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Performance Analysis of Hybrid Combining Schemes under Middleton Class-A and $S\alpha S$ Impulsive Noise Model

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Abstract: Impulsive noise is a significant concern for Single Input Multiple Output (SIMO) wireless communication systems. This paper evaluates the effectiveness of hybrid combining techniques in mitigating the impact of impulsive noise caused by both man-made and natural phenomena. The Selection combining-Equal Gain Combining (SC-EGC) and Selection Combining-Maximal Ratio Combining (SC-MRC) hybrid techniques are considered in the presence of three different noise models: Additive White Gaussian Noise (AWGN), Middleton Class-A impulsive noise model, and Symmetric Alpha Stable (SαS) impulsive noise model for the Rayleigh and Rician fading channels. Bit Error Rate (BER) is used to assess channel performance. The research contribution of this paper is the comprehensive evaluation of hybrid combining techniques in a set of noise models that can arise in wireless communication systems, including both man-made and natural sources of impulsive noise. The findings suggest that impulsive noise has a greater impact on channel performance than AWGN noise, and hybrid combining techniques are more effective in mitigating its effects. The results have significant research significance and practical implications for SIMO wireless communication systems, and can guide the development of more robust and reliable communication systems in the presence of impulsive noise.

1 Introduction

In a wireless communication system, the transmitted signal undergoes multipath propagation (see Fig. 1) due to reflections, diffractions, and scatterings. This results in the signal suffering from multipath fading, where the wave propagates through different paths with varying lengths, leading to a conflict among the waves and a reduction in signal strength. Along with noise, this distortion in the transmitted signal makes the recovery of the original signal challenging [1, 2]. To tackle this problem, diversity techniques have been widely studied, which use redundant information from multiple received signals. Transmit diversity and receiver diversity are two prominent diversity techniques, where multiple transmitter antennas and single receiver antennas, and multiple receiver antennas and one transmitter antenna, respectively, are used.

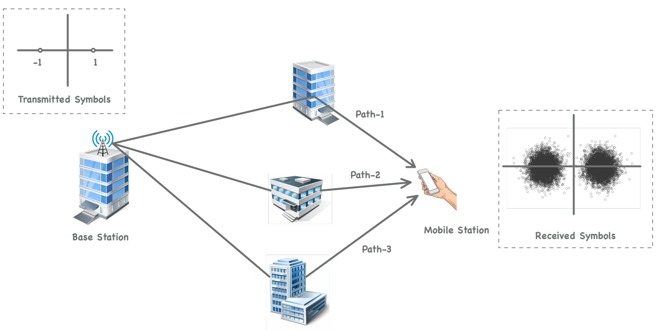


Fig. 1: A typical multipath propagation model

Another technique for minimizing the effect of multipath fading is the best path selection, which depends on the performance of individual paths to enable effective decoding of received signals. The signal-to-noise ratio (SNR) is primarily considered as the performance measure. SNR-based voting and equalized path's SNR are two techniques used for best path selection. The voting technique determines the maximum-SNR based path, whereas the equalization technique maximizes the SNR by weighting the received symbols from different paths.

However, combining diversity and best-path-selection techniques for optimally alleviating the multipath fading effect can be more effective in real-world scenarios (see Sec. 2). Therefore, in this paper, we propose a hybrid model to investigate the effects of multipath fading and impulsive noise on a hybrid combiner receiver. The proposed hybrid combiner incorporates three techniques: selection combining, maximal ratio combining, and equal gain combining. We consider Rayleigh fading for a non-line-of-sight (NLOS) communication channel and Rician fading for a dominant multipath line-of-sight communication channel. In addition, we consider Additive White Gaussian Noise (AWGN) and two variants of impulsive noise models ($S\alpha S$ and Middleton class-A).

To develop the combiner receiver model (see Sec.3), we experimentally verify its effectiveness in tackling the fading and noise effects on wireless communication systems (see Sec.4). Our work addresses the research gap of investigating the performance of a hybrid combiner receiver model that uses a combination of diversity techniques and best path selection for mitigating multipath fading and impulsive noise in wireless communication systems. We evaluate the performance of our proposed model in different communication channel scenarios with varying noise models. Our research contributes by demonstrating the effectiveness of a hybrid combiner receiver in combating fading and noise effects in wireless communication systems, which can help in designing robust communication systems.

2 Related Work

The diversity combining technique is commonly used to improve wireless communication performance by reducing the effects of multipath fading. Hybrid diversity combining, the latest form of wave propagation improvement technique, has been the focus of recent studies aimed at increasing signal output performance. However, the literature has several research gaps, and our work addresses some of these limitations.

