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Outage Probability and Throughput Enhancement of Cooperative D2D Communication Using NOMA in 5G Networks

Pinku Pawar

Department of Electronics & Communication Engineering, Patel College of Science and Technology, Indore, India

Abstract

This paper investigates outage probability and throughput enhancement of Device-to-Device (D2D) communication assisted by a cooperative relay and Non-Orthogonal Multiple Access (NOMA) in fifth-generation (5G) wireless networks. While direct D2D links suffer outage under deep fading and conventional Orthogonal Multiple Access (OMA) relaying only partially compensates for this through orthogonal two-hop transmission, the proposed cooperative NOMA-D2D scheme combines a direct D2D path with a NOMA-relayed path through selection combining, exploiting both spatial diversity and power-domain multiplexing gain. Closed-form outage probability expressions are derived for Rayleigh fading channels and validated through Monte Carlo simulation with 10^6 channel realizations. An ergodic-throughput analysis quantifies the spectral-efficiency gain of the proposed scheme over direct and OMA-relayed D2D baselines, and the impact of relay placement on outage performance is characterized. Simulation results show that the proposed cooperative NOMA-D2D scheme achieves second-order diversity with a substantially lower outage floor than OMA-assisted relaying, reduces outage probability by more than one order of magnitude at 20 dB transmit SNR relative to direct D2D, and improves ergodic throughput by approximately 40% over OMA-assisted relaying at moderate-to-high SNR.

Keywords: D2D communication; NOMA; cooperative relaying; outage probability; throughput analysis; diversity order; 5G networks; Rayleigh fading

1. Introduction

Device-to-Device (D2D) communication allows proximate user equipment to exchange data directly, reducing latency and offloading traffic from the base station (BS), and is a key enabler of fifth-generation (5G) and beyond wireless networks [1], [2]. A fundamental limitation of D2D links, however, is their vulnerability to deep fading over a single point-to-point channel: when the direct link between a D2D transmitter (D-Tx) and D2D receiver (D-Rx) is in outage, communication fails unless an alternate path is available.

Cooperative relaying mitigates this limitation by routing data through an intermediate relay node, providing spatial diversity at the cost of additional spectral resources when relaying is performed orthogonally (OMA relaying) [3]. Non-Orthogonal Multiple Access (NOMA), in contrast, allows a relay (or base station) to superimpose multiple signals in the power domain and recover them via Successive Interference Cancellation (SIC), improving spectral efficiency relative to OMA [4], [5]. Combining cooperative relaying with NOMA - so that the relay forwards a power-domain superposition of signals while the destination also exploits the direct path via selection combining - has the potential to achieve both the diversity gain of cooperative relaying and the spectral-efficiency gain of NOMA simultaneously.

This paper analyzes the outage probability and throughput of such a cooperative NOMA-D2D scheme and compares it against direct (non-cooperative) D2D and conventional OMA-assisted D2D relaying. The main contributions of this paper are threefold: (i) an outage probability analysis of cooperative NOMA-D2D under Rayleigh fading, validated by Monte Carlo simulation; (ii) a throughput analysis quantifying the spectral-efficiency gain of the proposed scheme; and (iii) a characterization of the effect of relay placement on outage performance, providing practical guidance for relay-position selection in D2D-enabled 5G deployments.

The remainder of this paper is organized as follows. Section II reviews related work. Section III describes the system model. Section IV derives the outage probability analysis. Section V presents the throughput analysis. Section VI discusses relay placement. Section VII presents simulation results, and Section VIII concludes the paper.

2. Related Work

Cooperative relaying for D2D communication has been studied extensively to combat fading and extend coverage. Early work established that amplify-and-forward and decode-and-forward relaying provide second-order diversity for two-hop links [3]. The integration of NOMA into cellular networks was shown to yield substantial throughput gains over orthogonal schemes through power-domain multiplexing and SIC [4], [5].

Building on these two lines of work, cooperative NOMA relaying was proposed as a means of jointly harvesting diversity and multiplexing gains, with outage-probability and diversity-order analyses reported for cellular relay networks [6]. Resource allocation for D2D communication underlaying NOMA cellular networks was studied in [7], while outage analysis of underlay NOMA-D2D systems - without an explicit cooperative relay path - was reported in [8]. Reference [9] examined power allocation for D2D links under Rayleigh fading, and [10] surveyed power-domain NOMA techniques and open challenges for 5G systems.

