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Energy-Aware Framework for Optimized Mode Selection in Device-to-Device Communication System

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Abstract
Device-to-Device (D2D) communication is a critical technology in wireless networks, enabling direct interaction between devices within cellular systems. This dissertation, titled "Effective Selection of Communication Mode in Device-to-Device (D2D) Communication," *aims to improve D2D communication through an optimized mode selection framework. The study focuses on analyzing D2D performance metrics within a cellular environment, proposing an improved mode selection set of rules, and evaluating the performance of these rules via simulations. Initially, a comprehensive literature review identified key performance metrics influencing D2D communication, including bit error rate (BER), signal-to-noise ratio (SNR), interference-to-signal ratio (ISR), received signal strength indicator (RSSI), and proximity. An improved mode selection model was optimized, incorporating direct D2D feasibility, relay feasibility, cellular mode and energy-aware adjustment. The problem was formulated as a Markov Decision Process (MDP) to maximize the system's expected reward, with the value iteration algorithm determining a stationary deterministic policy. Simulations validated the proposed model, with theoretical and simulated BER under Rayleigh fading showing consistency. The BER decreased as SNR increased, demonstrating model accuracy. Performance comparisons of mode selection rules revealed that the ISR rule achieved the highest average capacity (20.1 bps/Hz) due to reduced interference in interference-limited regions. The capacity rule and SNR rule followed with average capacities of 14.2 bps/Hz and 14.1 bps/Hz, respectively. RSSI and distance rules showed lower capacities of 8.0 bps/Hz and 8.5 bps/Hz respectively, due to proximity limitations*.

Keywords: *Mode selection, Device-to-device communication, Hybrid model, Effective selection.*

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I. Introduction

Mobile devices like smartphones and tablets can make and receive calls due to significant advancements in the telecommunications sector, primarily driven by cellular networks. These networks support real-time, two-way, full-duplex communication, enabling seamless voice and data transmission between users [1]. The term "cellular" originates from the network's structure, which consists of multiple interconnected cells, each containing at least one base transceiver station (BTS) along with other essential supporting equipment. These base stations are responsible for managing communication between devices by utilizing designated uplink and downlink frequency channels to maintain a stable connection [2]. By employing frequency reuse and handover mechanisms, cellular networks ensure continuous communication even as users move across different coverage areas. Additionally, modern cellular technologies such as 4G LTE and 5G integrate advanced signal processing techniques and network optimization strategies to improve spectral efficiency, reduce latency, and enhance overall communication performance.

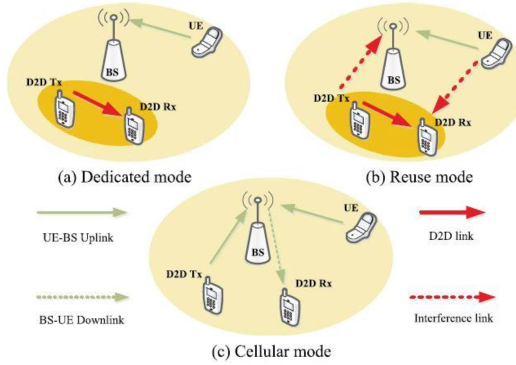

FIGURE 1: Three transmission modes of device-to-device (D2D) communication [1].

In the rapidly advancing field of device-to-device (D2D) communication, selecting the appropriate communication mode is crucial for maximizing performance and resource efficiency. However, most existing mode selection models primarily emphasize factors such as data rate, latency, and connectivity reliability, often neglecting the vital role of energy management. This oversight presents a major challenge, particularly in scenarios where devices operate under varying energy constraints, which can lead to premature device failures. Traditional mode selection approaches lack mechanisms to dynamically adjust based on energy availability, as they do not take into account the energy levels of communicating devices during the selection process. Consequently, there is a need for an improved mode selection framework that not only considers conventional performance indicators but also integrates energy awareness into its decision-making process. Such an approach would promote sustainable device operation, prolong battery life, and support continuous communication, especially in energy-constrained environments. Addressing energy efficiency in mode selection is essential for enhancing the overall effectiveness of D2D communication, paving the way for innovative solutions that adapt to the dynamic energy conditions of connected devices. The objective of this research is to develop an optimized mode selection framework for D2D communication that incorporates energy-aware adjustments, thereby improving both performance and sustainability by accounting for the energy levels of the devices involved.

