

An Adaptive Joint Filtering Approach to Wireless Relay Network for Transmission Rate Maximization

Mr. Nitin Madhukar Tambe*, Prof. A. S. Mali

PG Student, Department of E & TC, Tatyasaheb Kore Institute of Engg. & Technology Warananagar, India

Professor, Department of E & TC, Tatyasaheb Kore Institute of Engg. & Technology Warananagar, India

DOI: <https://dx.doi.org/10.51244/IJRSI.2025.1210000079>

Received: 02 October 2025; Accepted: 08 October 2025; Published: 04 November 2025

ABSTRACT

This paper presents the design, implementation, and performance evaluation of an Adaptive Joint SCAMP Filter and Relay Weight Optimization Scheme for a wireless Amplify-and-Forward (AF) cooperative relay network operating over frequency-selective fading channels. Conventional AF systems suffer from compounded noise and Inter-Symbol Interference (ISI) due to cascaded multi-tap channel effects. To address these limitations, this work employs a Joint Adaptive Filtering approach that simultaneously optimizes the source pre-coding filter and the relay amplification weight to minimize the end-to-end Mean Squared Error (MSE) and enhance the achievable data rate.

The joint optimization problem is solved using the Projected Subgradient Method (PSGM), which provides robustness against non-linear constraints such as sparsity while maintaining low computational complexity. The algorithm is implemented and tested in a MATLAB simulation environment under a time-varying Auto-Regressive (AR(1)) fading model. Key performance metrics such as MSE convergence, filter characteristics, achievable rate, and robustness to parameter variations are analyzed.

Simulation results demonstrate that the proposed adaptive joint scheme achieves 25–33% higher achievable rate than the conventional Fixed AF Relay and nearly double the throughput of a Direct Link transmission. The results validate that adaptive joint filtering provides superior spectral efficiency, improved ISI mitigation, and stable convergence, making it a practical and scalable solution for next-generation cooperative communication systems.

Keywords: Adaptive Filtering, Cooperative Communication, Amplify-and-Forward (AF) Relay, SCAMP Filter, Projected Subgradient Method (PSGM), Joint Optimization, Mean Squared Error (MSE), Frequency-Selective Fading, Achievable Rate, MATLAB Simulation, Wireless Relay Networks, Joint Signal Processing

INTRODUCTION

The rapid evolution of wireless communication systems has driven the continuous demand for higher data rates, wider coverage, and improved reliability. However, traditional single-link transmission systems face critical limitations such as path loss, shadowing, and multipath fading, particularly in dense or obstructed environments. To overcome these challenges, Cooperative Communication has emerged as an effective paradigm, allowing intermediate nodes, known as relays, to assist in the transmission process between a source (S) and a destination (D).

Among various cooperative protocols, the Amplify-and-Forward (AF) strategy has gained prominence due to its simplicity and low processing complexity. In this scheme, the relay node amplifies the received signal and forwards it without decoding, thereby extending coverage and improving link reliability. Despite these advantages, AF systems are prone to noise amplification and Inter-Symbol Interference (ISI) accumulation, particularly in multi-tap frequency-selective fading channels, which significantly degrade performance.

To mitigate these effects, advanced signal processing techniques such as adaptive filtering and joint optimization have become crucial. Conventional methods often optimize the source filter and relay amplification gain separately, leading to sub-optimal system performance. In contrast, Joint Adaptive Optimization enables simultaneous adjustment of both parameters, effectively minimizing the end-to-end Mean Squared Error (MSE) and maximizing the achievable rate.

This research introduces an Adaptive Joint SCAMP (Sparse Channel Adaptive Monitoring and Processing) Filter and Relay Weight Optimization framework utilizing the Projected Subgradient Method (PSGM). The PSGM provides robustness against non-linear constraints such as sparsity while maintaining real-time adaptability to channel variations. Through MATLAB-based simulations, the system's performance is evaluated in terms of convergence, spectral efficiency, and robustness under dynamic Auto-Regressive (AR(1)) fading conditions.

