Performance Analysis and Receiver Design for SDMA-Based Wireless Networks in Impulsive Noise

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Abstract. In this paper, performance analysis and receiver design in the uplink of SDMA-based wireless systems are performed in the presence of impulsive noise modeled as a symmetric alpha-stable process. The optimal receiver and several suboptimal receivers are proposed and the symbol-error-rates (SER) or upper bound of SER of the receivers are derived. Simulation results show the proposed receivers can achieve significant performance gain compared with conventional detectors in SDMA-based wireless systems.

1 Introduction

Space Division Multiple Access (SDMA) has been proposed recently as a promising technique to satisfy the growing demand for system capacity and spectral efficiency in wireless Networks, such as wireless LANs, GSM, third-generation (3G) networks and beyond [1]. Most of the analyses of SDMA-based systems so far have been based on the ideal Gaussian noise model [1]-[3]. However,many sources, such as automobile ignitions, electric-devices, radiation from power lines and multiple access interference, will cause the noise in many actual channels to be impulsive [4]-[6].

Among the many impulsive noise models suggested so far, such as Laplace distribution, Generalized Gaussian Distribution and student-t distribution, the family of alpha stable distribution is especially attractive [4]-[8]. This is mainly due to the Generalized Central Limit Theorem (GCLT), which indicates that the stable distribution arises in the same way as the Gaussian distribution does and can describe the noise resulting from a large number of impulsive effects. The alpha stable distribution can describe the impulsive noise and actually includes the Gaussian distribution as a special case.

In this paper, we consider the performance and receiver design in the uplink of SDMA-based systems in alpha stable impulsive noise. On the one hand, many detectors developed for Multi-Input Multi-Output (MIMO) systems and CDMA systems can be extended to SDMA-based systems, such as maximum likelihood (ML) detector and VBLAST detector [3][9]. But almost all of them are based on Gaussian noise assumption, so their performances are greatly degraded when

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impulsive noise appears. On the other hand, some enhanced receivers are developed according to the statistical characteristic of the alpha stable noise in Single-Input Single-Output (SISO) systems [4][5][8]. But they cannot be applied to SDMA-based systems because they do not take into account the multiple access interference (MAI). In this paper, we develop receivers of SDMA-based systems on the basis of impulsive noise assumption and analyze their performance.

2 System Model

2.1 Model of the Uplink of SDMA-Based Systems

Consider the uplink of a SDMA-based wireless system. The system has M terminals and the base station (BS) has N receive antennas. The channels between terminals and receive antennas are assumed to be independent Rayleigh flat fading with the symmetric alpha-stable ($S\alpha S$) impulsive noise. The channels' transfer coefficients are assumed to be known by channel estimation at the BS. The system can be described as follows:

$$\mathbf{r}(l) = \mathbf{H}(l)\mathbf{x}(l) + \mathbf{n}(l) \quad (1)$$

where $\mathbf{x}(l) \in \mathcal{C}^{M\times 1}$ has entries $x_m(l), m = 1, \ldots, M$, being the signal transmitted from terminal m at time l; $\mathbf{H}(l) \in \mathcal{C}^{N\times M}$ has entries $h_{nm}(l), n = 1, \ldots, N, m = 1, \ldots, M$, being the complex channel transfer coefficient from terminal m to receiver antenna n; $\mathbf{r}(l) \in \mathcal{C}^{N\times 1}$ has entries $r_n(l), n = 1, \ldots, N$, being the signal received from receive antenna n; and $\mathbf{n}(l) \in \mathcal{C}^{N\times 1}$ has the entries $n_n(l), n = 1, \ldots, N$, being the $S\alpha S$ impulsive noise observed at receive antenna n.

