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# Performance Analysis of DF Relay-Assisted D2D Communication in a 5G mmWave Network

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**Abstract:** Enabling D2D communication in the mmWave band has many obstacles that must be mitigated. The primary concern is the introduction of interference from various sources. Thus, we focused our work on the performance of decode-and-forward (DF) relay-assisted D2D communication in the mmWave band to increase the coverage probability and energy efficiency (EE). Three modes are proposed for D2D communication to prevail. The bitwise binary XOR operation was executed at the relay node, which increased the security feature. The radius of coverage was derived, which indicated the switching of the modes. The diffused incoherent scattering power was also considered as part of the power consumption. Furthermore, a unique relay selection scheme, the dynamic relay selection (DRS) method, is proposed to select the optimal relay for information exchange. A comparison of the proposed DF relay scheme with the amplify-and-forward (AF) scheme was also made. Finally, the simulation results proved the efficacy of the proposed work.

**Keywords:** dynamic relay selection; decode-and-forward; D2D communication; radius of coverage; coverage probability; mode selection; mmWave network; uplink channel



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## 1. Introduction

Device-to-device (D2D) communication is poised as the perfect candidate for 5G and beyond (B5G) communication in the mmWave band due to its inherent advantages over other contemporary technologies. This is due to the larger bandwidth, increased data rate, ultra-low latency, and lesser interference in the unused spectrum [1]. Furthermore, it enhances the spectral (SE) and energy efficiency (EE) of the network by setting up a direct information transfer among the devices without directly controlling the base station (BS). However, setting up D2D communication in the mmWave band of 28 GHz has some challenges associated with it [2]. Signal propagation in the mmWave band undergoes extensive degradation due to interference and blockages such as atmospheric attenuation, attenuation due to precipitation, blockage by humans, blockage by foliage, etc. This significantly reduces the strength of the received signal at the user, which subsequently reduces the signal-to-interference-plus-noise ratio (SINR). In addition to this, this decrease in the SINR lowers the data rate of the overall network, which results in a decrease in the SE and EE [3].

Relaying plays a pivotal role in extending the coverage area of D2D communication in mmWave networks. As the distance between the D2D users increases or if a D2D user is located at a far edge of the cell, the signal strength also drops extensively, which further diminishes the throughput of the D2D user. To solve this problem, the relaying technique is applied effectively to maintain the SINR above a certain predefined threshold level and to enhance the quality of service (QoS) of the communication network. In comparison to direct communication, relaying has more advantages in the case of mmWave networks such as increased throughput, increased network coverage, better capacity, etc. [4]. Among all relay types, decode-and-forward (DF) relaying is widely used in communication systems. The DF relay node receives a signal transmitted from a D2D transmitter, decodes the transmitted signal, then forwards it to the receiving D2D user after the self-interference cancellation procedure, which shows an advantage over amplify-and-forward (AF) relaying. It also helps enhance the security of the network. Although the computational time increases when implementing DF relaying, the huge benefit it provides balances these minor issues. In the next section, we present a literature survey of the state-of-the-art works to provide a glimpse at the current trends in D2D communication using DF relaying.

### 1.1. Related Works

As discussed above regarding the advantages of implementing DF relaying to enhance network coverage and provide the seamless operation of D2D communication in mmWave networks while satisfying the QoS constraints, DF relaying has widespread applications that enhance the SINR and thereby increase the data rate of D2D users. Some of the techniques related to the performance enhancement of relay-aided D2D communication are discussed as follows.