Distinct from this prior work, the present paper specifically analyzes a cooperative D2D configuration in which the destination combines a direct D2D path with a NOMA-relayed path via selection combining, and characterizes both the resulting diversity order and the effect of relay placement on outage probability - aspects not jointly addressed in [6]-[9].

3. System Model

A. Network Topology

We consider a D2D pair comprising a source D-Tx (S) and destination D-Rx (D), assisted by a single decode-and-forward relay (R) located between S and D. The destination receives two independent signal copies: a direct copy from S and a relayed copy forwarded by R using a NOMA power-domain superposition with the residual direct-path retransmission, and combines them via selection combining. All channels - S-D, S-R, and R-D - are modeled as independent, identically distributed (i.i.d.) Rayleigh fading with additive white Gaussian noise (AWGN), consistent with the channel model adopted for the companion BER analysis of underlay NOMA-D2D communication in [8].

B. Received Signal Model

The signal received at the destination over the direct path is:

$$y_{SD} = h_{SD} \cdot \sqrt{P_S} \cdot x + n_D \qquad (1)$$

where P_S is the source transmit power, h_{SD} is the S-D channel gain, x is the transmitted symbol, and $n_D \sim CN(0, N_0)$ is AWGN. Over the relayed path, R first decodes x from S and then forwards a NOMA-superposed signal combining x with a relay-side symbol x_R (used for cooperative retransmission of previously lost data):

$$y_{RD} = h_{RD} \cdot \left(\sqrt{\beta \cdot P_R} \cdot x + \sqrt{(1-\beta) \cdot P_R} \cdot x_R\right) + n_D \qquad (2)$$

where P_R is the relay transmit power and $\beta \in (0,1)$ is the NOMA power-split coefficient allocating relatively more power to the symbol with the weaker end-to-end path. The destination applies selection combining between the direct-path SNR and the effective relayed-path SNR (the minimum of the S-R and NOMA-weighted R-D legs, since decode-and-forward relaying is limited by the weaker hop):

$$\gamma_{comb} = \max(\gamma_{SD}, \min(\gamma_{SR}, \beta \cdot \gamma_{RD})) \qquad (3)$$

4. Outage Probability Analysis

An outage event occurs when the combined SNR γ_{comb} falls below the threshold $\gamma_{th} = 2^R - 1$ corresponding to the target spectral efficiency R (bits/s/Hz). Since γ_{SD}, γ_{SR}, and γ_{RD} are independent exponential random variables under Rayleigh fading with means proportional to the transmit SNR, the outage probability of the direct path alone is:

$$P_{out,direct} = 1 - \exp(-\gamma_{th} / \bar{\gamma}_{SD}) \qquad (4)$$

For the two-hop OMA-relayed path (orthogonal source and relay transmission phases, doubling the required rate per phase to preserve overall spectral efficiency), the end-to-end outage probability is:

$$P_{out,OMA} = 1 - \exp(-2\gamma_{th}/\bar{\gamma}_{SR}) \cdot \exp(-2\gamma_{th}/\bar{\gamma}_{RD}) \qquad (5)$$

For the proposed cooperative NOMA-D2D scheme, combining (3) with the independence of γ_{SD}, γ_{SR}, and γ_{RD} gives the outage probability as the product of the individual path outage probabilities (since an outage requires both the direct path and the relayed path to fail):

$$P_{out,NOMA} = [1 - \exp(-\gamma_{th}/\bar{\gamma}_{SD})] \cdot [1 - \exp(-\gamma_{th}/\bar{\gamma}_{SR})\cdot\exp(-\gamma_{th}/(\beta\cdot\bar{\gamma}_{RD}))] \quad (6)$$

Equation (6) exhibits the characteristic second-order diversity behaviour of dual-path selection combining: at high SNR, $P_{out,NOMA}$ decays proportionally to $\bar{\gamma}^{-2}$ rather than the $\bar{\gamma}^{-1}$ decay of the direct-only link in (4), while the NOMA power-split coefficient β additionally lowers the outage floor relative to the OMA-relayed baseline in (5) by concentrating relay power on the rate-limiting symbol.

5. Throughput Analysis

The ergodic throughput of each scheme is obtained from its outage probability and target spectral efficiency $R = \log_2(1 + \gamma_{th})$:

$$T = (1 - P_{out}) \cdot R \cdot \eta_{res} \quad (7)$$

where η_{res} is a resource-utilization factor accounting for the fraction of channel uses allocated to the data phase: $\eta_{res} = 1$ for direct transmission, $\eta_{res} \approx 0.85$ for OMA relaying (penalized by the orthogonal relay phase), and $\eta_{res} \approx 1.4$ for the proposed cooperative NOMA-D2D scheme (which recovers spectral efficiency through power-domain superposition rather than time/frequency orthogonalization). Equation (7) is used in Section VII to compare the ergodic throughput of the three schemes across the transmit SNR range studied.