2.2 Model of the Alpha Stable Impulsive Noise

The elements of $\mathbf{n}(l)$ are modeled as independently and identically distributed complex $S\alpha S$ random variables, that is $\forall n_i(l) = \Re(n_i) + j\Im(n_i), 1 \le i \le N$, $\Re(n_i)$ and $\Im(n_i)$ obey the bivariate joint $S\alpha S$ distribution. The probability density function (pdf) of $n_i(l)$ can be written as

$$\begin{aligned} &f_{\alpha,\gamma}\left(\Re(n_i), \Im(n_i)\right) \\ &= \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \exp(-\gamma\left|\omega_1^2 + \omega_2^2\right|^{\frac{\alpha}{2}}) \exp(-j\omega_1\Re(n_i)) \exp(-j\omega_2\Im(n_i)) d\omega_1 d\omega_2 \end{aligned} \quad (2)$$

where $\alpha \in (0, 2]$ is *characteristic exponent*, which implies the impulsiveness of the respective $S\alpha S$ noise. The larger the value of α is, the less impulsive the $S\alpha S$ noise is, and when $\alpha = 2$, the $S\alpha S$ impulsive noise is reduced to the Gaussian noise. The parameter $\gamma \in (0, \infty)$ is *dispersion*, which plays an analogous role to the variance of Gaussian distribution. For simplicity, we define special operator $\|\cdot\|_{F(\alpha,\gamma)}^2$ to denote (2)

$$f_{\alpha,\gamma}\left(\Re(n_i), \Im(n_i)\right) = \|n_i(l)\|_{F(\alpha,\gamma)}^2 = \|\Re(n_i) + j\Im(n_i)\|_{F(\alpha,\gamma)}^2 \quad (3)$$

Unfortunately, there are no closed form expressions for general complex $S\alpha S$ random variables except for the Gaussian ($\alpha = 2$) distribution and the Cauchy ($\alpha = 1$) distribution

$$Gaussian: \|\Re(n_i) + j\Im(n_i)\|^2_{F(2,\gamma)} = \frac{1}{4\pi\gamma}\exp\left(-\frac{\Re(n_i)^2 + \Im(n_i)^2}{4\gamma}\right) \quad (4)$$

$$Cauchy: \ \|\Re(n_i) + j\Im(n_i)\|^2_{F(1,\gamma)} = \frac{\gamma}{2\pi}\left(\sqrt{\Re(n_i)^2 + \Im(n_i)^2 + \gamma^2}\right)^{-3} \quad (5)$$

This leads to difficulties in performance analysis and receiver design in the alpha stable noise.

3 Receiver Design and Performance Analysis

In this section several receivers are proposed on the basis of $S\alpha S$ noise model and the SER or the upper bound of the SER of the receivers are derived.

3.1 The Zero-Forcing Receiver (ZF)

The zero-forcing receiver decorrelates the received signal vector to cancel the multiple access interference (MAI) and carries out the hard decisions according to the statistical characteristics of the noise, which can be formulated as

$$\tilde{\mathbf{x}}(l) = (\mathbf{H}(l)^H\mathbf{H}(l))^{-1}\mathbf{H}(l)^H \cdot \mathbf{r}(l) = \mathbf{x}(l) + (\mathbf{H}(l)^H\mathbf{H}(l))^{-1}\mathbf{H}(l)^H \cdot \mathbf{n}(l) \quad (6)$$

where $(\cdot)^H$ denotes the conjugate transpose. Due to the *stable property*, the elements of the vector $(\mathbf{H}(l)^H\mathbf{H}(l))^{-1}\mathbf{H}(l)^H \cdot \mathbf{n}(l)$ obey the stable distribution with parameters α and γ_{eq} ([10], pp.35). So the ZF receiver can be obtained as

$$\hat{x}_m(l)_{ZF} = \arg\max_{s_q \in \mathcal{C}^Q}\left(\|\tilde{x}_m(l) - s_q\|^2_{F(\alpha,\gamma_{eq})}\right), 1 \le m \le M \quad (7)$$

where $\hat{x}_m(l)_{ZF}$ denotes the (hard) estimate of the symbol transmitted from the mth terminal; $\tilde{x}_m(l)$ denotes the mth element of $\tilde{\mathbf{x}}(l)$; and $\left\{ s_q \in \mathcal{C}^Q \middle| q = 1, \ldots, Q \right\}$ denotes the transmitted symbol taken from a discrete constellation.