In [5], the authors addressed the power control problem between the D2D source and the relay node at a new anglefor EE in DF relay-aided D2D communication. The EE of the relay node to the D2D link was maximized while satisfying the minimum data rate of the cellular link. The maximization was performed by obtaining the optimal power at both the D2D transmitter and the relay node. In [6], a stochastic geometry was used to obtain the coverage probability for a relay-aided mmWave cellular network in the downlink channel. Blockages and beamforming gains were also considered while obtaining the coverage probability and SE for line-of-sight, as well as non-line-of-sight paths. In [7], three communication transmission modes were proposed to investigate the achievable sum rates of D2D communication assisted by DF relay nodes. The corresponding expressions for the ergodic achievable sum rates of each transmission mode were obtained to compare the performance metrics of direct communication to those of DF relay-assisted D2D communication. It was found that the DF relay-aided D2D communication exhibited better performance than direct communication. Again, the authors in [8] derived an ergodic rate for a D2D communication system aided by a two-way DF relay node. They formulated two scenarios, the weak interference case and the high-SNR case, giving better insight into the problem and deriving the closed-form power allocation strategy to showcase the improvement in system performance. The authors derived closed-form expressions of the coverage probability and transmission capacity for a full-duplex amplify-and-forward (FDAF) relay-aided D2D communication network in [9]. The parameters such as the D2D user density, relay node density, and distance between D2D pairs were also considered to simulate the environment. The authors in [10] considered two interference cancellation models to evaluate the transmission capacity of relay-assisted D2D communication. Furthermore, they investigated the effect of these parameters on the overall network performance. The authors in [11] put forward a power control problem in which two optimization objectives were considered, i.e., the maximization of the minimum SINR of the D2D users and the maximization of the sum rate of the D2D users for a two-way AF relay to assist the underlay D2D communication. In [12], an interference-free dual-hop D2D-aided cooperative relaying strategy (CRS) based on spatial modulation was proposed. Two scenarios were assumed, each operating in two different time slots. Interference-free information was received at the end user node without allocating any fixed transmit power. The bit error rate and SE were also derived to show the performance of the proposed work. A multi-objective combinatorial optimization problem was modeled in [13], which helped balance the trade-off between the total transmit power and the system data rate. The authors also proposed a centralized relay selection and power allocation algorithm, which achieved the Pareto-optimal solution in polynomial time. This method reduced the total transmit power and improved the system throughput. The authors in [14] proposed a scheme with manifold objectives in the form of the ability to improve the SE by using underlay spectrum sharing mode, alleviate co-channel interference, and enhance comprehensive performance while satisfying multiple QoS metrics. The relay selection overhead was reduced by implementing the greedy algorithm based on a distributed local search that improved the EE along with the convergence time through a power adjustment scheme, which was based on the improved potential game decision algorithm.

As relay selection is also an integral metric for relay-aided D2D communication, we put forward some research works to gain insight into the various techniques through which we can optimally select the relay for D2D communication to aid in its seamless operation. The authors in [15] put forward a relay selection scheme for a cooperative out-band D2D network based on the channel gain value and transmission link distance. A suitable relay was selected based on the minimum distance between the user and the relay node using the quantization-and-forward (QF) protocol. A cooperative electronic relay technique was proposed in [16] for a D2D communication system. The method uses three types of cooperative approaches together, namely the compress-and-forward relay, DF relay, and AF relay. It was found through the numerical results that the D2D outage probability of the proposed method was lower than that of the traditional relay transmission, which was again further minimized by an increase in the number of electronic relays. In [17], the authors proposed a global-positioning-system-based, location-aware, centralized approach to solve the problem of relay selection. A learning-based approach was formulated to detect the presence of static, as well as dynamic obstacles present in the environment. In [18], the authors proposed an optimization scheme using exhaustive search and a fast greedy algorithm for hybrid cellular/wireless local access area network (WLAN) communication with bad channel conditions, which tried to reduce the transmission power from the eNodeB (eNB) to the users. Lastly, in [19], a Markov-chain-theory-based mode selection scheme in a multi-user scenario was proposed to study the system performances. Resource allocation was performed by employing a greedy heuristic algorithm.

### 1.2. Motivation

The research works discussed in the above section portray various techniques involving DF relay-aided D2D communication. The optimal management of relays enhances the spectral efficiency (SE), as well as the energy efficiency (EE) of the overall network. Some papers [6,7,9,10,14] focused on extending the coverage area of D2D communication. Relay selection is also an important area that needs attention. Many researches in the literature have focused on the issues of coverage probability, EE [5,6], throughput [7,9,10], power optimization, etc. The urban mmWave network consists of a large number of users and is susceptibleto co-channel interference. Furthermore, the distance between the users in a mmWave network is much less in comparison to a cellular network, and with the increase in the distance, the SINR becomes degraded, thereby decreasing the data rate. To alleviate this shortcoming, we propose a scheme through which the interference can be minimized, thereby enhancing the SINR and the data rate of the users. The different modes in the proposed scheme operating at different frequencies help reduce the co-channel interference and increase the SINR, thereby enhancing the throughput of the users. Furthermore, the introduction of the existing DF relay from the literature survey in our model helps enhance the throughput and extend the coverage area of D2D communication in a mmWave network. Thus, this work focused on enhancing the coverage probability of the D2D users, as well as finding an optimal method of relay selection in a mmWave network.