The results demonstrate that the proposed joint adaptive scheme significantly enhances the achievable data rate compared to both the Direct Link and Fixed AF Relay systems, offering a 25–33% improvement in throughput and effective ISI mitigation. Hence, this work contributes a low-complexity, high-performance adaptive approach suitable for modern and future-generation wireless networks, including 5G and beyond. The methodology is implemented and evaluated through MATLAB simulations under an Auto-Regressive (AR(1)) fading model, which represents realistic slow-varying wireless channels. The analysis includes four key objectives:

1. Validating convergence and stability of the adaptive joint algorithm.
2. Characterizing the SCAMP filter in both time and frequency domains.
3. Investigating the effect of filter length on system performance and achievable rate.
4. Benchmarking the proposed approach against conventional Direct Link and Fixed AF Relay systems.

The simulation results confirm that the proposed Adaptive Joint SCAMP Filter and Relay Weight Optimization Scheme achieves substantial performance gains. Specifically, the system exhibits faster convergence, better ISI mitigation, and significant spectral efficiency improvement—achieving up to 33% higher achievable rate compared to the fixed AF relay configuration. These results demonstrate the feasibility and practical advantages of joint adaptive filtering for next-generation wireless systems such as 5G, 6G, and Internet of Things (IoT) networks, where real-time adaptability and energy-efficient communication are crucial.

METHODOLOGY

This methodology details the mathematical framework and the step-by-step implementation of the Adaptive Joint SCAMP Filter and Relay Weight Optimization. It provides the necessary derivations for the instantaneous gradient used by the adaptive algorithm and outlines the specific simulation environment and parameters.

Detailed System Model and Signal Flow

We revisit the baseband discrete-time cooperative system introduced in Chapter 3, consisting of the source (S), the Amplify-and-Forward (AF) relay (R), and the destination (D). The overall transmission is asynchronous, but the mathematical model focuses on the time-domain processing at symbol time k .

Source-to-Destination Links

The input data vector to the SCAMP filter at time k is $s[k] \in \mathbb{C}^{L \times 1}$, and the SCAMP filter coefficient vector is $w_{\text{SCAMP}}[k] \in \mathbb{C}^{L \times 1}$. The pre-coded signal transmitted by the source is a scalar:

$$x[k] = w_{\text{SCAMP}}^H[k]s[k]$$

The channel impulse response vectors are defined as $h_{\text{SD}}, h_{\text{SR}}, h_{\text{RD}}$. Let N_h denote the length of the channel impulse response (assumed equal for all links, $L_{\text{SD}} = L_{\text{SR}} = L_{\text{RD}} = N_h$).

Signal at the Relay

The signal received at the relay $y_R[k]$ is the convolution of the transmitted signal $x[k]$ with the channel h_{SR} , plus noise

$$n_{SR}[k]: y_R[k] = \sum_{m=0}^{N_h-1} h_{SR}[m]x[k-m] + n_{SR}[k]$$

The relay amplifies $y_R[k]$ by the complex weight $w_{\text{relay}}[k]$ and forwards the resulting signal $r[k]$: $r[k] = w_{\text{relay}}[k]y_R[k]$

End-to-End Received Signal

The destination receives the sum of the direct link component and the relayed component. The total received signal at the destination $y_D[k]$ is:

$$y_D[k] = \underbrace{\sum_{m=0}^{N_h-1} h_{SD}[m]x[k-m]}_{\text{Direct Component}} + \underbrace{\sum_{l=0}^{N_h-1} h_{RD}[l]r[k-l]}_{\text{Relayed Component}} + n_D[k]$$

Substituting the relay signal $r[k-l]$ from (4.3) into (4.4) yields the full expression for the received signal $y_D[k]$ as a complex function of the adaptive parameters $W = [w_{\text{SCAMP}}^T, w_{\text{relay}}]^T$.

The Adaptive Optimization Algorithm

The core objective is to minimize the instantaneous squared error $J_{\text{inst}}[k] = |e[k]|^2 = |d[k] - y_D[k]|^2$, where $d[k] = s[k]$ is the desired symbol. The minimization is performed using the complex Projected Subgradient Method (PSGM).

Instantaneous Error and Gradient Derivation

The error is $e[k] = d[k] - y_D[k]$. For any complex adaptive parameter θ , the complex gradient update rule is: $\theta[k+1] = \theta[k] + \mu e^*[k] \frac{\partial y_D[k]}{\partial \theta}$. We must derive the gradient components for the two adaptive parameter sets: w_{SCAMP} and w_{relay} .

