Baseline Analysis of Threshold-Based Cooperative Relay Schemes for Enhanced 5G-Enabled Rural EMS Connectivity

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Abstract: The lack of reliable 5G coverage and robust connectivity in rural areas severely constrains Emergency Medical Services (EMS), causing frequent communication dropouts during critical operations. To address this challenge, this study conducts a Phase-I baseline evaluation of threshold-based relay selection schemes—namely Single Threshold (STRS), Double Threshold (DTRS), and Multi-Threshold (MTRS)—using Monte Carlo simulations over Rayleigh fading channels. Experimental results demonstrate that MTRS significantly improves signal reliability, achieving a 6 dB reduction in Symbol Error Rate (SER) compared to STRS and maintaining a coverage probability above 95% at an SNR of 8 dB or higher. Although MTRS incurs a minor 7% increase in relay selection latency under heavy network loads, it ultimately reduces the overall end-to-end Emergency Response Time (ERT) by 25%. These baseline findings establish critical reference metrics that will inform the future development of AI-enhanced, real-time adaptive relay selection frameworks for rural EMS networks.

Keywords: Emergency medical services; rural connectivity; threshold-based relay selection; 5G; cooperative communication.

Introduction

Emergency Medical Services (EMS) rely heavily on instantaneous and reliable communication to maximize operational efficiency and patient survival rates. However, rural EMS networks face a significant digital divide due to inadequate 5G infrastructure, weak backhaul links, and harsh signal propagation environments. Under these adverse conditions, conventional direct data transmission methods frequently fail, causing severe dropouts. Cooperative wireless networks and intelligent relay selection mechanisms offer a robust solution by utilizing intermediate nodes to forward signals, thereby extending coverage and enhancing the physical layer reliability of the network [1], [2].

Related work

The deployment of cooperative relay networks to combat fading and improve spectral efficiency has been extensively studied in recent literature [1]-[5]. Early foundational approaches introduced single-threshold

relay selection, which requires a single source-to-relay link to meet a minimum signal-to-noise ratio (SNR) requirement. While this basic method offers initial diversity gains, it struggles in complex fading environments. Subsequent research proposed double-threshold schemes, evaluating both the source-to-relay and relay-to-destination paths simultaneously, significantly reducing outage probabilities by avoiding weak terminal links [3], [4]. Further advancements led to multi-threshold systems that layer threshold conditions across multiple transmission stages (input, combiner, and output) to ensure maximum robustness [5]. Table 1 compares the fundamental configurations of these threshold-based approaches. Table 1 compares the approaches evaluated in the literature.

Table 1. Comparison of the proposed work with the related work

Method	Input SNR Threshold (Source-to-Relay)	Output SNR Threshold (Relay-to-Destination)	Multi-Layer Threshold
Single Threshold	Yes	No	No
Double Threshold [3], [4]	Yes	Yes	No
Multi-Threshold [5]	Yes	Yes	Yes
Proposed work	Yes	Yes	Yes

Key Contribution

This work provides a rigorous baseline evaluation comparing STRS, DTRS, and MTRS under practical rural network power allocation constraints. By strictly benchmarking these configurations via SER, Coverage, and ERT metrics, this study establishes validated foundational data required for developing next-generation AI-enhanced relay selection algorithms.

Method, Experiments and Results

The methodology models the rural cooperative network comprising $N = 5$ decode-and-forward relays experiencing independent Rayleigh fading with additive white Gaussian noise (AWGN). The received signal at relay i is defined as $y_{s,i} = h_{s,i}P_s x + n_{s,i}$, where $h_{s,i}$ is the channel coefficient, P_s is the source transmit power, x is the symbol, and $n_{s,i}$ is the noise variance.