If QPSK is adopted at terminals and the transmit power of terminals is E_s. The SER for ZF receiver can be calculated as

$$\begin{aligned} SER_{ZF} &= \frac{1}{M}\sum_{m=1}^{M} P\left(\hat{x}_m(l) \ne x_m(l)\right) = \frac{1}{M}\sum_{m=1}^{M}\left(1 - P\left(\hat{x}_m(l) = x_m(l)\right)\right) \\ &= \frac{1}{M}\sum_{m=1}^{M}\left(1 - \sum_{q=1}^{4} P\left(s_q\right) P\left(\hat{x}_m(l) = s_q \left| s_q \ sent\right.\right)\right) \end{aligned} \quad (8)$$

If the transmitted symbols are equal probability, namely $P\left(s_q\right) = 1/4$, we have

$$SER_{ZF} = \frac{1}{M}\sum_{m=1}^{M}\left(1 - P\left(\hat{x}_m(l) = s_q \left| s_q \ sent\right.\right)\right) \quad (9)$$

where

$$
\begin{aligned}
&P\left(\hat{x}_m(l) = s_q \,|s_q \; sent\right) \\
&= P\left(\arg\max_{s_i}\left(\|\tilde{x}_m(l) - s_i\|^2_{F(\alpha,\gamma_{eq})}\right) = s_q \,|s_q \; sent\right) \\
&= \int_0^\infty\int_0^\infty \left(\|\tilde{x}_m(l) - s_q\|^2_{F(\alpha,\gamma_{eq})}\right) d\Re\left(\tilde{x}_m(l) - s_q\right) d\Im\left(\tilde{x}_m(l) - s_q\right)
\end{aligned}
\tag{10}
$$

Since the alpha stable distribution usually has no closed form pdf, (10) usually has no closed form expression. Nevertheless numerical methods can be adopted to evaluate the performance of the ZF receiver by (8)-(10).

3.2 The Optimal Receiver in the Alpha Stable Noise (ML-Alpha)

It is known that the optimal ML receiver performs a computation as follows:

$$
\hat{\mathbf{x}}(l)_{ML} = \arg\max_{\mathbf{x}(l)_q \in \mathcal{C}^{Q^M}} \left(p\left(\mathbf{r}(l)|\mathbf{x}(l)_q\right)\right) \tag{11}
$$

where $p\left(\mathbf{r}(l)|\mathbf{x}(l)_q\right)$ is the conditional probability density function of the received vector $\mathbf{r}(l)$, given that $\mathbf{x}(l)_q$ is transmitted, and $\mathbf{x}(l)_q$ is taken from the set of all possible transmitted vectors with a size of Q^M, where Q is the size of the constellation. The ML receiver searches all possible transmitted vectors and selects the one which gives the maximum value of conditional pdf.

For a specific channel $\mathbf{H}(l)$ and a given $\mathbf{x}(l)_q$, it is easy to see the received vector $\mathbf{r}(l)$ follows the same distribution as $\mathbf{n}(l)$ (with different parameters). Since the impulsive noise observed at different receive antennas is assumed to be independent, the joint pdf of the impulsive noise can be written as

$$
f_N\left(\mathbf{n}(l)\right) = f_N\left(n_1(l), n_2(l), \ldots, n_N(l)\right) = \prod_{n=1}^{N} \|n_n(l)\|^2_{F(\alpha,\gamma)} \tag{12}
$$

Use logarithmic likelihood, then the ML detection rule in (11) becomes

$$
\begin{aligned}
\hat{\mathbf{x}}(l)_{ML-Alpha} &= \arg\max_{\mathbf{x}(l)_q \in \mathcal{C}^{Q^M}} \log\left(f_N\left(\mathbf{r}(l) - \mathbf{H}(l)\cdot\mathbf{x}(l)_q\right)\right) \\
&= \arg\max_{\mathbf{x}(l)_q \in \mathcal{C}^{Q^M}} \left(\sum_{n=1}^{N} \log\left(\|r_n(l) - \mathbf{H}_n(l)\cdot\mathbf{x}(l)_q\|^2_{F(\alpha,\gamma)}\right)\right)
\end{aligned}
\tag{13}
$$

where $\mathbf{H}_n(l)$ denotes the nth row of channel matrix $\mathbf{H}(l)$.