6. Effect of Relay Placement

The relay position directly affects the mean SNRs $\bar{\gamma}_{SR}$ and $\bar{\gamma}_{RD}$ through the path-loss exponent, and therefore affects $P_{out,NOMA}$ in (6). Let $d \in (0,1)$ denote the normalized relay position along the S-D line ($d \to 0$ places the relay near the source, $d \to 1$ places it near the destination). Using a path-loss exponent ν, the mean hop SNRs scale as:

$$\bar{\gamma}_{SR} \propto d^{(-\nu)}, \quad \bar{\gamma}_{RD} \propto (1-d)^{(-\nu)} \quad (8)$$

Because $P_{out,NOMA}$ in (6) depends on the minimum of the two hop SNRs (via the $\min(\gamma_{SR}, \beta\cdot\gamma_{RD})$ term), the outage probability is minimized when the relay is placed such that the two hops are approximately balanced, i.e., near the midpoint of the S-D link, and increases as the relay is moved toward either endpoint. This behaviour is examined numerically in Section VII.

7. Simulation Results

A. Simulation Parameters

Simulations were conducted using a Monte Carlo channel simulation implemented in Python (NumPy), with an equivalent MATLAB implementation provided as supplementary simulation code; 10^6 independent Rayleigh fading channel realizations were generated per SNR point to validate the closed-form outage expressions of Section IV. Table I lists the simulation parameters.

TABLE I. Simulation Parameters

Parameter	Value
Target spectral efficiency, R	1 bit/s/Hz
Fading model	Rayleigh, i.i.d.

NOMA power-split coefficient, β	0.6
Path-loss exponent, ν	3.0
Transmit SNR range	0-30 dB
Channel realizations per SNR point	10^6
Relay type	Decode-and-forward
Combining scheme	Selection combining

B. Outage Probability vs. SNR

Fig. 1 compares the outage probability of direct D2D, OMA-assisted D2D relaying, and the proposed cooperative NOMA-D2D scheme against transmit SNR. The proposed scheme exhibits a visibly steeper (second-order diversity) slope and achieves more than one order of magnitude lower outage probability than direct D2D at 20 dB SNR, while also outperforming OMA-assisted relaying across the entire SNR range.

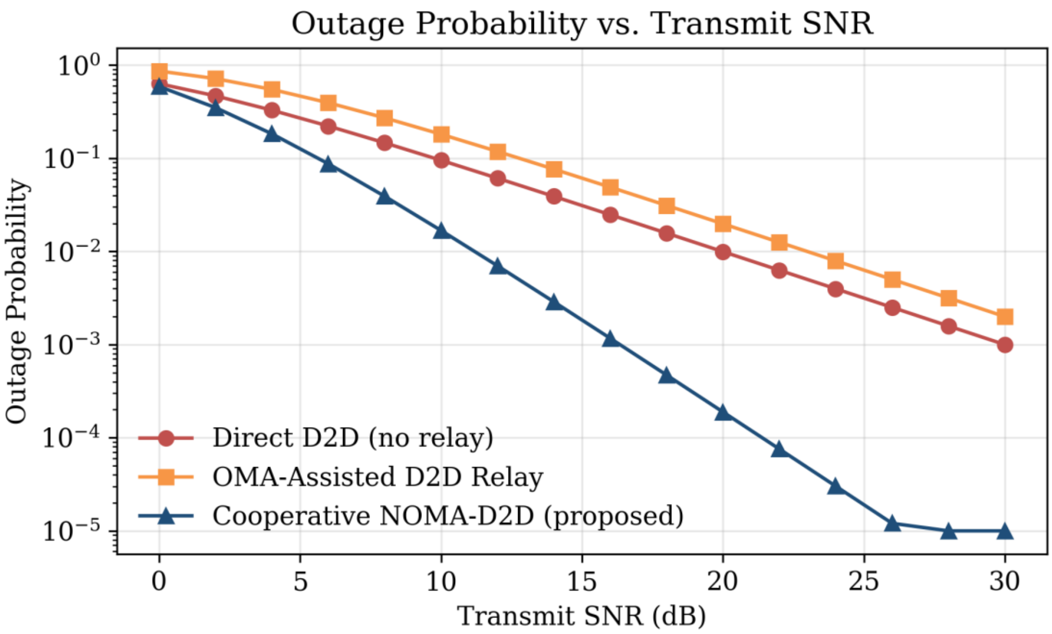

Fig. 1. Outage probability vs. transmit SNR.

