is based on clipping the error signal to its sign and it is also called least mean absolute deviation algorithm. The initialization of both algorithms is obtained by setting $\widehat{\mathbf{\Theta}}_0^l = 0$.

3.3. Structure of the Adaptive SC Receiver. The structure of the proposed adaptive SC is shown in Figure 1. At the start-up phase, the transmitter sends a preamble sequence to the receiver. The receiver uses this sequence to calculate the initial values of $\widehat{\mathbf{\Theta}}_n^l$ and γ_n^l for all diversity branches. The receiver selects the branch which has maximum γ_n^l. After selecting the strongest diversity branch, sequence detection is performed using MLSE-VA with trellis branch metric given by (14) to identify the survivor path. The data sequence corresponding to the survivor with the lowest metric is used to update the CPV. Then, the data sequence corresponding to the survivor with the lowest metric and the updated CPV is used to update γ_n^l for the next time period. This procedure is repeated until all the received data are processed.

4. Numerical Results

In this section, the performance of the proposed adaptive SC receiver in impulsive noise environment over frequency selective channel is evaluated. The parameters of simulation are as follows. The number of symbols is 100000. The number of diversity branches is $L = 3$. A class-A impulsive noise is generated with $\Gamma = 0.1$ and added to the signal at the input of the receiver. The impulsive index of the noise A is varied.

First, the convergence properties of the SA under severe impulsiveness of the noise are evaluated in terms of the normalized mean square error of estimation (NMSE). The parameters of the generated impulsive noise are $A = 0.0001$ and $\Gamma = 0.1$. The results are shown in Figure 2 which is obtained by performing 10 independent runs of the algorithms. The result for $A = 0.1$ is also included for comparison. The number of the processed symbols is 100000 and the step size parameter is set to $\mu = 0.01$ for the sign algorithm. The initial value is $\widehat{\mathbf{\Theta}}_n^{(i)} = 0$ and the SNR is 15 dB. The results show that the sign algorithm converges to a steady state value of the NMSE. It is also shown that the steady state value of the NMSE for $A = 0.0001$ is greater than that one in case of $A = 0.1$. This is because as A decreases, the impulsiveness of the noise increases, causing increase in the NMSE.

It is noted that the value of the NMSE depends on the SNR which is illustrated in Figure 3. Both figures (Figures 2 and 3) show that the SA is suitable for estimation of the channel over impulsive noise and converges to a steady state value even for severe impulsiveness of the noise ($A = 0.0001$).

To illustrate the effect of the impulsive noise on the performance of the SC receiver, we plot Figures 4 and 5. Figure 4 is plotted assuming that the channel is known while Figure 5 is plotted when the sign algorithm is used to estimate the channel. The performance of the receiver is measured in terms of bit error rate (BER). In these figures, the BER is plotted versus SNR for $A = 0.1$, $A = 0.01$, and $A = 0.001$.

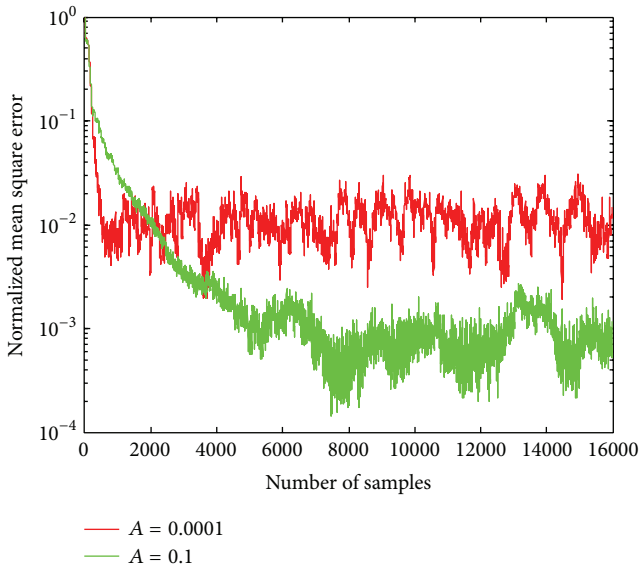

Figure 2: NMSE for the fifth channel estimation for different values of A and at SNR = 15 dB, and $\mu = 0.01$.

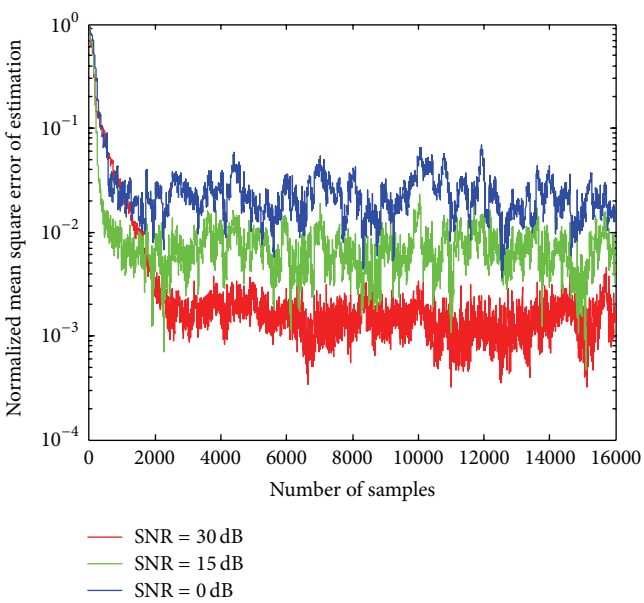

Figure 3: NMSE for the fifth channel estimation for different SNR, $\mu = 0.01$, and $A = 0.001$.