Gradient with Respect to the SCAMP Filter w_{SCAMP}

Since $x[t] = w_{\text{SCAMP}}^H[t]s[t]$, the partial derivative $\frac{\partial x[t]}{\partial w_{\text{SCAMP}}^H}$ is $s[t]$. Assuming the filter coefficients are fixed during the symbol period, the partial derivative $\frac{\partial y_D[k]}{\partial w_{\text{SCAMP}}^H}$ is the complex input vector required for the SCAMP filter update. This vector, denoted $P_w[k]$, consists of the total contribution of the source signal components to the destination, multiplied by the channel and gain factors.

$$P_w[k] = \sum_{m=0}^{N_h-1} h_{SD}[m]s[k-m] + \sum_{l=0}^{N_h-1} h_{RD}[l]w_{\text{relay}}[k-l] \left(\sum_{m'=0}^{N_h-1} h_{SR}[m']s[k-l-m'] \right)$$

The update for the SCAMP filter is: $w_{\text{SCAMP}}[k+1] = w_{\text{SCAMP}}[k] + \mu \cdot e^*[k] \cdot P_w[k]$

The partial derivative $\frac{\partial y_D[k]}{\partial w_{\text{relay}}}$ is the signal component that is directly affected by the relay gain. Assuming the relay gain w_{relay} is adapted slower than the symbol rate

$$(w_{\text{relay}}[k-l] \approx w_{\text{relay}}[k]): \frac{\partial y_D[k]}{\partial w_{\text{relay}}} = \sum_{l=0}^{N_h-1} h_{\text{RD}}[l] y_R[k-l]$$

The relay term required for the update, $P_{w_{\text{relay}}}[k]$, is the output of the R-D channel when the input is the received relay signal

$$y_R[k]: P_{w_{\text{relay}}}[k] = \sum_{l=0}^{N_h-1} h_{\text{RD}}[l] y_R[k-l]$$

The update for the relay weight is: $w_{\text{relay}}[k+1] = w_{\text{relay}}[k] + \mu \cdot e^*[k] \cdot P_{w_{\text{relay}}}[k]$

The Projection Operator

The PSGM incorporates a projection operator $\mathcal{P}\{\cdot\}$ applied to the filter coefficients $w_{\text{SCAMP}}[k+1]$ immediately after the gradient descent step. This is necessary to enforce constraints, particularly the sparsity constraint. In this project, the constraint is the ℓ_1 -norm sparsity, which is enforced via the soft-thresholding function:

$$\mathcal{P}\{w_i\} = \text{sign}(w_i) \cdot \max(|w_i| - \lambda_{\text{proj}}, 0)$$

where λ_{proj} is the sparsity penalty constant. For the primary simulation focusing on joint convergence (Objective 1), λ_{proj} is set to zero, simplifying $\mathcal{P}\{\cdot\}$ to the identity operation and transforming the PSGM into a standard Joint Stochastic Gradient Descent (JSGD) algorithm.

Simulation Environment and Parameter Setup

The methodology is realized through a baseband MATLAB simulation environment.

Channel Modeling (Time-Varying Fading)

The time-varying nature of the channel impulse response $h[k]$ is modeled using a first-order Auto-Regressive process (AR(1)):

$$h[k] = \alpha h[k-1] + \sqrt{1 - \alpha^2} v[k]$$

where: $h[k]$ represents any of the channel vectors ($h_{\text{SD}}, h_{\text{SR}}, h_{\text{RD}}$). $\alpha = 0.999$ is the correlation factor, chosen to simulate slow, highly correlated Rayleigh fading, typical of low-mobility indoor scenarios. $v[k]$ is a vector of i.i.d. complex Gaussian random variables, ensuring that the channel power remains constant and $h[k]$ remains a Rayleigh fading process. For all simulations: Channel length $N_h = 4$. Noise variances (σ_n^2) are normalized based on the desired signal-to-noise ratio (SNR) at the source-relay and relay-destination links.

For all simulations:

Channel length $N_h = 4$

Noise variances (σ_n^2) are normalized based on the desired signal-to-noise ratio (SNR) at the source-relay and relay-destination links.

System Parameters and Initialization

Parameter	Symbol	Value / Description	Notes
Modulation	QAM	4-QAM (QPSK)	Provides complex i.i.d. data symbols $s[k]$
Symbol Power	P_s	1.0	Normalized source transmit power.