The optimized mode selection framework enhances communication network performance by maximizing system capacity, minimizing interference, and integrating energy-aware adjustments to improve the efficiency and reliability of Device-to-Device (D2D) communication.

The main contribution of this paper include:

i. Determination of the performance metrics for device-to-device communication within a cellular environment.
ii. Development of an enhanced mode selection model tailored for device-to-device communication.
iii. Simulation and performance evaluation of the proposed mode selection model, including validation of its effectiveness in optimizing mode selection for device-to-device communication.

The remainder of this paper is structured as follows: Section 2 presents a literature review on device-to-device (D2D) communication and related areas. Section 3 details the adopted materials and methods used to achieve the paper's objectives, including the proposed algorithm and simulation setup. Section 4 presents the results, discussion, and validation of the proposed model. Finally, Section 5 provides the concluding remarks.

1.1 System Parameter

For every link, different system parameters have to be taken into account separately. For example, if the battery life of the wireless devices is the parameter of interest, we want to compare the transmitting power of a device when communication. But, if the channel capacity needs to be taken into account, then a comparison is made of the links based on the length of the links (i.e. the distance between the communicating nodes either direct or through BTS). To increase the overall performance of the link Interference-to-Signal Ratio (ISR) is taken into account. The order system parameters that are taken into account are: Distance, Signal to Noise Ratio (SNR), Interference to Signal Ratio (ISR), received signal strength indicator (RSSI) and capacity.

1.1.1 Distance

In device-to-device (D2D) communication, distance serves as a key threshold for determining whether direct communication can occur. This threshold helps identify whether devices are within the defined proximity region [35]. When devices fall within this region, they can establish direct D2D communication. Conversely, if they are outside the proximity range, communication must occur indirectly. The distance of each link, whether between two devices or between a device and the base transceiver station (BTS), is measured and analyzed to support decision-making in selecting the appropriate communication mode for each connection.

1.1.2 Signal to Noise Ratio

The signal-to-noise ratio (SNR) represents the relationship between the strength of a wireless signal and the level of noise affecting the connection [3]. A higher SNR is desirable, as it indicates stronger signal quality and improved transmission performance. However, various factors can cause a decline in SNR. For instance, atmospheric conditions such as rain or fog increase air density, leading to signal attenuation and a subsequent reduction in SNR. Additionally, strong electromagnetic fields, such as those generated by high-voltage power lines, can significantly degrade SNR [4]. Signal interference also contributes to a decrease in signal strength. The SNR for direct mode communication is expressed in equation (1).

$$\gamma_{direct} = \frac{\varepsilon_d |h_d|^2}{N_o}, \tag{1}$$

where h_d is the channel coefficient between the two terminals D_1 and D_2, ε_d is the energy coefficient and N_0 is the variance of AWGN. For indirect mode, since BTS is acting as a relay the overall SNR for indirect mode at the receiving end is defined as [5]:

$$\gamma_{indirect} = \frac{|h_2\, G h_1|^2}{(|h_2\, G|^2 + 1)\, N_o} = \frac{\frac{\varepsilon_1 |h_1|^2}{N_o}\, \frac{\varepsilon_2 |h_2|^2}{N_o}}{\frac{\varepsilon_2 |h_2|^2}{N_o} + \frac{1}{G^2\, N_o}} \qquad (2)$$

The relay captures the signal from the source, enhances it using an amplification factor G, and then transmits it to the destination. To optimize the end-to-end signal-to-noise ratio (SNR) in a two-hop system, the amplification factor G of the relay is determined as follows, based on [6]:

$$G^2 = \frac{1}{\varepsilon_1 |h_1|^2 + N_o} \qquad (3)$$

1.1.3 Interference to Signal Ratio

The Interference-to-Signal Ratio (ISR) is defined as the ratio of the average received co-channel interference power to the average received modulated carrier power [7-9]. In this paper, ISR is defined as the interference from cellular user equipment (CUE) to D_1 (which is source of D2D communication). To calculate the ISR, we need to define a δ_D-Interference limited area (ILA) control [10]. In Figure 2, the δ_D-ILA control scheme is defined as the area in which the ISR from CUE to D_2 is greater than a threshold δ_D.