An upper bound on SER for ML-Alpha receiver can be obtained by assuming all possible code words have the same distance. From this point, and after some manipulation, the upper bound of SER can be obtained as

$$
\begin{aligned}
&SER_{ML-Alpha} \le \tfrac{Q^M-1}{M} \sum_{m=1}^{M} \left(1 - \sum_{q=1}^{4} P\left(s_q\right) P\left(\hat{x}_m(l) = s_q \,|s_q \; sent\right)\right) \\
&= \tfrac{Q^M-1}{M} \sum_{m=1}^{M} \left(1 - \sum_{q=1}^{4} P\left(s_q\right) \int_0^\infty\int_0^\infty \left(\|\tilde{x}_m(l) - s_q\|^2_{F(\alpha,\gamma)}\right) d\Re(\tilde{x}_m(l) - s_q)\, d\Im(\tilde{x}_m(l) - s_q)\right)
\end{aligned}
\tag{14}
$$

3.3 The Optimal Receiver in the Gaussian Noise (ML-G)

Since Gaussian noise is a special case of alpha stable noise, the ML-G receiver is a special case of ML-Alpha receiver. Take $\alpha = 2$ in (13) and combine with (4), the ML receiver in the Gaussian noise can be obtained as

$$\begin{aligned}\hat{\mathbf{x}}(l)_{ML-G} &= \underset{\mathbf{x}(l)_q \in \mathcal{C}^{QM}}{\arg\min} \sum_{n=1}^{N} \left(\Re^2 (r_n(l) - \mathbf{H}_n(l) \cdot \mathbf{x}(l)_q) + \Im^2 (r_n(l) - \mathbf{H}_n(l) \cdot \mathbf{x}(l)_q) \right) \\ &= \underset{\mathbf{x}(l)_q \in \mathcal{C}^{QM}}{\arg\min} \left(\left\| \mathbf{r}(l) - \mathbf{H}(l) \cdot \mathbf{x}(l)_q \right\|^2 \right) \end{aligned} \quad (15)$$

Formula (15) is in accordance with the receiver developed in [3]. As is shown here it is only a special receiver in the alpha stable noise. It is the optimal receiver in the alpha stable noise when $\alpha = 2$. To derive the upper bound of SER of this receiver, use (4) and for QPSK: $\|s_q\|^2 = E_S, \forall q, 1 \le q \le 4$, thus

$$\begin{aligned} &P\left(\hat{x}_m(l) = s_q \,|s_q \; sent\right) \\ &= \frac{1}{4\pi\gamma} \int_0^\infty \int_0^\infty \exp\left(- \frac{\Re^2\left(\tilde{x}_m(l) - s_q\right) + \Im^2\left(\tilde{x}_m(l) - s_q\right)}{4\gamma} \right) \\ &\qquad \cdot d\Re\left(\tilde{x}_m(l) - s_q\right) d\Im\left(\tilde{x}_m(l) - s_q\right) \\ &= \left(1 - \frac{1}{2} erfc\left(\frac{\Re\left(s_q\right)}{2\sqrt{\gamma}}\right)\right)\left(1 - \frac{1}{2} erfc\left(\frac{\Im\left(s_q\right)}{2\sqrt{\gamma}}\right)\right) = \left(1 - \frac{1}{2} erfc\left(\frac{1}{2}\sqrt{\frac{E_s}{2\gamma}}\right)\right)^2 \end{aligned} \quad (16)$$

where $erfc\left(x\right) \overset{\Delta}{=} \frac{2}{\sqrt{\pi}} \int_x^\infty \exp\left(-t^2\right) dt$.