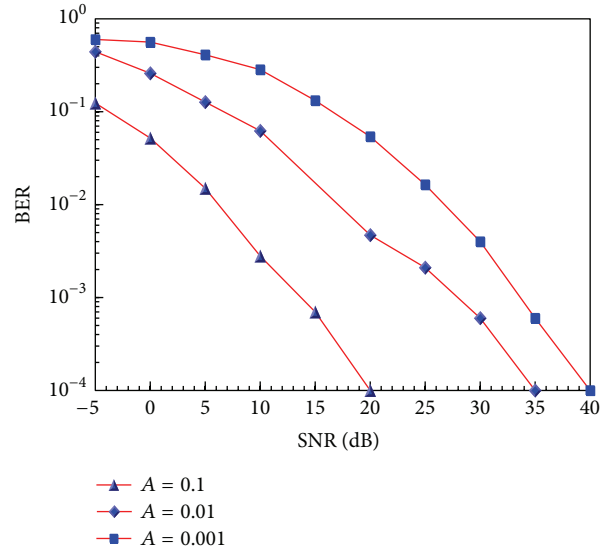

Figure 4: The performance of the adaptive SC receiver with estimated channel and for different values of impulsive index A.

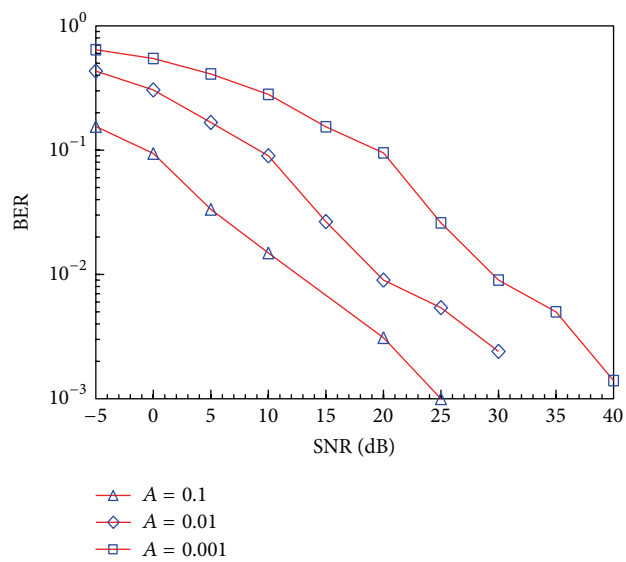

Figure 5: The performance of the adaptive SC receiver with known channel and for different values of impulsive index A.

The results show that at low SNR, the noise dominates the performance of the receiver and the BER is high for all values of A. When SNR increases, the performance of the SC receiver degrades as the value of A decreases. This is because as the value of the impulsive index A becomes smaller, the noise impulsiveness becomes stronger, thus causing larger performance degradation.

Finally, the comparison between the performance of the SC receiver with known channel and estimated channel is shown in Figure 6 for $A = 0.01$ and 0.001. The figure shows that there is a gap between the performance in case of known channel and estimated channel. This gap is due to the channel estimation error which affects the performance of the SC receiver.

5. Conclusion

An adaptive SC receiver has been proposed for time varying mobile communication channel contaminated with Class-A impulsive noise. The receiver adaptively selects one diversity branch out of the available branches and discards the others. This is performed by computing the maximum likelihood (ML) metric of each diversity branch and selects the branch which has maximum value. The proposed SC receiver

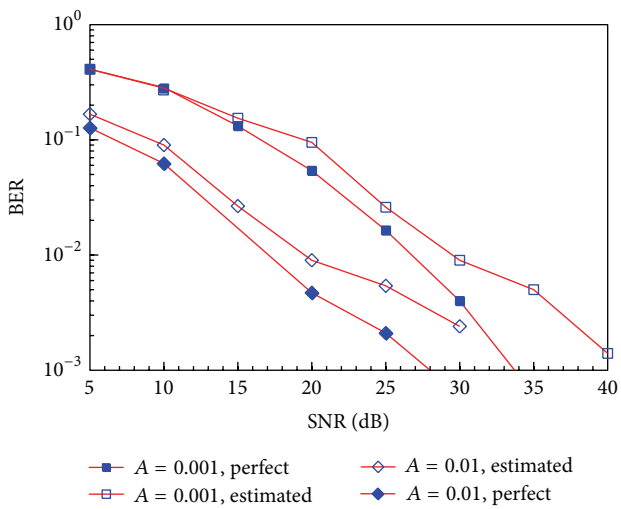

Figure 6: Comparison between the performance of the adaptive SC receiver for known and estimated channels.

dynamically selects the branch according to the time variations of the channel. Since the noise is impulsive, channel estimation is performed by sign algorithm which is more stable than LMS algorithm in presence of strong impulsiveness of the noise. The results show that the sign algorithm is adequate in estimation of the channel parameters in strong impulsiveness of the noise. The results also show that as the value of the impulsive index increases, the performance of the SC receiver is enhanced. This is because as the value of the impulsive index A becomes larger, the noise impulsiveness becomes weaker, thus causing enhancement in the receiver performance.

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