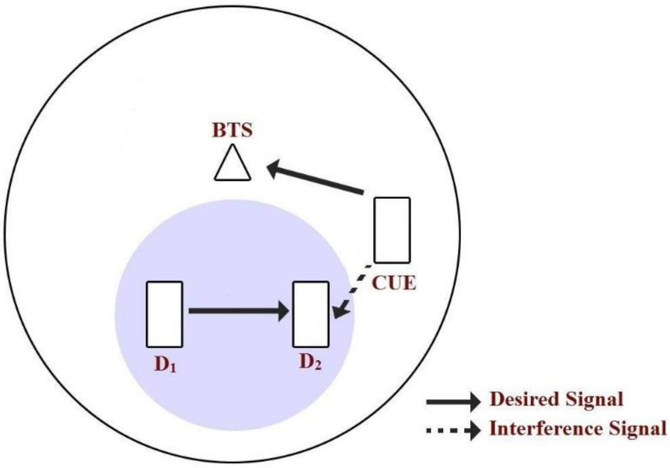

FIGURE 2: *δD-ILA* control scheme [38].

The constraint for *δD-ILA* is expressed as:

$$I_R = \frac{P_{I,C_{UE}D_2}}{P_{S,D_1D_2}} > \delta_D \qquad (4)$$

1.1.4 Capacity

Capacity refers to the maximum rate at which information can be transmitted reliably over a communication channel. The capacity for both direct and indirect communication modes is derived from the Shannon Capacity formula [11], [12]. While the capacity for the indirect mode is represented as a single-hop transmission system [41], they can be mathematically expressed as in equation (5).

$$C_{direct} = log_2\,(1 + \gamma_{direct}) \qquad (5)$$

From [11], the formula for *I*-hop capacity is defined as:

$$C_{indirect} = \frac{1}{I} log_2\,(1 + \gamma_{eq}) \qquad (6)$$

Where γ_{eq} is defined as [12]:

$$\gamma_{eq} = \frac{1}{2} log_2 \left(1 + \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2 + 1}\right) \qquad (7)$$

Substituting (7) in (6), indirect capacity is defined as:

$$C_{indirect} = \frac{1}{2} log_2 \left(1 + \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2 + 1}\right) \qquad (8)$$

where *I* is the number of hops, in this case *I* = 2.

II. Literature Review

The rapid advancements in telecommunications are largely driven by developments in cellular networks, which play a central role in enhancing security, privacy, network capacity, and data transfer speeds [1-2]. Device-to-device (D2D) communication, an emerging technology, offers promising solutions to these evolving demands. Historically, many cellular network operators were reluctant to adopt D2D communication, believing its functionality would be too spatially constrained. However, this perception shifted with the rise of mobile proximity-based applications, which demonstrated the potential of D2D communication. As a result, research in this area gained significant momentum, with major cellular network operators now taking the lead in advancing D2D communication technologies [3].

2.1 D2D Communication

Hadyanto et al. [4] conducted a literature review exploring the fundamental principles, benefits, and energy consumption of D2D communication within various 5G technology scenarios. Their study examined aspects such as D2D performance and interference [1,2,4], as well as methods for enhancing signal and data transfer. These include relaying signals through devices still connected to a base station, spectrum allocation for optimizing radio resource usage, and LTE-A transmission to reduce information diffusion time. The study also identified interference management as a major challenge in D2D communication [4,5].

Additionally, the research briefly classified D2D communication into in-band and out-band modes while highlighting privacy and security concerns, such as user rights violations. Other discussed topics included energy consumption, cellular and IoT relay schemes, cost implications, and the application of D2D in disaster management. However, mode selection in D2D communication was not addressed.

Studies in [1-3,13] focused on D2D applications for local data services, information sharing, data computation offloading, and network coverage extension. D2D communication plays a crucial role in emerging technologies such as Machine-to-Machine (M2M) and Vehicle-to-Vehicle (V2V) communication [14]. Furthermore, the D2D network architecture was analyzed under various subtopics, emphasizing key challenges, including synchronization issues when user equipment (UE) operates under different base stations or networks. Other challenges highlighted include peer discovery, mobility management, security, and pricing concerns [15-17].