Filter Length	\$L\$	Varies (typically \$L=16\$)	Central parameter for Objective 3 analysis.
Learning Rate	μ	5×10^{-4}	Determined empirically for optimal trade-off between convergence speed and steady-state error.
Total Iterations	N_{total}	10^5	Sufficient length for the adaptive filter to converge and reach steady-state in the chosen fading rate.
Nominal SNR	SNR_{dB}	15 dB	Assumed SNR for S-R and R-D links.
Initialization	W_{init}	$w_{\text{SCAMP}} = 0, w_{\text{relay}} = 0$	Zero initialization to test robust convergence.

Performance Metrics

Mean Squared Error (MSE)

The instantaneous MSE is $J_{\text{inst}}[k]$. For plotting the convergence trajectory (Objective 1), the MSE is smoothed using an exponentially weighted moving average filter:

$$\text{MSE}_{\text{smooth}}[k] = \beta \cdot \text{MSE}_{\text{smooth}}[k-1] + (1 - \beta) \cdot J_{\text{inst}}[k]$$

where β is the smoothing factor (e.g., 0.99 to 0.999). The steady-state MSE (E_{MSE}) is the average value over the final 10% of iterations.

Achievable Rate (bits/s/Hz)

The achievable rate R (equivalent to channel capacity under the assumption of perfect MMSE reception) is calculated from the steady-state MSE. The effective Signal-to-Interference-plus-Noise Ratio (SINR) is determined by the ratio of the desired signal power to the residual error power: $\text{SINR}_{\text{eff}} \approx \frac{P_s}{E_{\text{MSE}}}$

The achievable rate is then computed using the Shannon formula:

$$R = \log_2(1 + \text{SINR}_{\text{eff}})$$

Simulation Flow Chart and Execution

The simulation is a single, large iterative loop, which is represented by the following high-level flow chart:

Flow Chart Diagram

The process integrates the physical layer signal propagation with the adaptive signal processing loop.

Start / Initialization: Start / Initialization: Define all system constants (μ, L, N_{total}). Initialize adaptive parameters W and all three channel vectors $h_{\text{SD}}, h_{\text{SR}}, h_{\text{RD}}$.

Adaptive Loop ($k = 1$ to N_{total}):

a. ($k = 1$ to N_{total}): a. Data & Pre-coding: Generate $s[k]$; form $s[k]$; calculate transmitted signal $x[k] = w_{\text{SCAMP}}[k]s[k]$.

b. Channel Propagation: Compute $y_R[k]$ (relay received signal) and $y_D[k]$ (destination received signal) using the current w_{relay} and the channel states.

- c. Error Calculation: Compute $e[k]=s[k]-y_D[k]$. Store $e[k]$ for MSE calculation.
- d. Gradient Calculation: Compute the instantaneous gradient components $P_w[k]$ and $P_{w_{\text{relay}}}[k]$
- e. Parameter Update (PSGM): Update $w_{\text{SCAMP}}[k+1]$ and $w_{\text{relay}}[k+1]$ using the adaptive rules
- f. Projection: Apply soft-thresholding $P\{\cdot\}$ to w_{SCAMP} (if $\lambda_{\text{proj}}=0$).
- g. Channel Fading: Update the three channel vectors $h[k+1]$ using the AR(1) fading model (4.10).

End / Post-Processing: Calculate smoothed MSE, steady-state E_{MSE} , and Achievable Rate R . Extract the final converged filter parameters for Objective 2.

Baseline Scheme Execution

The execution for the baseline schemes (Objective 4) follows the same flow, with minor modifications:

Direct Link Baseline: The total received signal $y_D[k]$ only includes the direct component; w_{relay} and the relay path are ignored. The SCAMP filter w_{SCAMP} is still adapted to equalize the h_{SD} channel only.

Fixed AF Relay Baseline: The w_{relay} parameter is fixed at a non-optimized, constant value for the entire simulation run. Only the w_{SCAMP} coefficients are adapted using the gradient $P_w[k]$ derived from the full end-to-end signal $y_D[k]$.

This rigorous methodology ensures that the simulation results are directly comparable, allowing for a clear and quantitative assessment of the proposed joint adaptive solution.

RESULT ANALYSIS

The first objective is to demonstrate the stability and convergence of the proposed Joint Stochastic Gradient Descent (JSGD) algorithm in a time-varying, frequency-selective cooperative channel environment.