### 1.3. Contribution

The proposed work is focused on enhancing the coverage probability of the D2D users using the DF relay, as well as finding an optimal method for relay selection; thus, the contributions of the proposed work are given as follows:

(a) The bitwise binary XOR operation was executed to encode the message received at the relay node using a carrier frequency of 28 GHz in an uplink Rician fading channel, which resulted in an enhanced SINR with higher throughput. This scheme is rarely used in 5G mmWave networks;

(b) Mode switching was utilized to help reduce user traffic;

(c) The proposed dynamic relay selection (DRS) method selects the optimal DF relays based on the higher sum SINR, lower distance, and higher channel gain of the instantaneous SINR of D2D communication;

(d) The diffused incoherent scattering power $(P_S)$ as part of the power consumption was considered at the receiver node for the relay mode operating in the mmWave band for a more realistic and accurate analysis of the EE;

(e) The performance metric of the coverage probability of D2D communication was derived to demonstrate the efficacy of the communication system. The EE for the proposed DF relay was also compared with the AF relay scheme. Numerical results also validated the efficiency of the proposed work.

### *1.4. Notations*

The notations used in this paper are given as follows. The notation $\bigoplus$ represents the bitwise binary XOR operation. $\mathbb{P}$ denotes the probability function. The notation $f_y(.)$ is used to denote the probability distribution function (PDF) for the random variable $y$, see Table 1.

**Table 1.** List of notations.

| Sl. No. | Symbols | Significance |
|---|---|---|
| 1 | $f_c$ | Operating frequency |
| 2 | $d$ | Distance between T and R |
| 3 | $\alpha$ | Path loss exponent |
| 4 | $AT$ | Interference due to atmospheric absorption |
| 5 | $\chi_\sigma$ | Log-normal shadow fading having zero mean |
| 6 | $\sigma$ | Standard deviation (in dB) |
| 7 | $P_C, P_D, P_T, P_S$ | Cellular power, D2D power, circuit power, and scattering power, respectively |
| 8 | $h_{D2D}, h_{C2D}$ | Channel gain for D2D and the CU to D2D, respectively |
| 9 | $h_{C2B}, h_{D2B}$ | Channel gain for the CU to the BS and D2D to the BS, respectively |
| 10 | $d_{D2D}, d_{C2D}$ | Distance between D2D and the CU to D2D, respectively |
| 11 | $d_{C2B}, d_{D2B}$ | Distance between the CU to the BS and D2D to the BS, respectively |
| 12 | $n_D, n_C$ | AWGN noise at D2D and the CU users, respectively |
| 13 | $n_R, n_A, n_B$ | AWGN noise at the relay node, D2D A, and D2D B, respectively |
| 14 | $\gamma_{th}$ | Threshold SINR |
| 15 | $P_{AR}, P_{BR}$ | Received power at the relay node from D2D A and D2D users, respectively |
| 16 | $P_{RA}, P_{RB}$ | Received power at D2D A and D2D users from the relay node, respectively |
| 17 | $P_{SA}, P_{SB}, P_{CR}$ | Received power at D2D A and D2D users from the BS and from the CU to the relay, respectively |

The remainder of the article is organized as follows. Section 2 describes the system model where the basic assumptions along with the path loss model and the information model are discussed. Section 3 gives the problem formulation and analysis. Expressions for the coverage probability of D2D users and the relay selection technique are formulated in this section. In Section 4, the simulation results are analyzed and discussed. Finally, Section 5 concludes the work with remarks about the proposed work along with a brief discussion about the future scope and directions.