Resource allocation emerged as a critical challenge in D2D communication since network resources must be shared between D2D and conventional cellular communication modes [18]. This, in turn, increases the likelihood of interference, making interference management a major concern. The study acknowledged that resource allocation, interference management, and mode selection are interdependent.

In [19], the primary objective was to enhance energy efficiency in D2D communication systems. The authors argued that optimizing resource allocation—covering aspects such as mode selection, channel assignment, and power control—is essential to achieving this goal. Since multiple D2D communication modes exist, including dedicated, cellular, and reuse modes, selecting an optimal mode is crucial.

Energy efficiency, defined in [20] as the ratio of the sum rate to total power consumption, was optimized using various resource allocation strategies. The study emphasized that these resources should not be considered in isolation but rather in their interrelated contexts.

Using a programming-based approach, the study in [21] investigated the joint optimization of mode selection and power control to enhance energy efficiency in D2D communication. Their algorithm covered both dedicated and selection modes, utilizing combinatorial fractional programming and the branch-and-bound algorithm to determine an optimal solution. However, this approach was deemed too limited given the vast range of possibilities within D2D communication.

The proposed solution in [22] still relied heavily on base station resources, which could negatively impact spectral efficiency. Meanwhile, [23] suggested that shared cellular mode offers better spectral efficiency than dedicated mode in D2D communication. However, as highlighted in [24], one of the biggest challenges with shared mode is interference management. This occurs when both licensed and unlicensed spectrum links are reused, leading to interference between D2D connections and cellular resources.

To address interference challenges associated with resource sharing, researchers in [25-27] proposed a learning framework based on Markov approximation to design a tailored Markov chain. This was considered an efficient interference-aware resource allocation scheme. However, the approach was not well-suited for dense D2D networks.

The game-theoretic approach proposed in [28] for power and channel allocation provided some solutions but struggled with the dynamic nature of D2D channel conditions. Similarly, the method in [29] aimed to give user devices greater control over their actions based on locally available information. However, this raised concerns about user privacy, as it was unclear how much information could be shared without violating privacy regulations.

2.2 Research Gap

From the literature reviewed, it is evident that conventional mode selection methods for Device-to-Device (D2D) communication largely prioritize traditional performance metrics such as bit error rate (BER), signal-to-noise ratio (SNR), interference-to-signal ratio (ISR), received signal strength indicator (RSSI), and proximity. However, these methods lack a critical mechanism for incorporating energy-aware adjustments into the decision-making process. The energy levels of the devices involved in communication, which play a significant role in ensuring sustainable and efficient operation within D2D systems, are often overlooked. This oversight limits the adaptability and effectiveness of existing frameworks, particularly in scenarios where energy constraints are pivotal. Addressing this research gap, the proposed work integrates energy awareness with traditional performance metrics to develop an optimized mode selection framework, thereby enhancing the overall efficiency and reliability of D2D communication systems.

III. Materials and Method

An enhanced mode selection model is introduced, incorporating three communication flows: direct D2D, relay, and cellular. The optimized mode selection model for Device-to-Device (D2D) Communication is outlined in Algorithm 1. The problem is framed using the Markov Decision Process (MDP) approach, aiming to maximize the system's total expected reward. This algorithm is designed to dynamically select the optimal communication mode by considering factors such as distance, channel quality, and network conditions, thereby promoting efficient and adaptive D2D communication.

The mode selection criteria are determined by evaluating ergodic channel capacity, signal-to-noise ratio (SNR), received signal strength indication (RSSI), interference-to-signal ratio (ISR), and distance metrics. Furthermore, the mode selection detection issue is approached as a hypothesis testing problem, with analytical expressions developed to quantify correct detection, false alarms, and missed detections.