For instance, several studies have proposed new hybrid diversity schemes, such as MRC/EGC, which was proposed in [3] and analysed the performance based on the outage probability and Average Bit Error Rate (ABER). Other studies have considered multipath fading and the performance of hybrid diversity schemes with different M-ary modulation schemes. In [4], a better model for multipath fading than the Rayleigh channel was presented using the Nakagami-m channel. Moreover, a new model with SEC/MRC dual hybrid diversity scheme was proposed in [5], which connected branches that were switched according to an adaptive switching threshold to determine whether a dual branch should be combined via MRC in a multi-branch system. Analyzation was also done for an adaptive M-QAM system in [6] for MRC diversity combing under log-normal shadowing and Nakagami-m fading channels. Good performance was achieved due to slow adaptive modulation, which adapts the constellation signal to smooth channel variations.

Other studies have focused on the use of Ultra-wideband Radio for high-rating wireless communication systems, such as the Multi-band Orthogonal Frequency Division Multiplexing UWB system, which was designed to improve performance using linear precoding and multiple antenna techniques [7]. It was found that increasing the amount of outage threshold affects the outage probability of the signal and distorts the system performance of an OFDM UWB signal. In this case, Equal Gain Combining (EGC) gave better BER performance than Maximum Ratio Combining (MRC) [8]. OFDM-based Light Fidelity (LiFi) also provides the opportunity for higher data transmission speeds along with room illumination [9]. BER and SNR analyzation was done for Two-wave with Diffuse Power environment (TWDP) for hybrid diversity models under BPSK and QPSK modulation [10]. Additionally, packets errors due to severe propagation delay and collisions can be mitigated using Multipacket Detection (MPD) and Diversity combining (DC) [11]. A new model, Switching GSC (SGSC), is proposed to combine all the branches that exceed the threshold if the SNR of all branches drops below the threshold value [12].

Besides, impulsive noises, which are categorized as with or without memory in the mainstream, have been causing significant distortions in wireless communication. For instance, the effects of impulsive noise have been studied in terms of their probability distribution of peak amplitude, which was found to be around 918 MHz having 120-150 ns pulse duration [13]. Additionally, the effects of S alpha S noise were observed in the case of Genie-Aided Receiver (GAR) and Linear Matched Filter receiver (LMF), where both proved to obtain a higher diversity order in increasing the number of antennas [14]. However, the literature lacks studies on the performance of hybrid diversity schemes under impulsive noise. Our work fills this gap by investigating the performance of hybrid diversity schemes under impulsive noise and proposing an improved model.

3 Proposed Combiner Receiver Model

The origin of the concept of combining techniques can be traced back to spatial diversity, which comprises two types of techniques, transmit diversity and receive diversity. In this research work, our primary focus is on receive diversity, which involves the use of multiple receiver antennas. The signals received by different antennas are combined using various techniques, resulting in different combining techniques. The three most widely used models for receiver diversity are selection combining, equal gain combining, and maximal ratio combining. In this research work, we investigate the performance improvement that can be achieved by creating a cascaded system through the combination of these models.

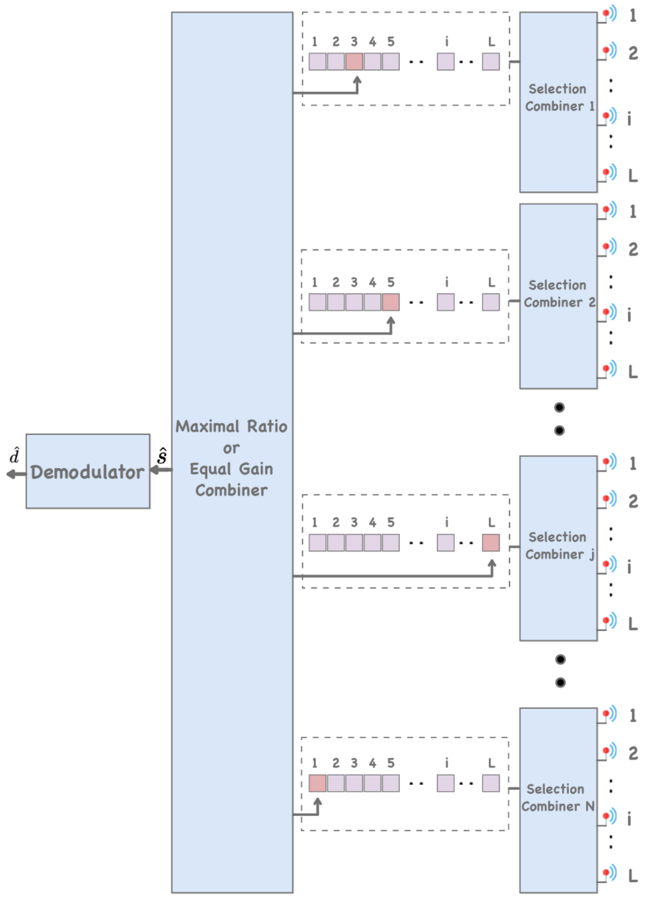


Fig. 2: SC-EGC/ SC-MRC hybrid combining technique for $N \times L$ antennas on receiver module