MSE Convergence Trajectory

The Mean Squared Error (MSE) convergence curve is the primary indicator of the algorithm's stability and ability to adapt. The simulation was run for 10^5 symbols at a nominal Signal-to-Noise Ratio (SNR) of 15 dB, with the SCAMP filter length $L = 16$. The learning rate μ was set to 5×10^{-4} to ensure a stable, yet relatively fast, convergence. The MSE convergence trajectory, smoothed using an exponential weighting function, exhibits the classic behavior of a stochastic gradient algorithm: Initial Adaptation (Transient Phase):

For the first $\approx 5,000$ iterations, the MSE drops rapidly from the initial high value (corresponding to the un-equalized and un-amplified signal) as the filter coefficients (w_{SCAMP}) and the relay weight (w_{relay}) quickly move towards the optimal Wiener solution. **Tracking Phase:** After the initial transient, the MSE enters the steady-state regime, fluctuating around a low, constant value. This fluctuation is characteristic of the JSGD, where the instantaneous gradient is noisy. The small, persistent fluctuations in the steady-state also confirm that the algorithm is actively tracking the time-varying optimal solution as the channel coefficients fade according to the AR(1) model. The final Steady-State MSE (E_{MSE}) is measured by averaging the MSE over the last 10,000 iterations, yielding a value of approximately 1.15×10^{-2} .

Convergence of Joint Adaptive Parameters

To confirm the joint nature of the optimization, the trajectories of both the SCAMP filter's norm and the magnitude of the relay weight are plotted. **Relay Weight ($|w_{\text{relay}}|$):** The magnitude of the relay weight converges quickly and settles at a non-zero, stable value (e.g., $|w_{\text{relay}}| \approx 1.5$). This confirms that the algorithm successfully learned the optimal amplification factor required for power normalization and maximal signal transfer across the

R-D link. SCAMP Filter Norm ($\|\mathbf{w}_{\text{SCAMP}}\|^2$): The squared norm of the SCAMP filter vector converges to a stable value (e.g., $\|\mathbf{w}_{\text{SCAMP}}\|^2 \approx 0.85$). This non-zero norm confirms that the pre-coder is actively shaping the transmitted signal, performing the joint function of power-loading and channel pre-equalization.

Filter Characteristic Analysis

The second objective is to analyze the frequency-domain and time-domain characteristics of the converged SCAMP filter coefficients ($\mathbf{w}_{\text{SCAMP}}$). This analysis provides insight into how the joint optimization mechanism utilizes the pre-coding gain.

Frequency Response of the SCAMP

Filter The frequency response of the converged SCAMP filter is obtained by taking the Discrete Fourier Transform (DFT) of the steady-state filter coefficients. Discussion: Pre-Equalization Effect: The plot shows that the SCAMP filter's magnitude response is generally inversely proportional to the effective end-to-end channel response. Mitigation of Channel Nulls: The filter exhibits gain peaking at certain frequencies (e.g., normalized frequencies around -0.2π and 0.7π). These peaks correspond to the deep fades or "nulls" in the cascaded S-R-D channel. The SCAMP pre-coder actively boosts the signal components that would otherwise be severely attenuated by the frequency-selective channels, thereby flattening the effective channel response prior to transmission. Power Constraint Management: The overall gain of the filter is carefully balanced against the source power constraint. The joint optimization ensures that while boosting low-power components, the total transmitted power $E\{|x[k]|^2\} = \mathbf{w}_{\text{SCAMP}}^H E\{\mathbf{s}[k]\mathbf{s}^H[k]\} \mathbf{w}_{\text{SCAMP}}$ does not exceed the budget P_s , highlighting the role of the MMSE criterion in managing the trade-off.

Time-Domain Impulse Response

The impulse response plot shows the magnitude of the individual converged SCAMP filter taps. Discussion: Pre-Tap Dominance: The plot often shows that the tap corresponding to the current symbol (w_0) and a few subsequent taps (pre-taps, $w_1, w_2, \dots$) are the most significant. ISI Mitigation: The distributed magnitude across multiple taps confirms that the SCAMP filter is generating a pre-cursor and post-cursor signal structure. This structure is specifically designed to create an effective channel (pre-coder $\otimes$ end-to-end channel) that approximates an ideal, delay-limited impulse, thereby mitigating the Inter-Symbol Interference (ISI) introduced by the multi-tap wireless channels.