Algorithm 1: Optimized Mode Selection for Device-to-Device (D2D) Communication

```
Input:
        $D$: Distance between devices.
        $SINR$: Signal-to-Interference-plus-Noise Ratio.
        NLoad: Network load on the base station.
        E: Device energy leve
        Thresholds: $D_{max}, SINR_{min}, Load_{max}$.
Outputs:
        Selected Mode: Direct D2D, Relay, or Cellular.
Steps:
1.      Initialize parameters based on network conditions
2.      Input device parameters: Measure $D, SINR, NLoad, E$
3.      Check Direct D2D Feasibility:
            If $D \leq D_{max}$ AND $SINR \geq SINR_{min}$:
                Select Mode: Direct D2D.
                Exit
4.      Check Relay Feasibility:
            If $D > D_{max}$ OR $SINR < SINR_{min}$ BUT:
                A relay device is available AND the relay's SINR satisfies $SINR_{relay} \geq SINR_{min}$
                    Select Mode: Relay.
                    Exit.
5.      Fallback to Cellular Mode:
            If neither Direct D2D nor Relay is feasible OR:
                $NLoad \leq Load_{max}$:
                    Select Mode: Cellular.
6.      Energy-Aware Adjustment:
            If $E$ (device energy level) is critically low:
                Override to Cellular Mode to preserve device power.
7.      End
```

Proposed mode would be the maximum of the mode selection rule for RSSI. The rule shows that P_{R_direct} would have a higher value than $P_{R\_indirect}$ whenever the devices are near to each other compared to them being further away from the BTS. For instance, when is P_R is -40 dB for direct and -60 dB for indirect, direct mode is chosen due to a higher level of RSSI.

The summary of the mode selection rules is shown in Table 1. For every mode selection rule, decision rule was formulated. Depending on the hypothesis, and the system parameters for the mode selection rules, a mode was selected to enhance the performance of the D2D communication.

Table 1: Summary of mode selection rules.

Mode Selection Rule	Decision Rule	Hypothesis
Capacity	$z_c = C_{indirect} - C_{direct}$	$H_0 : z_c > 0$ $H_1 : z_c \leq 0$
SNR	$z_s = \gamma_{indirect} - \gamma_{direct}$	$H_0 : z_s > 0$ $H_1 : z_s \leq 0$
Distance	$z_d = d_{direct} - \gamma$	$H_0 : z_d > 0$ $H_1 : z_d \leq 0$
ISR	$z_i = \gamma_{\delta_D\_indirect} - \gamma_{\delta_D\_direct}$	$H_0 : z_i > 0$ $H_1 : z_i \leq 0$
RSSI	$z_r = P_{R\_indirect} - P_{R\_direct}$	$H_0 : z_r > 0$ $H_1 : z_r \leq 0$

3.1 Simulation Setup

The simulation was set up in MATLAB R2021a within a single-cell environment, where the base transceiver station (BTS) was positioned at the center of the cell. The simulation accounted for signal strength decay around the BTS. After defining the simulation area, devices were strategically placed within the environment. The simulation was conducted on an HP system with a Core i7 processor (3.0 GHz speed), 16GB RAM, and a 512GB SSD. The key parameters used in the simulation are outlined in Table 2.

Table 2: Simulation parameters.

Parameters	**Value**
Coverage Area, R	700 m
Carrier Frequency	800 MHz
BTS Transmission (Tx) Power	43 dBm
D2D Tx Power	27 dBm
Noise Power	-116.4 dBm
$\boldsymbol{\delta_B}$	0.01

The device *D*$_1$, is placed at a fixed place in every simulation, whereas the device *D*$_2$ is placed randomly across the radius *R*. Additionally, *D*$_1$ and *D*$_2$ cannot be at the same location at the same time. To evaluate the performance of D2D modes, we consider a large number of simulations. In every simulation, all the possible D2D communication modes are calculated and analyzed. Figure 3, shows a random snap shot of the simulation setup where the device *D*$_2$, are randomly being placed across the radius *R*, although there are 200,000 D2D pairs considered for our simulation.

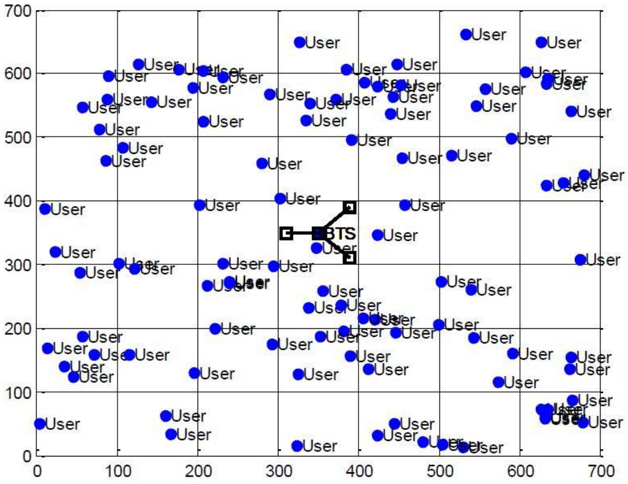

FIGURE 3: Devices being randomly placed around the BTS.