3.1 Hybrid Combining Techniques

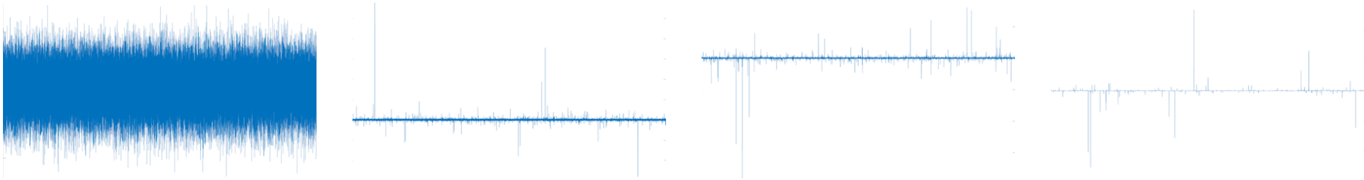
Hybrid combining techniques utilizes features of several combining techniques at once. In our research work, we mainly focus on two hybrid combining techniques. The first one is SC-EGC (Selection Combining-Equal Gain Combining) and the second one is SC-MRC (Selection Combining-Maximal Ratio Combining).

Fig 2 shows a receiver module that uses hybrid combining to exploit spatial diversity. It can be divided into three main stages. In the first stage, there are N selection combiner modules, each of which has L-number of antennas, resulting in a total of $N \times L$ number of antennas. Each selection combiner module selects only one particular branch from the L number of branches. All N selection combiners do the same, resulting in the N number of best-selected paths going into the second stage. In Fig. 2 for the first selection combiner the third branch, for the second selection combiner the fifth branch, for the j^{th} selection combiner L^{th} branch, and for the N^{th} selection combiner the first branch is selected. A simple algorithm for the selection combiner is shown in Algorithm 1 which works for a range of SNR values.

The signals received in these particular branches are sent to the second stage, which is an equal gain combiner or a maximal ratio combiner. The third stage is a demodulator that performs demodulation on the combined signal passed from the second stage. But between SC-EGC and SC-MRC which should be used depends on several factors. Even though SC-MRC should give better performance, it requires perfect channel estimation on $N \times L$ branches.

3.2 Noise Models

Noise in a communication system is usually modelled by using a Gaussian noise model. Although in some cases that might be sufficient, sometimes the presence of interference requires modification