Therefore the upper bound of ML-G receiver can be got by substituting (16) into (14), and after some simplification

$$SER_{ML-G} \le \left(Q^M - 1\right) \cdot erfc\left(\frac{1}{2}\sqrt{\frac{E_s}{2\gamma}}\right) \cdot \left(1 - \frac{1}{4} erfc\left(\frac{1}{2}\sqrt{\frac{E_s}{2\gamma}}\right)\right) \quad (17)$$

3.4 Cauchy Receiver

The Cauchy receiver is the optimal receiver when Cauchy noise appears. Take $\alpha = 1$ in (13) and combine with (5), the Cauchy receiver can be developed as

$$\hat{\mathbf{x}}(l)_{Cauchy} = \underset{\mathbf{x}(l)_q \in \mathcal{C}^{QM}}{\arg\min} \left(\sum_{n=1}^{N} \log\left(\left\| r_n(l) - \mathbf{H}_n(l) \cdot \mathbf{x}(l)_q \right\|^2 + \gamma^2 \right) \right) \quad (18)$$

Comparing (15) with (18), we can see that the Cauchy receiver depends on the *dispersion* of the alpha noise, while ML-G receiver dose not, which is the main reason why their performances are strikingly different in the impulsive noise, as is shown in the simulation results.

For Cauchy receiver, following the same steps as for ML-G, we can get the upper bound as follows:

$$SER_{Cauchy} \leq \frac{Q^M - 1}{M} \sum_{m=1}^{M} \left(1 - \sum_{q=1}^{4} P\left(s_q\right) P\left(\hat{x}_m(l) = s_q \left| s_q \ sent \right.\right) \right) \quad (19)$$

where

$$P\left(\hat{x}_m(l) = s_q \left| s_q \ sent \right.\right) = \frac{\gamma}{2\pi} \int_0^{\infty}\int_0^{\infty} \left(\Re^2\left(\tilde{x}_m(l) - s_q\right) + \Im^2\left(\tilde{x}_m(l) - s_q\right) + \gamma^2\right)^{-\frac{3}{2}} \cdot d\Re\left(\tilde{x}_m(l) - s_q\right) d\Im\left(\tilde{x}_m(l) - s_q\right) \quad (20)$$

3.5 VBLAST Receiver

The VBLAST receiver is one of the well-known space-time signal processing algorithm adopting a cancelling and nulling precessing [9]. We include it here for comparison with other receivers.

4 Comparisons of the Receivers

4.1 Performance

The performance of the receivers is mainly determined by two factors. One is the diversity order and the other is to what degree the receivers take into account the statistical characteristic of the noise. (1) ML-Alpha, ML-G and Cauchy Receiver have the same diversity order of N, but due to the different degrees they take into account the statistical characteristic of the alpha stable noise, their performances are different. ML-Alpha considers the pdf of the alpha stable noise, so its performance is the best of the three. The performances of the other two receivers depend on the value of α. (2) When α is away from 2, the Cauchy receiver performs better than ML-G and when α is close to 2, ML-G performs better than Cauchy receiver. (3) The ZF performs the worst in all cases due to the smallest diversity order $N - M + 1$ it has.

Table 1. Performances of Receivers

$\alpha = 1$	ML-Alpha = Cauchy Receiver > ML-G > VBLAST > ZF
$\alpha = 2$	ML-Alpha = ML-G > Cauchy Receiver > VBLAST > ZF
$0 < \alpha < 2$ and $\alpha \neq 1$	ML-Alpha > Cauchy Receiver, ML-G > VBLAST > ZF

Table 2. Complexity of Receivers

	ZF	ML-Alpha	ML-G	Cauchy Receiver	VBLAST
Size of candidate signal set	Q	Q^M	Q^M	Q^M	Q

4.2 Complexity

The complexity of the receivers is shown in Table.2. (1)ML-Alpha is the most complex one, which needs to search a vector set of size Q^M and requires lots of numerical integrals for each candidate vector. Despite the optimal performance ML-Alpha has, the computational complexity prevents it from practical applications. (2) For ML-G and Cauchy Receiver, they have the almost the same computational complexities, because the candidate sets they need to search are of the same size, and the their computational complexities for each candidate vector are approximate the same.