IV. Results and Discussions

4.1 Results of the Measurement Campaigns

This section provides a performance analysis of the simulation setup. The signal transmitted from the BTS experiences fading, modeled as Rayleigh fading. Both the theoretical bit error rate (BER) for Rayleigh fading and the simulated BER from the Rayleigh fading model were calculated within the simulation setup. These values indicate the number of bits that failed to reach the destination due to factors like multipath propagation, obstacles, signal bandwidth, or the user's speed. Figure 4 illustrates the BER in the Rayleigh channel, demonstrating that the simulated and theoretical BER values are identical.

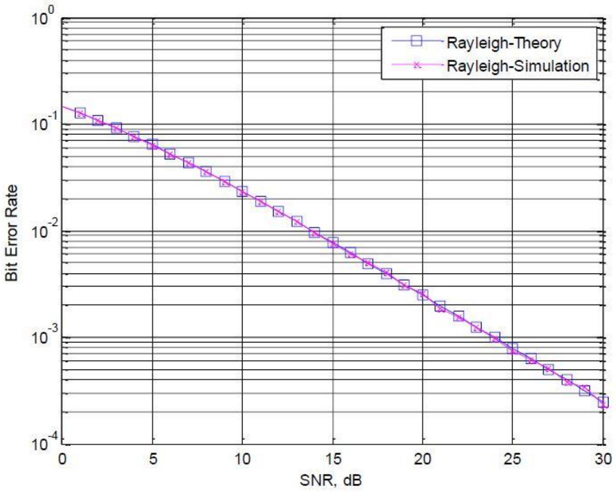

FIGURE 4: BER for BPSK in a Rayleigh channel.

Figure 5 presents a comparison of the average capacity for different mode selection rules. The ISR rule demonstrates the highest average capacity, as it minimizes interference in the interference-limited area, thereby enhancing capacity. At one point, the ISR rule achieves a capacity of 20.1 bps/Hz. In comparison, the capacity rule has an average capacity of 14.2 bps/Hz at the same instant, followed closely by the SNR rule with an average capacity of 14.1 bps/Hz. The RSSI rule has a lower average capacity of 6.4 bps/Hz, while the distance rule shows the lowest capacity at 6.1 bps/Hz, due to the defined proximity region. If the devices fall outside this proximity region, indirect mode would be selected.

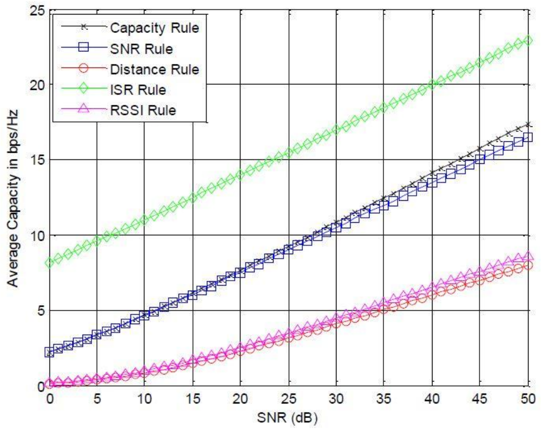

FIGURE 5: Average capacities for different rules.

Figure 6 illustrates the SNR for both direct and indirect communication modes. The SNR using the δD-ILA control scheme is higher compared to the standard SNR, as interference was calculated for an area with minimal interference, resulting in an improved SNR. The graph shows that the SNR for direct mode is 31.2 dB at a given instant, while after applying the δD-ILA, the SNR-ILA for direct mode increases to 57.4 dB. Similar calculations for the indirect communication mode are also shown. The graph indicates that the SNR for indirect mode is 20.2 dB initially, and after the introduction of δD-ILA, the SNR-ILA for indirect mode rises to 44.3 dB. It is evident that the SNR for direct mode is higher than that for indirect mode. The improvement in SNR for direct mode with the δD-ILA control scheme is 26.2 dB, while the gain for indirect mode is 24.1 dB.