(a) $\alpha = 2$ (b) $\alpha = 1.8$ (c) $\alpha = 1.5$ (d) $\alpha = 1$

Fig. 3: Symmetric alpha stable distribution for different values of α

Algorithm 1 Selection Combiner Algorithm

```
Bits ← 10^5                              ▷ Number of bits to be transmitted
P ← rand(1, Bits) > 0.5                  ▷ Generate random bitstream
S ← 2 × P − 1                            ▷ Constellation Mapping
nRx ← L                                  ▷ No. of Rx antennas per SC module
SC ← N                                   ▷ No. of SC modules
SNR_range ← 0 : 35
for all k = 0 : length(SNR_range) do
    for all t = 1 : SC do
        a, b ← randn(nRx, Bits)
        h(:,:,t) ← (1/√2)(a + jb)        ▷ Fading Channel
    end for
    hPower ← h ⊙ conj(h)
    [hmax, ind] ← max(hPower, [ ], 1)
    hMat ← repmat(hmax, nRx, 1)
    hSel ← h(hPower == hMat)
    pmat(k,:) ← transpose(hSel)
end for
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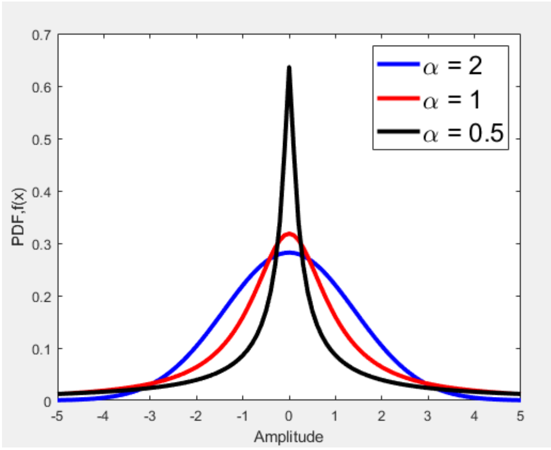

Fig. 4: Symmetric alpha stable distribution for different values of α

in the noise model. Impulsive noise is one of those cases where in addition to thermal noise from transmitter-receiver and background noise, there is also the presence of interference both man-made and natural. Different statistical models are required to model such impulsive behaviour in noise. Gaussian noise distribution usually has fatter tails, whereas impulsive noise has much thinner tails. Moreover, the impulsive noise model distribution has a sharper peak compared to the Gaussian distribution, which results in a sudden sharp spike in impulsive noise.

3.2.1 Symmetric Alpha Stable Distribution Noise: Symmetric Alpha Stable, also known as $S\alpha S$ noise model, is one of the widely used models for modelling impulsive noise.

$$f_S(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \varphi(t)e^{-ixt}dt \tag{1}$$

The probability density function of $S\alpha S$ distribution is shown in equation (1) which is the inverse Fourier transform of the characteristics equation given by equation (2).

$$\varphi(t;\alpha,\beta,c,\mu) = \exp\left(it\mu - |ct|^{\alpha}(1 - i\beta\,\mathrm{sgn}(t)\Phi)\right) \tag{2}$$

In the expression shown in equation (2) Φ can be expanded further as shown in equation (3).

Table 1 $S\alpha S$ Distribution Parameters

Parameters	Symbol	Values
Characteristic exponent	α	$\alpha \in]0,2]$
Scale parameter	γ	$\gamma > 0$
Location parameter	δ	$\delta \in]-\infty,+\infty[$
The symmetry parameter	β	$\beta \in [-1,1]$

$$\Phi = \begin{cases} \tan\left(\frac{\pi\alpha}{2}\right) & \alpha \neq 1 \\ -\frac{2}{\pi}\log|ct| & \alpha = 1 \end{cases} \tag{3}$$

The parameters used in the equation are summarized in Table 1 along with their theoretical bounds. All these parameters describe the distribution shape.