5 Simulation Results

An SDMA-based system with 2 terminals and 2 receiver antennas at BS is simulated. Both terminals adopt the QPSK modulation. The simulation results are plotted as BER vs. Signal-to-Noise-Dispersion Ratio (SNDR) rather than common SNR, since the variance of the impulsive noise does not exist for $\alpha < 2$. The SNDR is defined as $SNDR = \frac{1}{N}\sum_{i=1}^{N} SNDR^i$, where $SNDR^i = \frac{M \cdot Es}{2\gamma}$ is the ratio of received signal power from all M terminals to the dispersion of alpha stable noise at the ith receive antenna. When $\alpha = 2$, the $SNDR$ is identical to the common SNR definition in Gaussian noise.

5.1 Performances of VBLAST and ML-G

Fig.1 shows the performances of VBLAST and ML-G in the alpha stable noise. It can be seen that:(1) Their performances in the impulsive noise are much worse than in the pure Gaussian noise. The more impulsive the noise is, the worse they perform. For example, when $\alpha = 1.5$, namely middle impulsive noise, at $BER = 3 \times 10^{-3}$, there are about 9dB and 11dB performance losses in VBLAST and ML-G respectively. When $\alpha = 0.5$, the performances of both systems degrade to unacceptably low levels. (2)The more impulsive the noise is, the less performance gain ML-G can attain over VBLAST. For example, when $\alpha = 2.0$, at $BER = 3 \times 10^{-3}$, there is about 5dB performance gain, but when $\alpha = 0.5$, their performances are almost the same. This is because both systems are based on Gaussian noise, so when the impulsive noise appears, their performances are mainly determined by the impulsive noise. As a result, the performance gain of ML-G in the Gaussian noise is lost.

5.2 ZF Versus ML-G

Fig.2 shows the performances of ZF and ML-G in the alpha stable noise. It can be seen that: ZF performs badly in the impulsive noise. This is because ZF pays much attention to cancel the MAI rather than the noise, so the noise is enlarged during the decorrelation process.

5.3 Cauchy Receiver Versus ML-G

Fig.3 shows the performances of Cauchy Receiver and ML-G in the alpha stable noise. It can be seen that:(1) Cauchy receiver can achieve a significant performance gain over ML-G in the impulsive noise. Even in middle impulsive noise, e.g. $\alpha = 1.5$, at $BER = 3\times10^{-3}$, it has about 5dB performance gain over ML-G. (2) Cauchy receiver seems quite robust in the impulsive noise although it is based on the Cauchy noise ($\alpha = 1.0$). Even in the Gaussian noise, its performance is only a little worse than ML-G, the optimal receiver in this occasion.

5.4 ML-Alpha, Cauchy Receiver Versus ML-G

Fig.4 shows the performances of ML-Alpha, ML-G and Cauchy receiver. It can be seen that: (1) The receivers designed by taking into account the statistical characteristic of the impulsive noise will gain a lot performance gain compared with the receiver designed on the basis of Gaussian noise. For example, ML-Alpha can attain about 6dB performance gain over ML-G at $BER = 3 \times 10^{-3}$ when $\alpha = 1.5$, and 9dB at $BER = 1\times10^{-2}$ when $\alpha = 1.0$. (2) Cauchy receiver is very robust compared to the optimal receiver ML-Alpha. This conclusion accords with the case in the SISO system, where Cauchy receiver is found to perform almost as well as the optimal receiver for a wide range of α [8].