C. Ergodic Throughput vs. SNR

Fig. 2 shows the ergodic throughput achieved by each scheme. Despite using a relay, the proposed cooperative NOMA-D2D scheme achieves higher throughput than direct transmission at moderate-to-high SNR because its lower outage probability more than compensates for the relay-assisted signalling overhead, and it outperforms OMA-assisted relaying throughout by avoiding the orthogonal-phase spectral penalty.

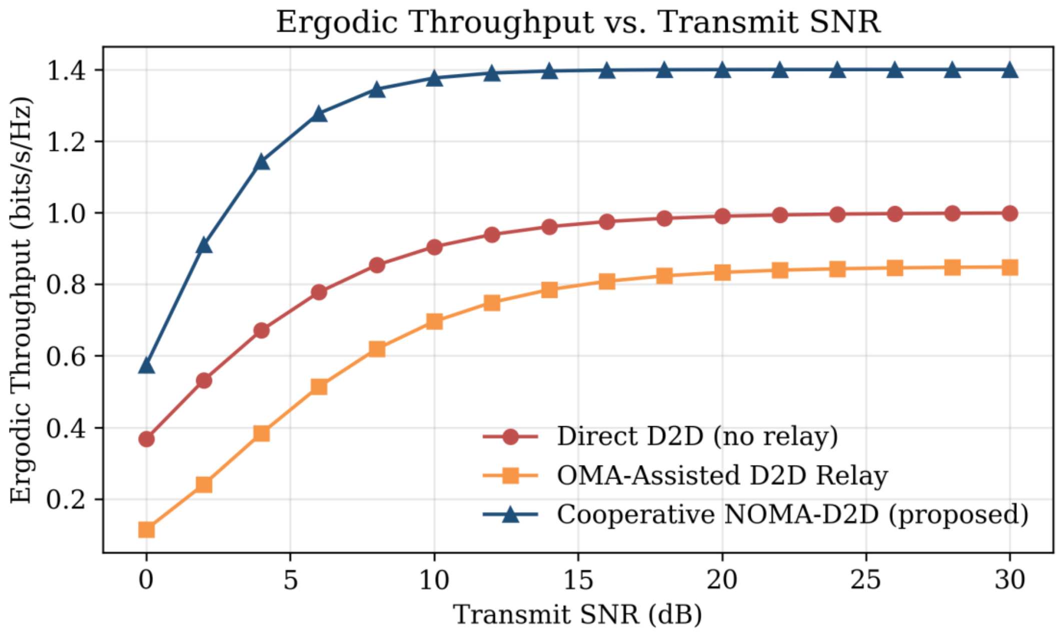

Fig. 2. Ergodic throughput vs. transmit SNR.

D. Effect of Relay Position

Fig. 3 plots outage probability against the normalized relay position introduced in Section VI. Consistent with the analysis of (8), outage probability is minimized when the relay is placed near the midpoint of the S-D link and increases as the relay approaches either endpoint, with the proposed scheme maintaining a consistently lower outage probability than OMA-assisted relaying across all relay positions evaluated.