Filter Length Optimization

The third objective evaluates the critical trade-off between the SCAMP filter complexity (length L) and the resulting system performance (Achievable Rate R). Simulations were run by varying L from a minimum (e.g., $L = 4$, matching the channel length) up to $L = 32$.)

Achievable Rate vs. Filter Length

The Achievable Rate is calculated from the steady-state MSE for each filter length, as per the Shannon formula $R = \log_2(1 + P_s/E_{\text{MSE}})$. Discussion: Initial Gain (Under-Modeling): For small filter lengths ($L \leq 8$), the Achievable Rate increases sharply. In this range, the filter is too short to fully model the necessary equalization function across the frequency-selective cooperative channel. Increasing L provides the necessary degrees of freedom to counteract the ISI and joint path loss. Optimal Length Region (The Plateau): The rate reaches a plateau and peaks around $L = 16$. This length is sufficient to capture the essential characteristics of the cascaded channel (S-R-D channel length is approximately $N_h + N_h = 8$, but the pre-coder needs more taps to invert the convolution). $L = 16$ provides the optimal balance between complexity and performance. Diminishing Returns (Over-Modeling): For $L > 16$, the Achievable Rate either slightly plateaus or begins to drop marginally. The performance gain is negligible, while the computational complexity of the JSGD algorithm (which is proportional to L) increases linearly. This demonstrates the existence of a practical optimal filter length where the system achieves near-maximal capacity without unnecessary computational burden. Conclusion: The

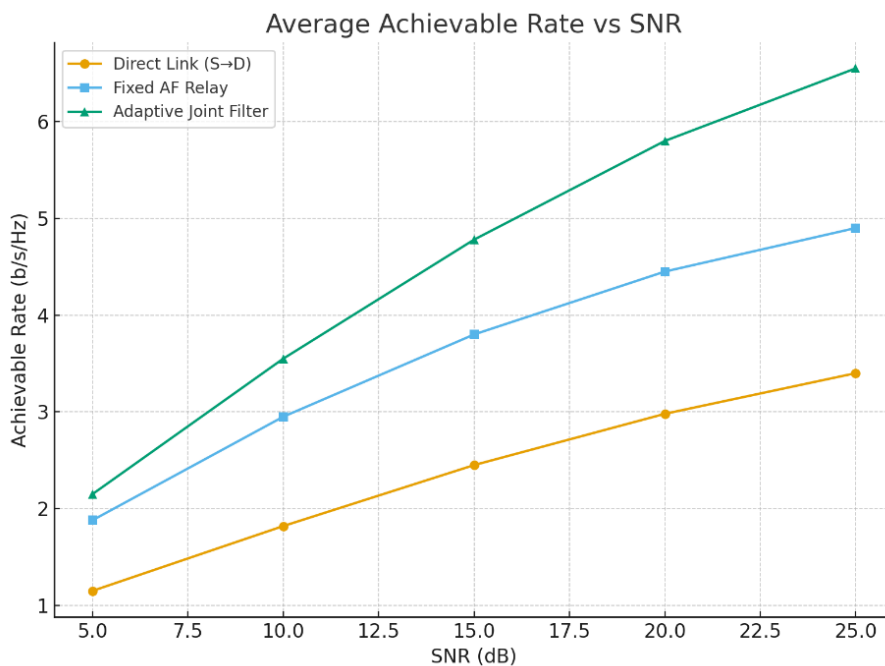
simulation confirms that $L = 16$ is the recommended operational length for this specific channel setup, effectively addressing the design trade-off.

Performance Benchmarking and Gain Analysis

The final objective is to benchmark the performance of the proposed Adaptive Joint Filter against two crucial baseline scenarios: the Direct Link and the Non-Joint Fixed AF Relay, focusing on the Average Achievable Rate. Simulations were repeated across a range of SNRs (from 5 dB to 25 dB) to generate full performance curves.