## 2. System Model

This section provides the system model for the proposed work along with the scenario description. Let us consider cellular and D2D users present in a cell communicating with each other in a 5G mmWave cellular network using an uplink channel through the assistance of a two-way DF relay protocol, as shown in Figure 1. The cardinality of cellular and D2D users may be denoted by $N$ and $M$, respectively. In this scenario, the cellular users utilize the uplink channel of the spectrum to communicate with the BS. The D2D users reuse the uplink resources of the cellular spectrum to communicate among each other. The cellular, as well as the D2D users are randomly distributed in the cell following a Poisson point process ($PPP$) $\phi$ with densities $\lambda_c$ and $\lambda_d$, respectively, in a finite, two-dimensional plane $\mathbb{R}^2$. The cell consists of two zones for communication to take place among D2D users, namely Zone 1 and Zone 2, respectively. Additionally, the proposed work portrays three modes of communication for seamless communication to take place.

Mode 1: Direct D2D communication takes place at an operating frequency of 2 GHz in Mode 1 while satisfying the QoS constraints of the Zone 1 area.

Mode 2: As the distance between the D2D users and the BS increases toward a certain predefined value, mode switching takes place from Mode 1 to Mode 2, where direct D2D communication occurs at a frequency of 28 GHz.

Mode 3: In Mode 2, if the radius of coverage among the D2D users is greater than a certain predefined threshold, the SINR also reduces significantly. Thus, the data rate also diminishes, which results in a reduced QoS. Thus, to satisfy the QoS constraints and provide seamless operation among the D2D users, mode switching takes place from Mode 2 to Mode 3. The communication in Mode 3 takes place at a frequency of 28 GHz through the assistance of the conventional two-way DF relay node. The relaying occurs with the help of two time slots, $T1$ and $T2$, respectively.

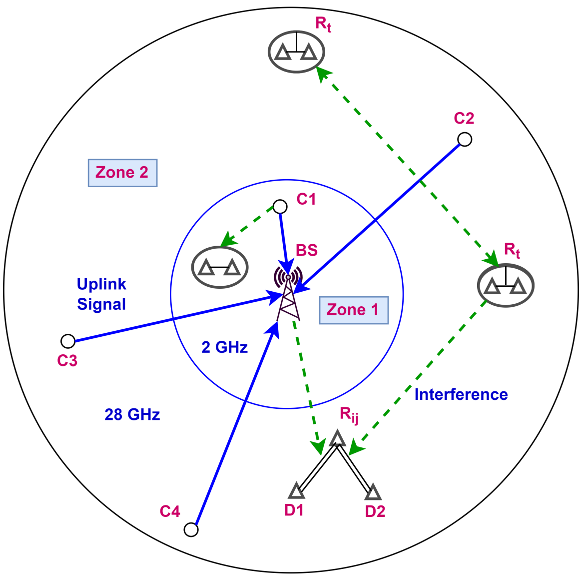


**Figure 1.** System model representing interference acting on D2D users.

### 2.1. Information Model

To realize the proposed scenario, some assumptions were made. The BS has complete knowledge of the channel state information (CSI). Furthermore, it has prior knowledge of the locations of the D2D users and their respective path loss exponents. It was also assumed that the total number of channels available is equal to the total number of cellular users present in the cell. Moreover, the distribution of the relay nodes follows a PPP distribution in a finite, two-dimensional plane $\mathbb{R}^2$ with density $\lambda_{RN}$.

### 2.2. Path Loss Model

The communication between the D2D users in the mmWave band is affected by several environmental factors that cause interference. Therefore, in order to accurately portray the impact of various interference factors on the mmWave network, a path loss model is mentioned in the system model. According to the NYUSIM channel model [20], the path loss model considered for the free-space path loss (FSPL) is as follows,

$$\begin{aligned} FSPL(f,1m)(dB) &= 20\log_{10}\frac{(4\pi f_c \times 10^9)}{c} \\ &= 32.4(dB) + 20\log_{10} f_c \end{aligned} \tag{1}$$

where $f_c$ is the carrier frequency and c is the speed of light. $FSPL(f,1m)$ denotes the free-space path loss in dB with a transmitter–receiver (T–R) distance of 1 m. For high-penetration losses, a large-scale path loss model was considered for a 1m reference distance as per NYUSIM [20], which is shown as follows,

$$\begin{aligned} PL(f,d)(dB) = FSPL(f,1m)(dB) + 10\alpha\log_{10}(d) \\ + AT(dB) + \chi_\sigma \end{aligned} \tag{2}$$

where $d$ is the separation distance (in 3D) between the T–R and $\alpha$ and $\chi_\sigma$ denote the path loss exponent and the log-normal shadow fading having zero mean with $\sigma$ the standard deviation (in dB). $AT$ represents the interference due to atmospheric absorption. The channel gain (Rician fading channel) $h$ between the two D2D users can be represented as [21],

$$h = 10^{-PL(f,d)(dB)/10} \tag{3}$$

$h$ is dependent on the distance between the T–R and is independently and identically exponentially distributed with a mean $\mu^{-1}$.