β is the symmetry parameter, represents skewness of the distribution, where -1$\leq \beta \leq$1.

α is the characteristic exponent and is a measure of the 'thickness' of the tail of the distribution.

δ is the localization parameter. It is the mean when $1 \leq \alpha \leq 2$ and the median when $0 \leq \alpha \leq 1$.

γ is the scale parameter or dispersion and is similar to the variance of the Gaussian distribution, where $\gamma \geq 0$ in general.

Even though all these parameters can be used to fine-tune the distribution shape, actually in most cases changing the value of α is sufficient. Fig 3 shows how the amount 'impulsiveness' changes with change in the value of α. In the upper bound, for $\alpha = 2$, it is almost Gaussian in nature. For a decrease in the value of α the noise becomes more impulsive. But using a tiny value of α to model noise is impractical because there is always a Gaussian noise present in the background. Fig 3 shows the effect of change in α and how it can be used to control the amount of 'impulsiveness'.

The noise samples are generated by sampling from the symmetric alpha stable distribution. Fig 4 shows the symmetric alpha stable distribution for different values of α. It is also apparent from the figure that for $\alpha = 2$ the distribution is nearly Gaussian and the more it deviates from $\alpha = 2$ and tends to $\alpha = 0$ the more impulsive it becomes.

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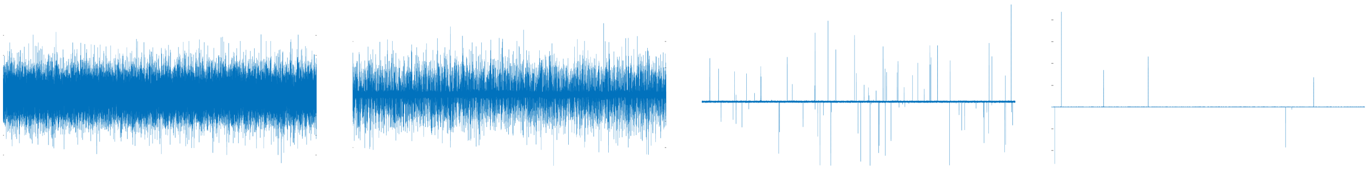
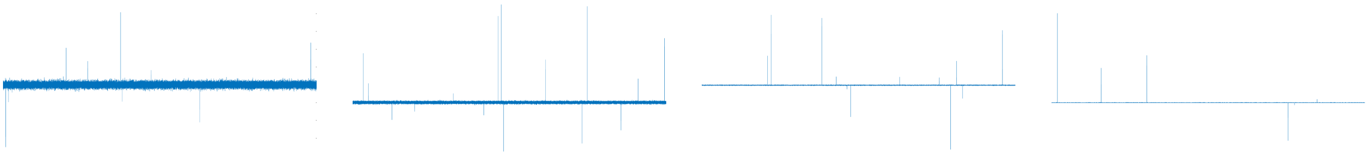
3.2.2 Middleton Class-A Noise: Middleton Class-A noise model is another prominent noise model for modelling impulsive noise, which is used in numerous pieces of literature.

The noise model can be described totally by two parameters A (Impulsive factor) and Γ (Gaussian noise factor).



(a) $A = 1$ (b) $A = 0.1$ (c) $A = 0.001$ (d) $A = 0.0001$

Fig. 5: Middleton class-A noise for different values of A (impulsive factor) with fixed $\Gamma = 0.1$



(a) $\Gamma = 10$ (b) $\Gamma = 1$ (c) $\Gamma = 0.1$ (d) $\Gamma = 0.01$

Fig. 6: Middleton class-A noise for different values of Γ(Gaussian noise factor) with fixed $A = 10^{-4}$

By controlling the value of these two parameters, the shape of the distribution and behaviour of the noise model can be changed.

$$f_M(x) = e^{-A} \sum_{q=0}^{\infty} \frac{A^q}{q! \sqrt{2\pi\sigma_q^2}} e^{-\frac{x^2}{2\sigma_q^2}} \tag{4}$$

The probability density function(PDF) of the Middleton Class-A noise model is given by the (4) where the parameter σ_q^2 is given by equation (6).

$$\Gamma = \frac{\sigma_G^2}{\sigma_I^2} \tag{5}$$

The parameter Γ can be further expanded to the equation shown in (5).

$$\sigma_q^2 = \frac{\frac{q}{A} + \Gamma}{1 + \Gamma} \tag{6}$$