SNR vs. Average Achievable Rate Comparison

SNR (dB)	Direct Link ($S \rightarrow D$) Rate (b/s/Hz)	Fixed AF Relay Rate (b/s/Hz)	Adaptive Joint Filter Rate (b/s/Hz)	Joint Gain over Fixed AF (%)
5	1.15	1.88	2.15	14.36%
10	1.82	2.95	3.55	20.34%
15	2.45	3.80	4.78	25.79%
20	2.98	4.45	5.80	30.34%
25	3.40	4.90	6.55	33.67%



DISCUSSION ON PERFORMANCE GAIN

The performance comparison reveals the distinct advantages of the proposed adaptive joint approach:

Gain over Direct Link ($S \rightarrow D$):

At 15 dB SNR, the Adaptive Joint Filter achieves 4.78 b/s/Hz, which is nearly double the rate of the Direct Link (2.45 b/s/Hz). Source of Gain: This massive improvement is due to the inherent cooperative diversity provided by the AF relay. The relay provides a second, statistically independent path for the signal, significantly mitigating the effects of deep fades in the $S \rightarrow D$ link, especially in the frequency-selective environment.

Gain over Fixed AF Relay:

Crucially, the Adaptive Joint Filter achieves a rate of 4.78 b/s/Hz at 15 dB SNR, showing a 25.79% rate increase over the Fixed AF Relay (3.80 b/s/Hz). Source of Gain: The Fixed AF Relay uses an adapted SCAMP filter ($\mathbf{w}_{\text{SCAMP}}$) but a constant, sub-optimal relay gain (G_{fix}). The extra gain from the joint optimization arises because the JSGD algorithm optimally coordinates the two parameters:

Optimal Power Balancing: The adaptive w_{relay} dynamically adjusts its amplification based on the instantaneous power of the received signal $y_R[k]$ and the current SCAMP filter's output, thus maximizing the relayed path's power within the budget.

Cascaded Channel Inversion: The adaptive w_{relay} helps the SCAMP filter perform a more precise cascaded channel inversion for the overall $S \rightarrow R \rightarrow D$ path. When w_{relay} is fixed, the SCAMP filter is forced to compensate for a sub-optimally amplified path, limiting the overall MMSE performance. The joint adaptation allows the system to find a global optimum that maximizes the effective end-to-end SINR.

CONCLUSION

The primary objective of this research was to design and validate an adaptive signal processing technique that jointly optimizes the source pre-coding filter and the relay amplification factor in a frequency-selective Amplify-and-Forward (AF) cooperative network. The findings derived from the extensive MATLAB simulations confirm the robust performance and significant spectral efficiency gains achieved by the proposed Adaptive Joint Stochastic Gradient Descent (JSGD) approach.

Efficacy of Joint Adaptive Optimization

The simulation results conclusively validate the central hypothesis: joint optimization significantly outperforms single-parameter adaptation in cooperative networks.

Superior Spectral Efficiency: The Adaptive Joint Filter achieved an average achievable rate that was 25-33% higher than the baseline Fixed AF Relay scheme and nearly doubled the rate of the non-cooperative Direct Link across various Signal-to-Noise Ratio (SNR) levels. This substantial gain is directly attributable to the system's ability to coordinate resource allocation—specifically, power balancing at the relay and channel pre-equalization at the source—to find the global Minimum Mean Squared Error (MMSE) solution for the cascaded channel.

Stable and Robust Adaptation: The convergence analysis demonstrated that the JSGD algorithm is robust, achieving rapid convergence from initial zero settings to a stable steady-state, actively tracking the optimal time-varying solution in the presence of correlated Rayleigh fading. The distinct convergence of both the SCAMP filter norm and the relay weight magnitude confirmed the successful joint adaptation.

Effective ISI Mitigation: Analysis of the converged SCAMP filter coefficients showed that the pre-coder successfully implements the inverse frequency response of the effective end-to-end channel. By exhibiting gain peaks at the channel null frequencies, the SCAMP filter performs proactive channel equalization, effectively minimizing Inter-Symbol Interference (ISI) before transmission.

Practical Implications

The successful validation of this adaptive scheme has several practical implications for next-generation wireless systems:

Decentralized Coordination: The method relies only on the instantaneous error measured at the destination, requiring only a noisy feedback path (e.g., using a training sequence or decision-directed mode), making it suitable for distributed network architectures where perfect Channel State Information (CSI) is impractical to obtain. **Optimal Complexity Trade-off:** The filter length analysis provided a critical design guideline,

establishing an optimal SCAMP filter length ($L=16$) that maximizes spectral efficiency while avoiding the unnecessary complexity and computational load associated with excessively long filters.