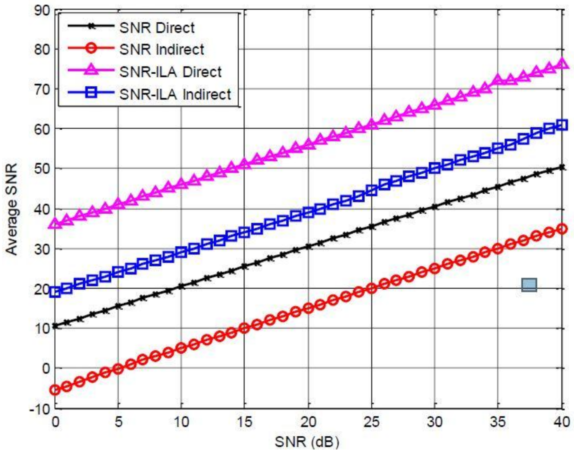

FIGURE 6: Average SNR for direct and indirect mode of communications.

Figure 7 presents the capacities for both direct and indirect communication modes. The capacity with the δD-ILA control scheme is higher than the standard capacity, as the interference was calculated for a region with minimal interference, leading to a higher capacity. According to the graph, the capacity for direct mode is 7.3 bps/Hz at a given instant, and after applying the δD-ILA control scheme, the capacity-ILA for direct mode increases to 13.8 bps/Hz. Similar values for the indirect communication mode are also depicted. The graph shows that the capacity for indirect mode is 3.4 bps/Hz initially, and after the introduction of δD-ILA, the capacity-ILA for indirect mode rises to 6.1 bps/Hz.

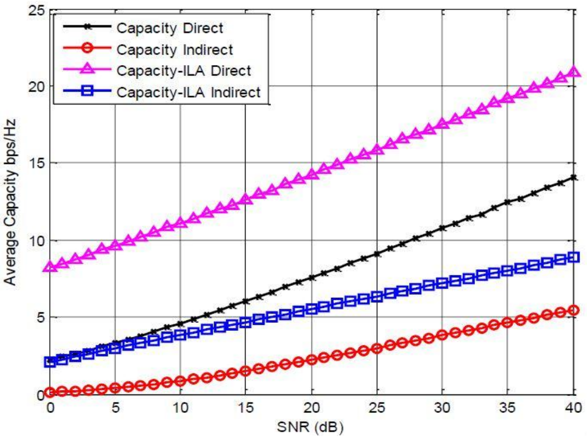

FIGURE 7: Average capacity for direct and indirect mode of communications.

Figure 8 displays the normalized frequency histogram for various communication modes based on different performance metrics. It is observed that the capacity rule selects direct communication mode more frequently than the other mode selection rules, as the capacities are measured and compared. The highest capacity is chosen regardless of the devices' location, whether they are close to each other or far apart. A similar trend is observed for the SNR and ISR mode selection rules. Interestingly, since a limited distance is preferred for optimal D2D communication performance, a higher probability is shown for selecting the indirect mode. When the devices are within the proximity region, direct mode is chosen, enhancing the effectiveness of D2D communication. As received power decreases with increasing distance, the RSSI rule follows a pattern similar to the distance rule, where indirect mode is selected more frequently according to the hypothesis defined in the previous chapter.

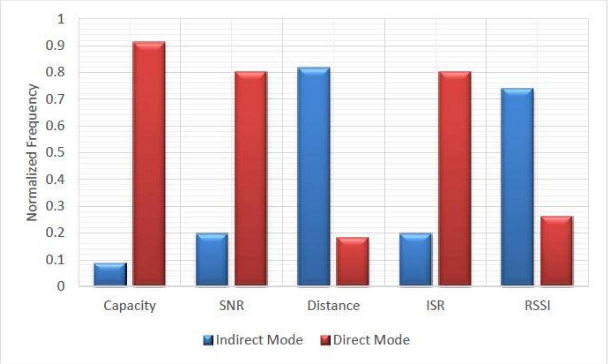

FIGURE 8: Normalized frequency histogram for modes of communication.