Combining the analysis in section 4 and the simulation results, we deduce that: (1) The performances of conventional receivers of SDMA-based systems designed on the basis of the Gaussian noise are greatly degraded by the impulsive noise. When high impulsive noise appears, the performances of these receivers are degraded to unacceptably low levels. (2) The optimal receiver, ML-Alpha, has the optimal performance in the alpha stable noise, but it is not suitable for practical applications due to its complexity. (3) The ZF receiver can attain little performance gain in impulsive noise. (4) Cauchy receiver has good performance with reasonable computational complexity and is very robust in the $S\alpha S$ noise. So it is a very attractive scheme for SDMA-based system in impulsive noise.

6 Conclusions

In this paper the performance and receiver design in the uplink of SDMA-based wireless systems in impulsive noise are analyzed and discussed. The impulsive noise is modeled as a complex symmetric alpha stable process, which is an extension of Gaussian process and includes the Gaussian process and Cauchy process as the special cases. The optimal ML receiver and several suboptimal receivers,

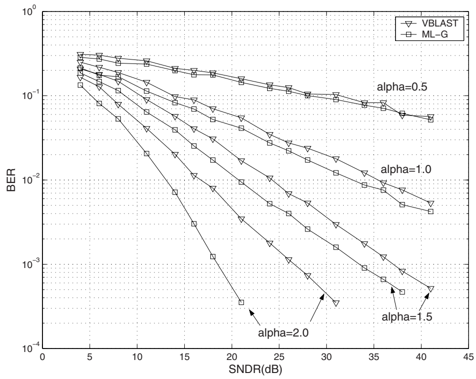

Fig. 1. Performances of VBLAST and ML-G in the impulsive noise

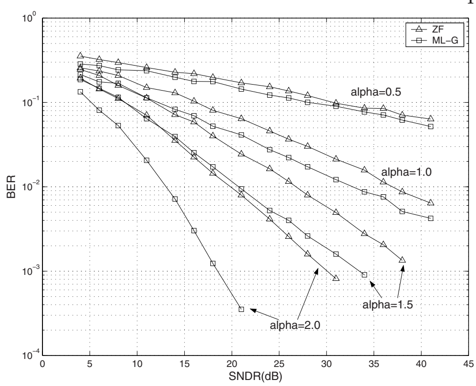

Fig. 2. Performances of ZF and ML-G in the impulsive noise

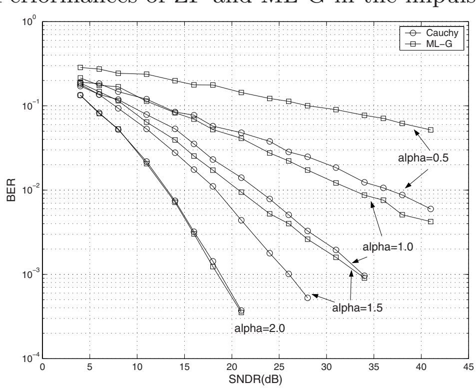

Fig. 3. Performances of Cauchy receiver and ML-G in the impulsive noise

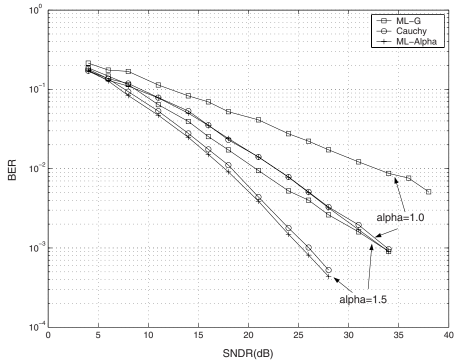

Fig. 4. Performances of ML-Alpha, Cauchy receiver and ML-G in the impulsive noise

such as ZF, ML-G and Cauchy receiver, are proposed. The SER or upper bound of SER is derived for each proposed receiver. Simulation results show the proposed receivers can achieve significant performance gain compared with the conventional detectors of SDMA-based wireless systems.

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