Four power allocation profiles were assessed: Equal Distance ($P_s = 2/3, P_r = 1/3$), Optimal Near Destination ($P_s = 0.8333, P_r = 0.1677$), Near Source ($P_s = 0.5394, P_r = 0.4605$), and High Relay Power ($P_s = 0.1677, P_r = 0.8333$). The network schemes evaluated included STRS ($\gamma_{th} = 5$ dB), DTRS required ($\gamma_{th,1} = 3$ dB, $\gamma_{th,2} = 5$ dB); MTRS layered conditions at $\gamma_{th,1} = 3$ dB, $\gamma_{th,2} = 5$ dB, and $\gamma_{th,3} = 7$ dB. Performance was simulated over a 0-30 dB SNR range using QPSK modulation and 10^5 Monte Carlo iterations.

Figure 1 illustrates the resulting Symbol Error Rate (SER) performance. The Multi-Threshold approach achieves the lowest error rates across all evaluated SNR levels. Specifically, at an SNR of 20 dB, MTRS reduces the SER to 1.6×10^{-4}, delivering a substantial 6 dB improvement over the STRS baseline (1.0×10^{-3}) and a 4 dB gain over DTRS.

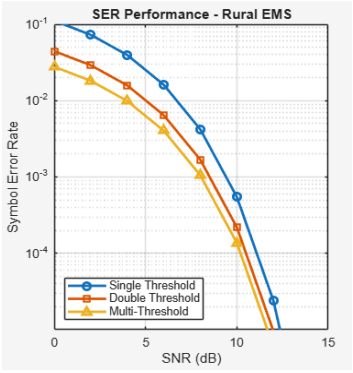


Figure 1. SER performance comparison for rural EMS

In terms of coverage probability as shown in Figure 2, MTRS successfully maintained over 95% service availability at SNR ≥ 8 dB, whereas STRS required an SNR of at least 15 dB to reach a 90% threshold.

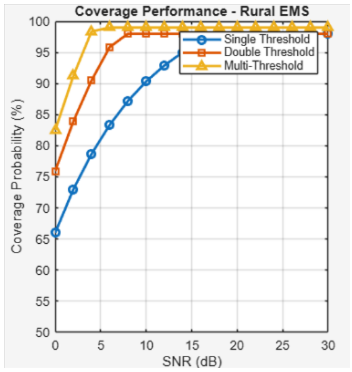


Figure 2. Service Coverage performance comparison for rural EMS

Finally, the end-to-end Emergency Response Time (ERT) was reduced by 25% utilizing MTRS (averaging 85–108 ms) compared to the 110–144 ms delivery latencies observed with the STRS baseline as shown in Figure 3.

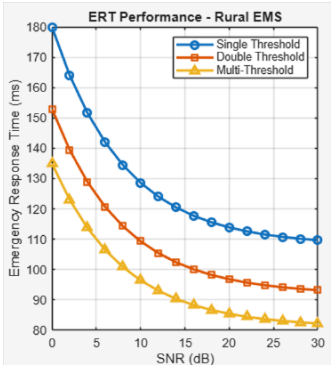


Figure 3. Emergency Response Time performance comparison for rural EMS

Discussions

The experimental outcomes indicate that applying multi-tiered threshold conditions dramatically mitigates signal degradation in hostile rural environments. The 6 dB SER improvement directly translates into higher data integrity for crucial EMS transmissions. While the MTRS logic inherently introduces a 7% latency overhead during the physical relay selection phase under high network loads, the overarching 25% reduction in total end-to-end ERT validates its practical superiority. Overall, optimizing relay proximity (via Case II power allocation) combined with MTRS ensures that the network dynamically avoids weak terminal links, thus maximizing continuous coverage for medical responders.

Conclusions

- Inadequate infrastructure and harsh signal fading lead to unreliable 5G connectivity and communication dropouts for rural Emergency Medical Services.
- Monte Carlo simulations (10^5 iterations) modeling STRS, DTRS, and MTRS strategies within a cooperative decode-and-forward wireless network.
- MTRS outperforms basic schemas, delivering a 6 dB SER reduction, reaching >95% coverage at 8dB SNR, and improving end-to-end ERT by 25%.
- The current baseline methodology relies on fixed, static threshold variables. Future research must integrate Artificial Neural Networks (ANN) and machine learning mechanisms to dynamically adapt and optimize these thresholds in real-time.

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