Figure 9 illustrates the probability of correct detection for various mode selection rules. It is observed that as the variance increases, the probability of correct detection decreases for each rule. From the graph, at a specific moment, the probability of correct detection for the capacity rule is 0.976, for the SNR rule it is 0.964, for the ISR rule it is 0.9615, and for the RSSI rule it is 0.96.

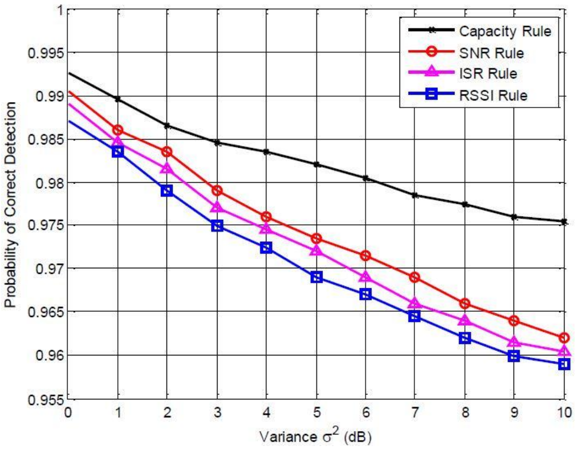

FIGURE 9: Performance results for probability of correct detection.

As the variance increases, the likelihood of making an incorrect decision rises, which in turn increases the probability of a false alarm, as depicted in Figure 4.13. From the figure, it can be observed that at a specific moment, the probability of a false alarm for the capacity rule is 0.0047, for the SNR rule it is 0.0056, for the ISR rule it is 0.0062, and for the RSSI rule it is 0.0115. The data demonstrates that when a mode selection rule has a higher probability of correct detection compared to others, its probability of a false alarm will be lower. For instance, since the capacity rule has the highest probability of correct detection, it also has the lowest probability of a false alarm.

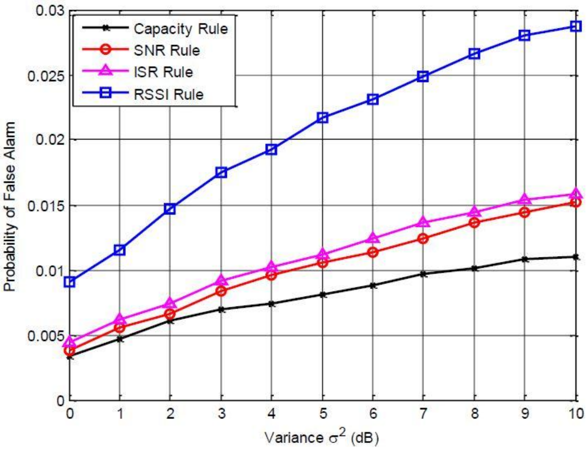

FIGURE 9: Performance results for probability of false alarm.

V. Conclusion

This paper has presented an optimized framework for mode selection in Device-to-Device (D2D) communication, addressing critical performance challenges within cellular networks. Through a comprehensive analysis of D2D performance metrics, the research identified key factors such as bit error rate (BER), signal-to-noise ratio (SNR), interference-to-signal ratio (ISR), received signal strength indicator (RSSI), and proximity, which significantly influence D2D communication. By formulating the problem as a Markov Decision Process (MDP) and employing the value iteration algorithm, the study proposed a robust mode selection framework aimed at maximizing the system's total expected reward.

Simulation results demonstrated the efficacy of the proposed model, with theoretical and simulated BER under Rayleigh fading showing strong alignment and validating the simulation setup. The framework's ability to adaptively select the optimal mode was evident in the performance of various selection rules, with the ISR rule achieving the highest average capacity of 20.1 bps/Hz, followed by the capacity and SNR rules. The δD-ILA control scheme further enhanced performance, significantly improving both direct and indirect mode capacities.

Additionally, the probability of correct detection for the capacity rule outperformed other selection criteria, highlighting its reliability under diverse conditions. These findings underscore the critical role of an effective mode selection strategy in optimizing D2D communication and mitigating interference in cellular networks.

Overall, the research provides a practical and scalable solution for improving the performance of D2D communication systems. The insights gained from this study are not only applicable to current cellular networks but also serve as a foundation for future advancements in 5G and beyond, where efficient resource allocation and interference management are paramount.

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