## 3. Problem Formulation and Analysis

As stated in Section 2, the cell is divided into two parts, Zone 1 and Zone 2. The carrier frequency in Zone 1 was taken to be 2 GHz. The D2D users reuse the uplink cellular resources for direct communication among each other. The D2D communication takes place in Mode 1.

### 3.1. Zone 1

Thus, the received signal at the D2D end user can be expressed as,

$$Y_D^1 = \sqrt{P_D} h_{D2D} d_{D2D}^{-\alpha/2} x_1 + \sqrt{P_C} h_{C2D} d_{C2D}^{-\alpha/2} x_2 + n_D \tag{4}$$

Similarly, the received signal at the cellular user from the BS can be given as follows,

$$Y_C^1 = \sqrt{P_C} h_{C2B} d_{C2B}^{-\alpha/2} x_2 + \sqrt{P_D} h_{D2B} d_{D2B}^{-\alpha/2} x_1 + n_C \tag{5}$$

Thus, the SINR at the respective cellular and D2D users can be derived from Equations (4) and (5) as follows,

$$\gamma_C^1 = \frac{P_C |h_{C2B}|^2 d_{C2B}^{-\alpha}}{P_D |h_{D2B}|^2 d_{D2B}^{-\alpha} + N_0} \tag{6}$$

$$\gamma_D^1 = \frac{P_D |h_{D2D}|^2 d_{D2D}^{-\alpha}}{P_C |h_{C2D}|^2 d_{C2D}^{-\alpha} + N_0} \tag{7}$$

Now, the SINR at the receiver cellular user should be above a certain predefined threshold given by $\gamma_{th}$, i.e.,

$$\gamma_C^1 \geq \gamma_{th} \tag{8}$$

Furthermore, the maximum tolerable interference that the cellular user can withstand is given by,

$$P_{max}^1 = P_D |h_{D2B}|^2 d_{D2B}^{-\alpha} \tag{9}$$

Thus, by equating Equations (8) and (9), we obtain,

$$P_{max}^1 = \frac{P_C |h_{C2B}|^2 d_{C2B}^{-\alpha}}{\gamma_{th}} - N_0 \tag{10}$$

The maximum transmit power, i.e., $P_D = P_{dmax}^1$, that can be attained by the D2D users in Zone 1 can be expressed as follows,

$$P_{dmax}^1 = \frac{P_C |h_{C2B}|^2 d_{C2B}^{-\alpha} - N_0 \gamma_{th}}{\gamma_{th} |h_{D2B}|^2 d_{D2B}^{-\alpha}} \tag{11}$$

EE is an important performance metric to evaluate the proposed communication system. EE may be defined as the ratio of the D2D sum rate to the total power consumption [3]. It has become an indispensable part of green communication. This is because, in recent times, low-power equipment is required to enable D2D communication in mmWave networks. To evaluate the total power consumption in Zone 1, we considered the circuit power consumption $(P_T)$ along with the D2D transmission power $(P_D)$ and the incoherent diffused scattering power $P_S$ at the receiver node. Thus, the total power consumption in Zone 1 can be expressed as,

$$P_{Total} = P_D + P_T + P_S \tag{12}$$

Therefore, the EE of the D2D users in Zone 1 can be expressed as,

$$EE^1 = \frac{Log(1 + \gamma_D^1)}{P_{Total}} \tag{13}$$

Equation (13) gives us the expression for the EE of D2D users in Zone 1 considering different power consumption factors.

### 3.2. Zone 2

As the distance between the D2D user and the BS exceeds the value derived in Equation (11), the mode is switched to Mode 2. In Zone 2, D2D communication may take place through two modes, Mode 2 and Mode 3. Therefore, Zone 2 can be further sub-divided into the primary and secondary phases.

#### 3.2.1. