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Robust Detection for Cooperative Communication System in Alpha-stable Noise Environments

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Abstract: In the Decode-and-forward (DF) cooperative communication system, to suppress the effects of detector caused by non-Gaussian noise, a robust detector is proposed. The proposed detector adopts the limiter as the front-end of detector which aims to remove large-amplitude outliers that occur due to impulsive noise. In contrast to the existing limiters, the proposed limiter can set adaptively the threshold of limiter according to the received signal and doesn't require knowing the Channel State Information (CSI) and the sending power of signal. The proposed system contains an equalization detector which would process the signals passing through limiter to trim the outlier noise components. The robust detector so designed is shown to outperform the conventional equalization detector without the limiter.

Key words: Cooperative communication, α-stable noise, limiter, threshold setting

INTRODUCTION

In wireless networks, signal fading arising from multipath propagation is a particularly severe channel impairment that can be mitigated through the use of diversity (Proakis, 2001). Space or multiple-antenna diversity techniques are particularly attractive as they can be readily combined with other forms of diversity, e.g., time and frequency diversity and still offer dramatic performance gains when other forms of diversity are unavailable. In contrast to the more conventional forms of space diversity with physical arrays, cooperative diversity builds upon the classical relay channel model and creates space diversity using a collection of distributed antennas belonging to multiple terminals, each with its own information to transmit (Laneman *et al*., 2004; Yang *et al*., 2013; Wang *et al*., 2009; Yu *et al*., 2013).

Most studies of cooperative communication are based on Gaussian noise model (Hasna and Alouini, 2003; Cover and Gamal, 1979; Laneman *et al*., 2004; Anghel and Kaveh, 2004; Ribeiro and Giannakis, 2005). However, In many physical channels, such as urban and indoor radio channels (Blackard *et al*., 1993; Middleton, 1973, 1977) and underwater acoustic channels (Middleton, 1987), the ambient noise is known through experimental measurements to be decidedly non-Gaussian due to the impulsive nature of man-made electromagnetic interference and a great deal of natural noise as well. It is well known that non-Gaussian noise can cause significant performance degradation to conventional methods based on the Gaussian assumption (Shao and Nikias, 1993). In cooperative communication system, to obtain better performance, multiple relay nodes may be needed. Each relay node receives signals with different non-Gaussian noise because the signals are transmitted via different paths and then retransmits them to the destination. The received signals at the destination include all the non-Gaussian noise from different relay nodes. Thus the extent of non-Gaussian noise is more serious than that in the point-to-point (noncooperative) system. The conventional detection technologies would exhibit performance deterioration in the presence of non-Gaussian noise of impulsive nature (Ahmed *et al*., 2012). Therefore it is needed to adopt robust procedures so as to combat deviations in the noise distribution from nominal Gaussian assumption. In Guney *et al*. (2006), an amplitude limiter as the front-end of a receiver to reduce the impact of non-Gaussian noise for a point-to-point communication system is proposed which determine the threshold of the limiter according to the channel parameters and sending power. However, in practice, the parameters are hard to get which renders the threshold setting of the limiter difficult to realize. McCain and McGillem (1987) considers determining the

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threshold according to empirical value. However, the empirical value is only suitable for some specific non-Gaussian noise and it cannot be adjusted adaptively according to the variation of non-Gaussian noise. Especially for cooperative communication system, the extent of non-Gaussian noise is related with the number of cooperating nodes which make the threshold setting of the limiter more difficult.

In order to decrease the performance degradation caused by non-Gaussian noise, we consider extending the limiter technique in Guney *et al*. (2006) to cooperative communication system. An adaptive method to set the threshold of the limiter based on received signals is proposed. The main idea is to obtain the threshold by averaging the maximum amplitudes of the received symbols. The limiter doesn't require knowing the global knowledge of Channel State Information (CSI) of all links and the sending power of all nodes. Hence, the proposed detector is more suitable for practical cooperative communication systems.

SYSTEM MODEL

Consider a cooperative communication network as shown in Fig. 1, where the source node S transmits messages to the destination node D with the help of a set of K nearby relays R = $\{R_1, R_2, \ldots, R_K\}$. Each node can transmit and receive signal at the same time.

In this study, we mainly focus on a two-hop scenario whose mathematical model is shown in Fig. 2 and assume the Decode-and-forward (DF) relaying. In the two-hop case, signaling of the packet occurs over two time slots. During the first slot, the source broadcasts to both D and all the relays. During the second slot, relays immediately demodulate after receiving the signals. Then, signals are modulated and sent again to the destination by the relays. It is assumed that all the channels between any pair of nodes are frequency selective channel. In addition, quasi-static fading is assumed, where the path gains remain fixed during the transmission of a whole packet, but the path gains are independent from node to node and packet to packet.

The signals in Fig. 2 can be shown as:

$$r_{S-R_K}(t) = h_{S-R_K}(X_s(t)) + n_K(t) \tag{1}$$

$$r(t) = \sum_{j=1}^{K} h_{R_j-D}(X_{R_j}(t)) + h_{S-D}(X_s(t)) + n_D(t) \tag{2}$$

where, $h_{S-R_K}(X_s(t))$ is the output of the channel between S and R_K with the input $X_s(t)$, $h_{R_j-D}(X_{R_j}(t))$ is the output of the channel between R_j and with the input $X_{R_j}(t)$. $n_K(t)$ and $n_D(t)$ is the non-Gaussian noise received by the K-th relay node and the destination receiver.

In this study, we use the symmetric α-distributions (SαS) to model the non-Gaussian noise. The distributions have heavier tails than those of Gaussian distribution and they exhibit sharp spikes or occasional bursts in their realizations. A random variable is called symmetric alpha-stable if its characteristic function has the following form:

$$\phi(t) = e^{-\gamma|t|^{\alpha}} \tag{3}$$

where, $\gamma>0$, $0<\alpha\le 2$. α is the most important parameter of a symmetric alpha-stable distribution known as characteristic exponent. A small value of α signifies more impulsive type of behavior and as it approaches 2, the non-Gaussian alpha-stable distribution approaches the Gaussian distribution in a continuous fashion. γ (γ>0) is a scale parameter known as the dispersion which plays a role similar to the variance of the Gaussian model. An important property of all stable distributions is that only the lower order moments are finite. That is, if x is a stable random variable, then $E_x\{|x|^p\}<\infty$ if $p<\alpha$. A well known consequence of this property is that all stable random variables with $\alpha<2$ have infinite variance. Figure 3 shows an example of Alpha-stable Noise. It can be seen from Fig. 3 that there are many large amplitude impulse interferences.

Since alpha-stable distributions with $\alpha<2$ have infinite variance, researchers are confronted with the difficulty of defining Signal Noise Ratio (SNR) based on second-order statistics. The geometric SNR (G-SNR), based on the theory of Zero-order Statistics (ZOS), is an approach towards a mathematically and conceptually valid characterization of the relative strength between information-bearing signal and channel noise with infinite variance. The G-SNR is defined as (Yoon *et al*., 2004):

$$G-SNR = \frac{1}{2C_g}\left(\frac{\sqrt{E}}{S_0}\right)^2 \tag{4}$$

where, $C_g \simeq 1.78$ is the exponential of the Euler's constant, and:

$$S_0 = (C_g\gamma)^{\frac{1}{\alpha}} / C_g$$

denotes the geometric power. The normalization constant $2C_g$ in (4) is used to ensure that the definition of the SNR corresponds to that of the SNR in the Gaussian case.

PROPOSED METHOD

Here, a robust detector that is robust against the impulsive nature of the noise is introduced. We consider using a limiter at the front end of the detector. The transfer function of the limiter is as follows:

$$g(s,G)=\begin{cases} s, & |s|\le G \\ \mathrm{sign}(s)G, & \text{elsewhere} \end{cases} \tag{5}$$

where, G is the saturation point of the limiter. It can be easily shown that any random process which is passed through a limiter have finite variance.

Now the problem is: How to determine the value of G to achieve the minimum Bit Error Rate (BER). In a cooperative communication system, its value is related to the number of relay nodes, channel parameters and transmission power. The method that was proposed in Guney *et al*. (2006) is:

$$G=\sum_{k=1}^{L} A_k\sqrt{E} \tag{6}$$

where, A_k is the path gain of the k-th path and L is the number of the path between two nodes. However, it is difficult to estimate the parameters in Eq. 6 which makes the value of G hard to derive. Therefore, we propose the adaptive method to get G.

Adaptive method to get G: Due to small probabilities that noises of large amplitude which play an important role in the system performance degradation, there is only few symbols in a packet affected by the large amplitude noises. We consider averaging the maximum amplitude of each received symbol to determine G. Through averaging, the value of G has nearly nothing to do with large amplitude noise. Therefore, the effect for estimating G by the large amplitude is removed. The algorithm to get the threshold value G is as follows:

- **Sample the received signal:** Assuming that the received packet has N symbols. The sampled value of the received signal can be expressed as r:

$$r=\{[r_{1,1}\ \ r_{1,2}\cdots r_{1,k}]\ \ [r_{2,1}\ \ r_{2,2}\ \cdots\ r_{2,k}]\ \ \cdots\ \ [r_{N,1}\ \ r_{N,2}\ \cdots\ r_{N,k}]\}$$

where , $r_{i,j}$ is the j-th sampled value of the i-th symbol.

- Select the maximum amplitude value of each T period which is the duration of a symbol:

$$r_{i,\max}=\max(|r_{i,j}|)\quad j=1,2,\ldots,k$$

- Average $r_{i,\max}$ to get the threshold value G:

$$G=\frac{r_{1,\max}+r_{2,\max}+r_{3,\max}+\ldots+r_{N-1,\max}+r_{N,\max}}{N} \tag{7}$$

However, there is a defect in the proposed method. The received signals cannot be immediately processed by the robust detector. The equalization detector can work

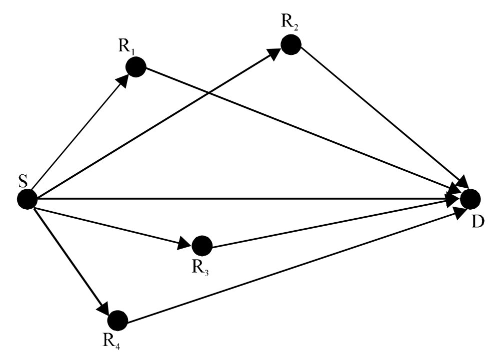

Fig. 1: Cooperative communication wireless network. Node S wishes to communicate with node D with the help of nodes R_1, R_2, ..., R_4

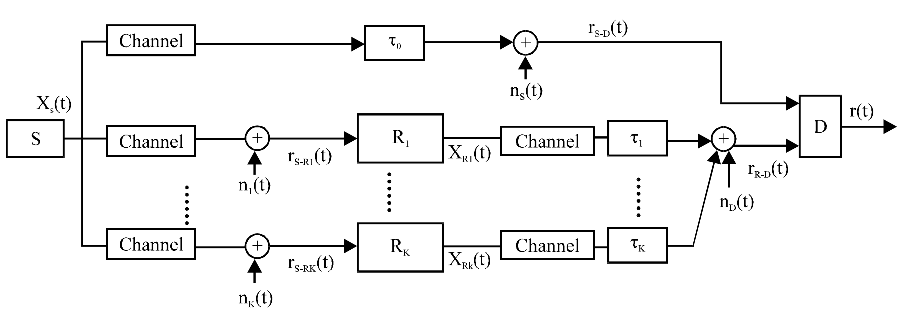

Fig. 2: Mathematical model of an cooperative communication wireless network

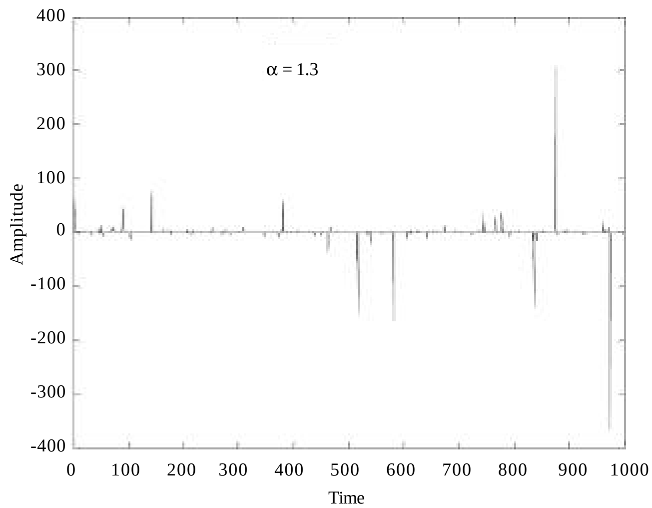

Fig. 3: Alpha-stable Noise with α = 1.3

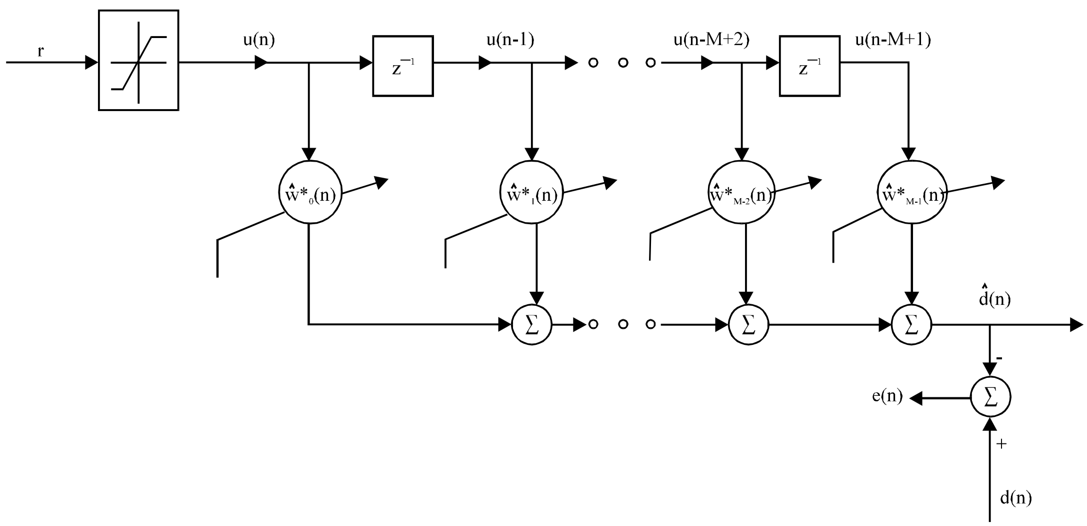

Fig. 4: The structure of the detector. r is the sampled value vector of the received signal and u(n) is the output of the limiter

until the process of Eq. 7 for the whole data packet is finished. In addition, the storage of received signals also requires much memory space.

Modified adaptive method to get G: Due to the drawback of method shown in Eq. 7, we propose a modified method for Eq. 7. The modified method need to update the value of G at each time when the sampled signal of each symbol is processed by the detector. We can update the value of G as follows:

$$G_i = \frac{G_{i-1} \times (i-2) + r_{i-1,max}}{i-1} \quad i \geq 2 \tag{8}$$

where, G_i is the saturation point of the limiter for the i-th symbol. In this way, the data can be processed immediately after they are received.

The receiver: The outputs of the limiter have finite variance after limiting amplitude. So we can apply the conventional adaptive algorithms to the equalization detector. The structure of the detector is shown in Fig. 4. The Recursive Least Squares (RLS) algorithm is considered here as it has a high speed of convergence (Haykin, 1986), thus it can improve the efficiency of the system.

The output $\hat{d}(n)$ of the equalization detector can be calculated by:

$$\hat{d}(n) = \hat{w}^H(n-1)u(n) \tag{9}$$

where, the vector $\hat{w}^H(n-1)$ is the filter coefficients, vector u(n) is the output of the limiter and the input of the equalizer.

The vector of filter coefficients $\hat{w}(n)$ can be updated as follows:

$$\widehat{w}(n) = \widehat{w}(n-1) + k(n)\xi(n) \tag{10}$$

where, $\xi(n)$ is the priori estimation error and k(n) is the Kalman gain vector. $\xi(n)$ and k(n) are calculated as follows:

$$\xi(n) = d(n) - \widehat{w}^H(n-1)u(n) \tag{11}$$

$$k(n) = \frac{P(n-1)u(n)}{\lambda + u^H(n)P(n-1)u(n)} \tag{12}$$

where, d(n) is the desired output of the equalizer. P is initially defined as $P(0) = \boldsymbol{\delta}^{-1}I$, $\boldsymbol{\delta}$ is the initialization value, I is the identity matrix of rank M+1, M is the order of the filter and λ is the 'forgetting factor' which gives exponentially less weight to older error samples. And then:

$$P(n) = \lambda^{-1}P(n-1) - \lambda^{-1}k(n)u^H(n)P(n-1) \tag{13}$$

SIMULATION RESULTS

In simulation, we assume that there are 10 relay nodes for the signal transmitted from the source to the destination. The channel between any two nodes is frequency-selective. The transmitted information sequence is generated by binary phase shift keying (BPSK) signaling. Each packet consists of 1000 symbols, the 50 symbols are used as the training sequence. To evaluate the BER performance of the proposed method, a Monte-Carlo simulation is set up.

Figure 5 shows the BER as a function of G-SNR in a cooperative communication network with 10 relay nodes under alpha-stable noise. The channel noise is highly impulsive with different α = (1.0, 1.2, 1.3) and all nodes are assumed to have equal powers. The full line shows the BER of the system without limiter and dotted line shows the BER of the system with limiter. We can see from the full line of Fig. 5 that, the BER performance of system is different for different characteristic exponent α. With the value of α increasing, the BER performance would be improved. This is because the smaller value of α is, the more impulsive interference is in the Alpha-stable noise which play an important impact on the system performance. It is observed that for each value of α, the BER performances with proposed limiter are better than that without limiter (at about BER =10-2, 7 dB performance gain when α = 1.0, 6dB performance gain when α = 1.2 and at about BER=10-3, 6 dB performance gain when α = 1.3). This is because the limiter can reduce the effect of spiky characteristic of the alpha-stable noise. In view of the

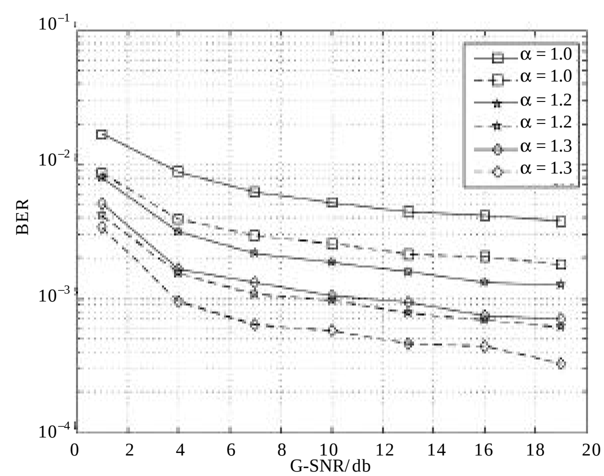

Fig. 5: Bit error rate of our proposed method with different value of α. The full line shows the BER of the system without limiter and dotted line shows the BER of the system with the help of the limiter

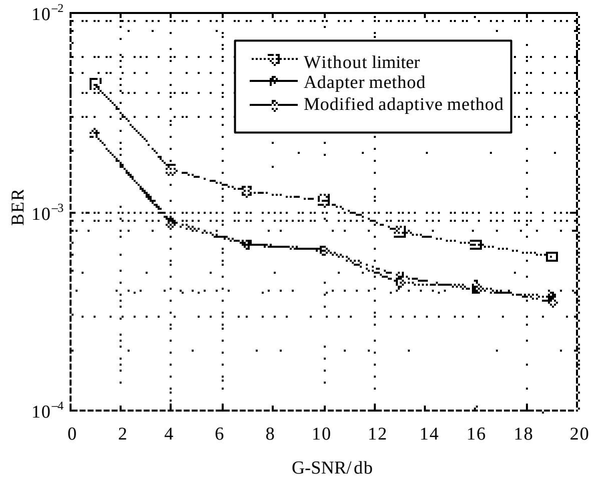

Fig. 6: The perforamnce comparision of adaptive method and modified adaptive method with α = 1.3

simulation results, it is testified that the proposed limiter can really work for the suppression of alpha-stable noise.

Figure 6 shows the comparison of the BER performance of adaptive method and the modified adaptive method. We can see from the Fig. 6 that modified adaptive method achieves almost the same performance compared with the adaptive method. In addition, compared with the adaptive method, the modified adaptive method can process data immediately and save much memory space. Hence, the modified adaptive method is more suitable for practical cooperative communication system.

CONCLUSION

In this study, robust detection method for cooperative communication system in alpha-stable noise environments is proposed. The proposed method takes into account the characteristic of cooperative communication system that many parameters (for example, the channel state information) may be difficult to be obtained at the receiver, the threshold of the limiter can be obtained adaptively according to the received signals. To evaluate the performance of the proposed method, Monte-Carlo simulation was set up. Simulation results show that the proposed limiter can suppress effectively the impulsive interference in Alpha-stable noise and thus achieve better BER performance than that without the limiter.

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