The Gaussian factor Γ represents the ratio of the power of AWGN, denoted by σ_G^2, to the power of impulsive noise, denoted by σ_I^2 [**?**]. Intuitively, a higher value of Γ indicates a greater presence of Gaussian noise compared to impulsive noise, and vice versa. Similarly, the behaviour of impulsive noise varies with changes in the parameter A, as shown in Fig.5. The value of Γ is fixed at 0.1 while varying the value of A. On the other hand, Fig.6 illustrates the change in impulsive behaviour when Γ is varied, while the value of A is kept fixed at 10^{-4}. However, extreme values of Γ and A are impractical; rather, some intermediate value is feasible, as is the case with the symmetric alpha-stable noise model. Fig. 7 presents two different sets of probability density functions for the Middleton Class-A noise model, which validate the interpretations mentioned above concerning the values of A and Γ.

4 Results and Analysis

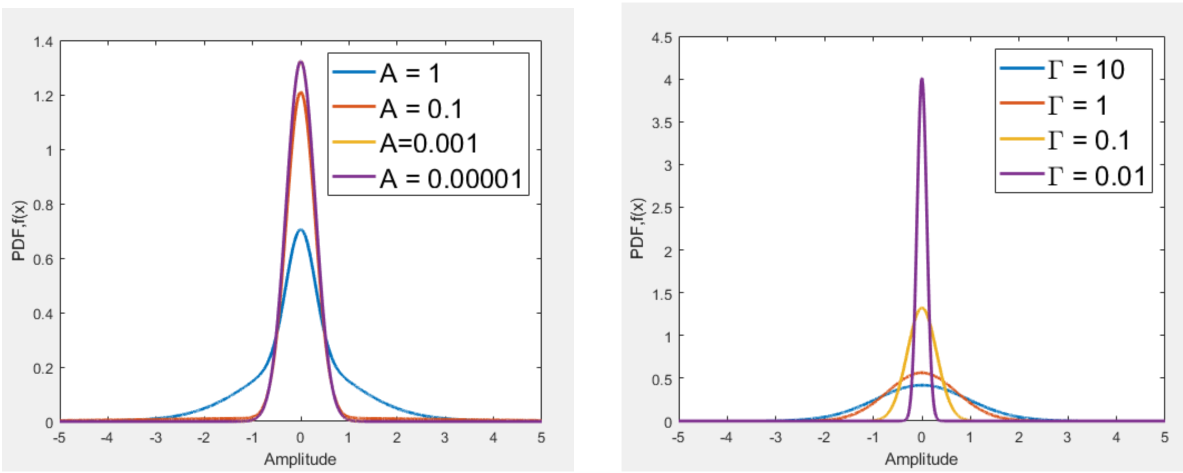
Performance of the hybrid combining techniques is first analysed. Fig. 8 shows the constellation diagram of MRC, SC and EGC for $L = 4$ number of receiver antennas under the Rayleigh and Rician fading channels. It is obvious that with hard decision, some bits will be interpreted as erroneous bits as the spread of the symbols crosses the decision boundary. We also observed that the SC-MRC hybrid combining technique with same number of antennas clearly distinguishes the decision boundaries of the spread of symbols. This proves the superiority in the performance of the hybrid combining technique.

Among SC-ECG and SC-MRC hybrid combining techniques, SC-MRC has better performance. From Fig 9a, it is apparent that for a given SNR value, SC-MRC hybrid combining technique has a better performance compared to the SC-EGC hybrid combining technique. But as mentioned before, there is a trade-off between the performance increase and the complexity of the system. SC-MRC scheme requires perfect Channel State Information(CSI) at the receiver end, which might not be feasible depending on a variety of other factors. Fig 9a shows how the performance changes with an increase in number of antennas per SC module for a fixed number of SC modules $N = 2$. With increase in number of antennas per SC module, the performance increases significantly as expected. We did some trial and error simulation for different combinations of SC module and number of antennas per SC module, for all of them, this trend retained. The simulation was done for a Rayleigh fading channel, which again done for Rician fading channel as shown in Fig 9b.