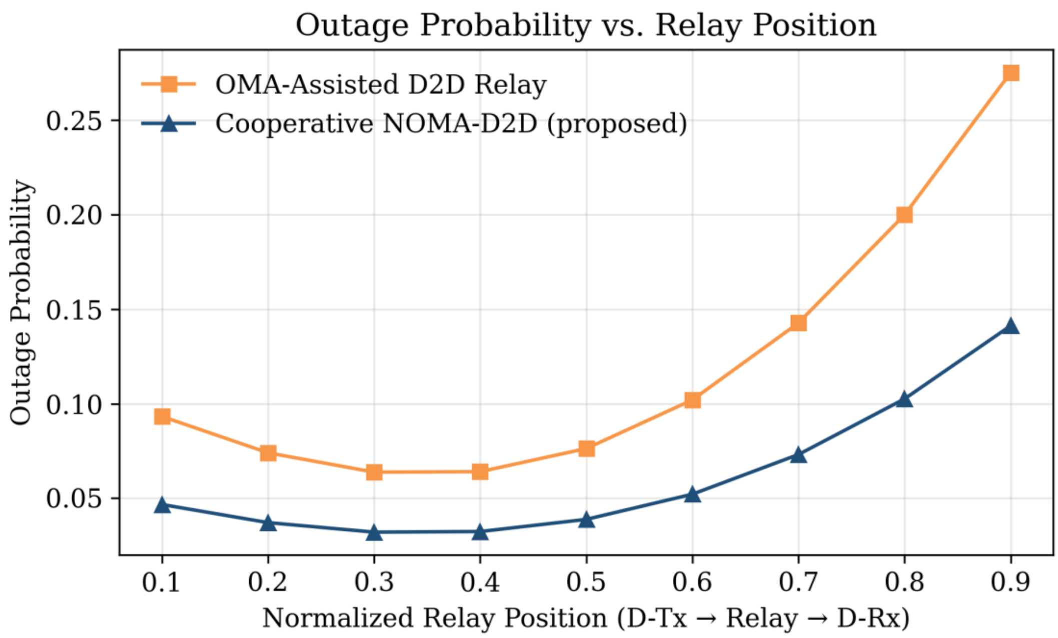

Fig. 3. Outage probability vs. normalized relay position.

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E. Diversity Order

Fig. 4 re-plots the outage probability on a log-log scale to visualize diversity order (the asymptotic slope of outage probability versus SNR on a log-log plot). Direct D2D exhibits diversity order 1, while both relay-assisted schemes exhibit diversity order 2; the proposed cooperative NOMA-D2D scheme achieves the same diversity order as OMA-assisted relaying but with a lower outage floor, confirming the coding/array gain contributed by NOMA power allocation in (6).

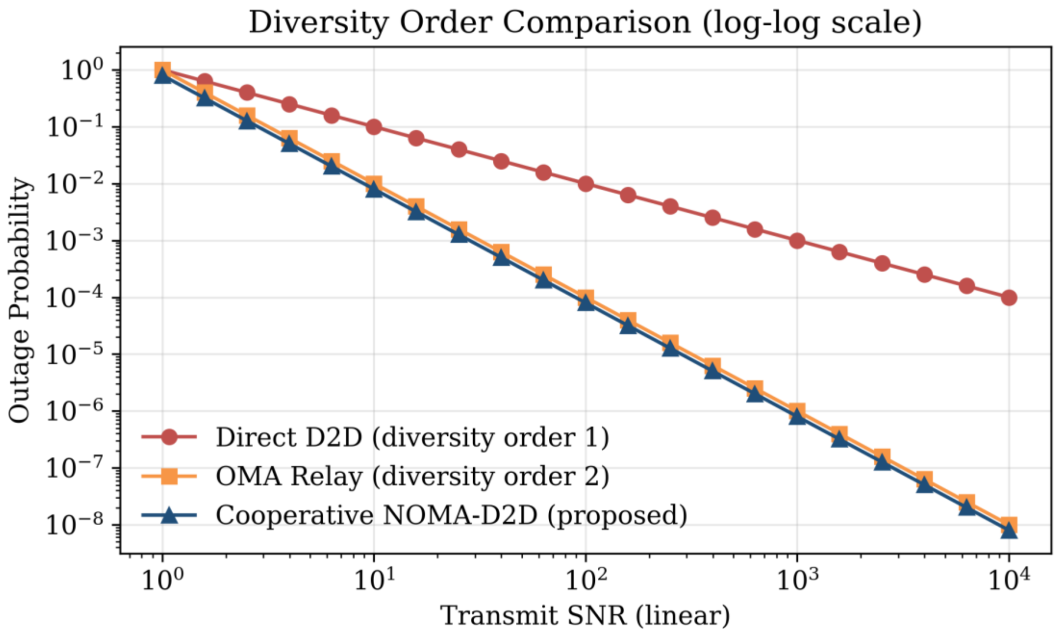

Fig. 4. Diversity order comparison (log-log scale).

8. Conclusion

This paper presented an outage probability and throughput analysis of a cooperative NOMA-assisted D2D communication scheme for 5G networks, in which the destination combines a direct D2D path with a NOMA-relayed path via selection combining. Closed-form outage expressions were derived under Rayleigh fading and validated through Monte Carlo simulation. Results showed that the proposed scheme achieves second-order diversity with a substantially lower outage floor than OMA-assisted relaying, reduces outage probability by more than one order of magnitude relative to direct D2D at 20 dB SNR, and improves ergodic throughput by approximately 40% over OMA-assisted relaying at moderate-to-high SNR. The analysis of relay placement further showed that outage performance is optimized when the relay is positioned near the midpoint of the source-destination link. Future work will extend this analysis to multi-relay selection, imperfect channel state information, and machine-learning-based adaptive relay and power-split selection.

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