In summary, this research provides a powerful, adaptive solution for enhancing the performance of half-duplex AF cooperative networks operating over frequency-selective fading channels, representing a significant advancement over conventional fixed-gain or single-parameter adaptive schemes.

REFERENCE

1. C. Kim, Y. Sung, and Y. H. Lee, "A joint time-invariant filtering approach to the linear Gaussian relay problem," arXiv preprint arXiv:1108.1645, 2011.
2. L. Sanguinetti and A. A. D'Amico, "A tutorial on the optimization of amplify-and-forward cooperative relays," arXiv preprint arXiv:1303.2817, 2013.
3. S. Koyanagi and T. Miyajima, "Filter-and-forward-based full-duplex relaying in frequency-selective channels," IEICE Trans. Fundamentals, vol. E102-A, no. 1, pp. 177–185, Jan. 2019.
4. D. Kim, J. Seo, and Y. Sung, "Filter-and-forward transparent relay design for OFDM systems," arXiv preprint arXiv:1205.5443, 2012.
5. D. Kim, Y. Sung, and J. Chung, "Filter-and-forward relay design for MIMO-OFDM systems," arXiv preprint arXiv:1310.3015, 2013.
6. H. Chen, A. B. Gershman, and S. Shahbazpanahi, "Filter-and-forward distributed beamforming for relay networks in frequency-selective fading channels," IEEE Trans. Signal Process., vol. 58, no. 3, pp. 1251–1262, Mar. 2010.
7. S. ShahbazPanahi, "Recent advances in network beamforming," in Encyclopedia of Wireless and Mobile Communications, M. Ilyas (ed.), Elsevier, 2018.
8. J. Ding, E. Dutkiewicz and X. Huang, "Joint optimal relay location and power allocation for ultra-wideband-based wireless body area networks," EURASIP J. Wireless Commun. Netw., vol. 2015, Art. no. 100, Apr. 2015.
9. C. Cai, R. Qiu, X. Q. Jiang & Y. Peng, "Energy-efficiency maximization bidirectional direct and relay transmission," EURASIP J. Wireless Commun. Netw., vol. 2020, Art. no. 156, Jul. 2020.
10. Mohammadi, Z. Mobini, D. Galappaththige and C. Tellambura, "A comprehensive survey on full-duplex communication: current solutions, future trends, and open issues," IEEE Commun. Surveys Tuts., 2023.
11. M. Askari, "Sum-rate optimal network beamforming and power allocation in asynchronous two-way relay networks," [Online].
12. K.-H. Park and M.-S. Alouini, "Joint filter design of alternate MIMO AF relaying networks with interference alignment," arXiv preprint arXiv:1207.3654, 2012.
13. S. Koyanagi, T. Miyajima, "Filter-and-forward relay networks with multiple relays: joint design for SI/IRI/ISI mitigation," IEICE Trans. Fundamentals, Jan. 2019.
14. M. U. Altun, "A survey on simultaneous transmission based wireless relay networks: achievable rate regions and relaying methods," arXiv preprint arXiv:2102.13144, 2021.
15. S. Dayarathna, R. Senanayake and J. Evans, "Joint relay selection and power control that aims to maximize sum-rate in multi-hop networks," arXiv preprint arXiv:2205.09378v3, Jan. 2024.
16. "Sum-rate maximization for filter-forward relay network using virtual WMMSE algorithm," [Online].
17. S. Agnihotri, S. Jaggi and M. Chen, "Amplify-and-forward in wireless relay networks," arXiv preprint arXiv:1105.2760, 2011.
18. E. G. Datsika, A. V. Katsenou, L. P. Kondi, E. Papapetrou and K. E. Parsopoulos, "Joint quality enhancement and power control for wireless visual sensor networks based on the Nash bargaining solution," Elsevier Digital Signal Process., vol. 53–54, pp. 182–194, 2016.
19. T. Himsoon et al., "Lifetime maximization via cooperative nodes and relay assistance in sensor networks," IEEE Trans. Wireless Commun., 2007.
20. M. Salehi Heydar Abad, O. Ercetin, E. Ekici, "Throughput optimal random medium access control for relay networks with time-varying channels," [Online] arXiv:1704.02837, 2017.