All the statement for Rayleigh fading channel holds for Rician fading channel as well. The result is almost similar with a slight deviation. For Rician fading channel, the K factor should also be considered. It should be mentioned that, for our simulation, we decided to use $K = 3$ empirically. Table 2 summarizes the numerical quantities found for different combining scheme. The combining schemes are arranged in an ordered sequence, which makes it apparent that to achieve the same BER, selection combining technique requires the least SNR and SC-MRC requires the most SNR. Another important thing to note here is, Rician fading is slightly more robust than Rayleigh fading as SNR requirement is less for Rician compared to Rayleigh fading channel and this is true for all the combining schemes.

Table 2 Comparison between diversity combining schemes

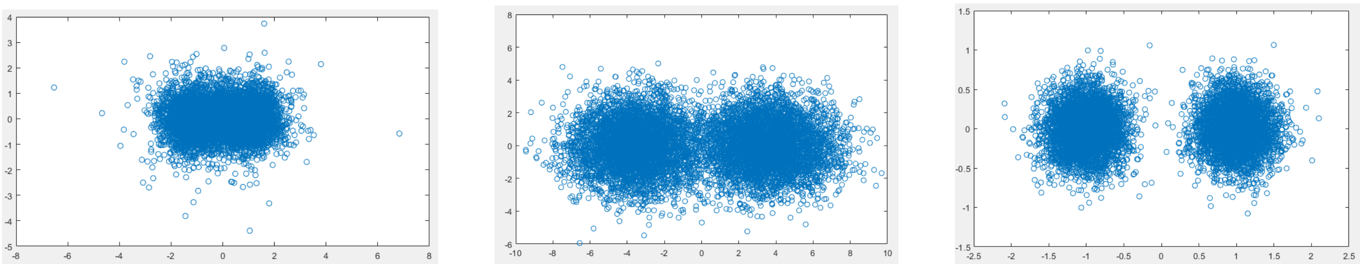
Combiner	**SC**	**EGC**	**MRC**	**SC-EGC**	**SC-MRC**
Modulation	BPSK	BPSK	BPSK	BPSK	BPSK
Tx module	1	1	1	1	1
Rx module	1	1	1	2	2
Rx antenna	4	4	4	4	4
BER (Rayleigh)	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
SNR (Rayleigh)	14.614	12.185	11.205	9.615	9.443
BER (Rician, K=3)	10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
SNR (Rician, K=3)	13.369	11.912	10.782	9.582	9.433



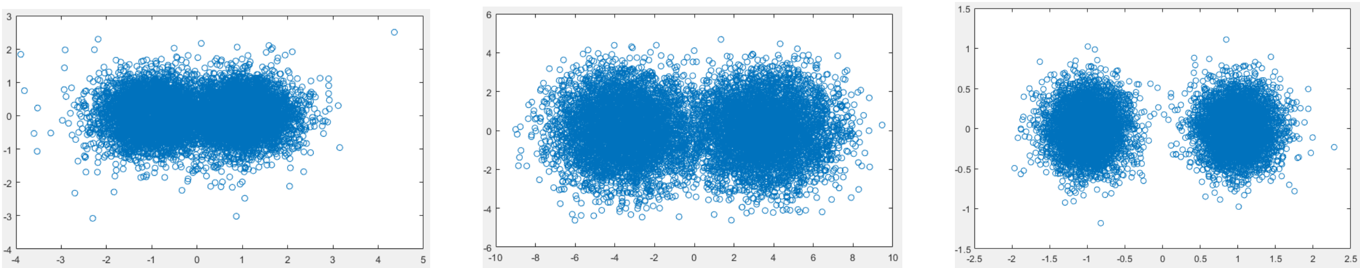
(a) Different values of A

(b) Different values of Γ

Fig. 7: Middleton class-A probability density functions



(a) (b) (c)



(d) (e) (f)

Fig. 8: Constellation diagrams of (a–c) Rayleigh and (d–e) Rician fading channels with L=4 at low SNR for different combining techniques: (a, d) SC, (b, e) SC-EGC, and (c,f) SC-MRC

From the above-mentioned analysis, it can be concluded that SC-ECG is favourable for practical application as its performance is almost close to SC-MRC and also because of its less complexity.

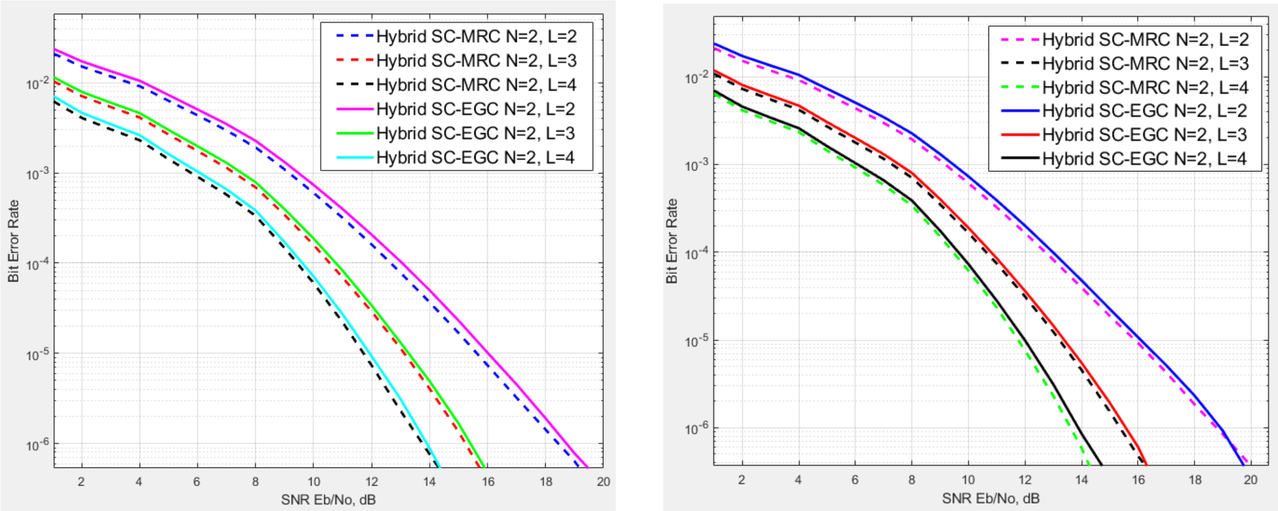
Fig 10a shows the change in BER for the SC-ECG scheme for varying the number of receiving antennas, where the number of antennas is decided empirically. The pattern is apparent from the figure, which is as predicted. With an increase in number of receiving antennas, the BER increases for a given SNR. The same pattern holds true for Fig 10b which shows an SC-MRC receiver combining scheme. But increasing the number of antennas without any limit is unreasonable, as there is possibility for interference between antennas. For a few numbers of antennas this interference might go unnoticed, but if the number of antennas crosses a certain threshold this will severely degrade the performance of the system.

Now we analyse the effect of impulsive noise in the developed hybrid combining system. Fig 11 shows the BER vs $\frac{E_b}{N_o}$ curve for a range of 0 to 35 dB.This range was decided empirically and reflects the real-world scenario. The AWGN noise performance is used as a reference to compare the other two impulsive noise models. For all the plots, it is obvious that the system has better BER performance for AWGN noise.

Table 3 SNR gain for constant BER 10^{-3}

Noise Model	MRC	EGC	SC	SC-MRC	SC-EGC
AWGN	6	8	9	6	6
Class-A (A= 10^{-3}, Γ =5)	6	8	11	7	8
SαS (α =1.9)	14	16	17	23	24

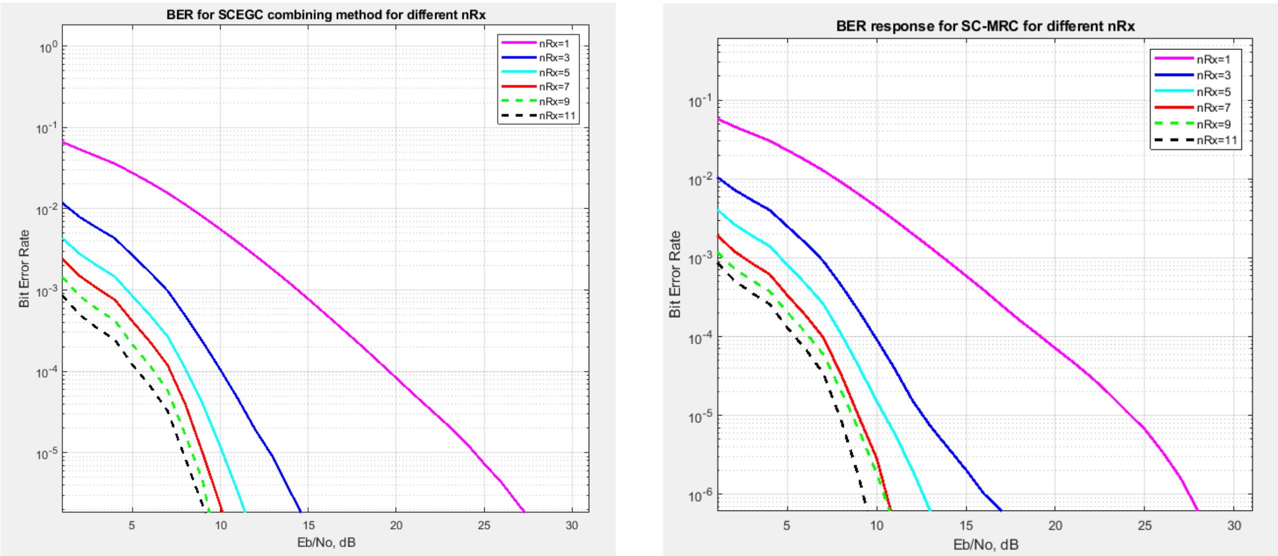
After that, Middleton Class-A noise and the worst performance is shown by SαS model. This corroborates with the theoretical intuition developed in the earlier sections. Among the combining techniques, selection combining scheme shows the worst performance. Subsequently, ECG and MRC show almost similar performance



(a) Rayleigh fading channel

(b) Rician fading channel

Fig. 9: BER vs SNR Performance comparison between SC-MRC and SC-EGC with AWGN



(a) SC-EGC

(b) SC-MRC

Fig. 10: BER of different number of receiver antennas for hybrid combining techniques

while maintaining the sequence for noise distortion. The better performance is shown by the hybrid combining techniques. To get a better understanding, SNR gain for the BER of 10^{-3} is shown in Table 3. The reason for the improved performance of hybrid combining techniques is that in the first stage, each selection combiner chooses the best path. The best path chosen for each selection combiner is fed to the next stage. In the case of other vanilla combining techniques, it cannot be made sure that the receiver branches will have the best SNR. Due to this reason, the second stage in the hybrid combining technique can fully utilize the spatial diversity gained for multiple receiver antennas.

5 Conclusion

In conclusion, this paper has evaluated the effectiveness of hybrid combining techniques in mitigating the impact of impulsive noise on SIMO wireless communication systems. The study considered three different noise models and evaluated channel performance using BER as the assessment metric. The findings suggest that impulsive noise has a greater impact on channel performance than AWGN noise, and hybrid combining techniques are more effective in mitigating its effects. The comprehensive evaluation of hybrid combining techniques in a set of noise models that can arise in wireless communication systems, including both man-made and natural sources of impulsive noise, is a significant research contribution of this paper. The results have practical implications for the development of more robust and reliable communication systems in the presence of impulsive noise, and can guide future research in this field. The research methodology used in this paper, including the observation of noise PDF and signal, can serve as a foundation for further research in this area. Overall, this paper provides valuable insights into the mitigation of impulsive noise in SIMO wireless communication systems.

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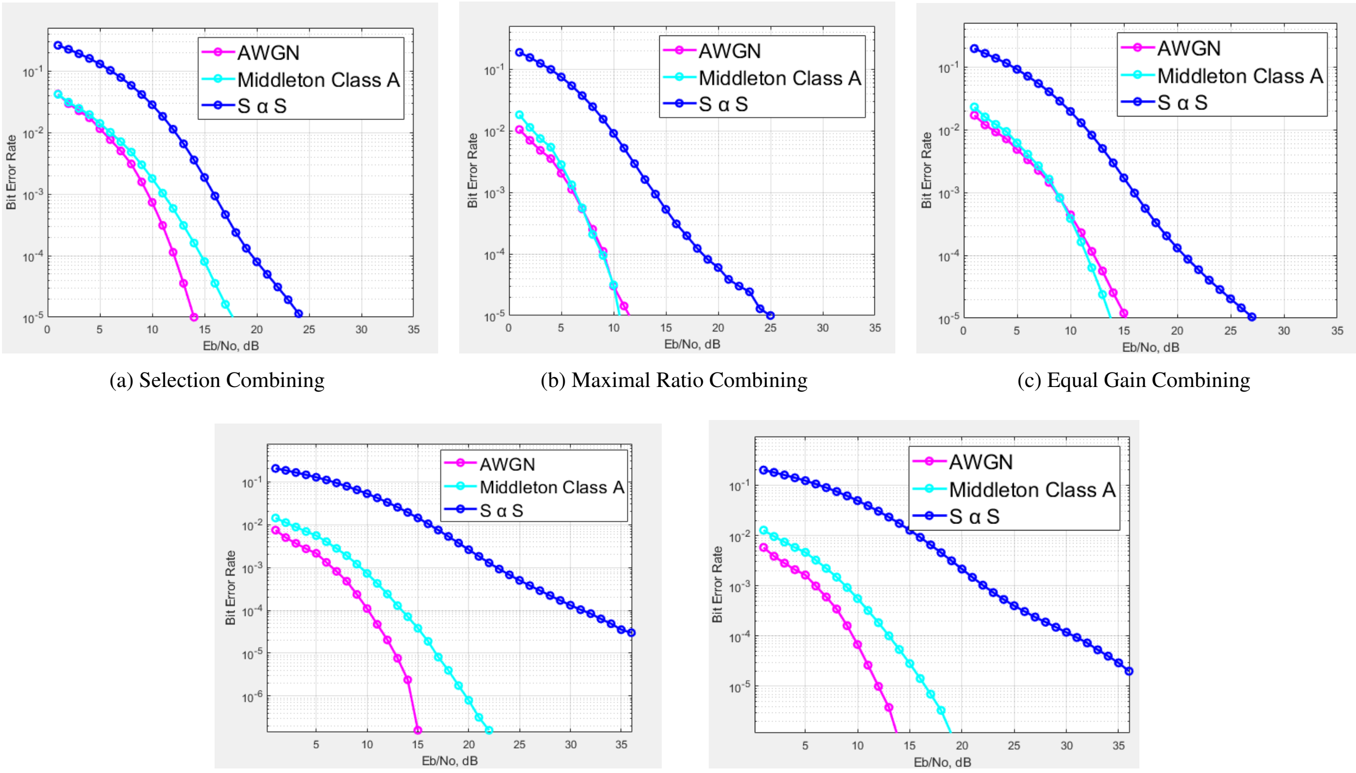

(a) Selection Combining (b) Maximal Ratio Combining (c) Equal Gain Combining

(d) SC-EGC Scheme (e) SC-MRC Scheme

Fig. 11: Bit Error Rate response for combining schemes in Rayleigh channel under various noise model

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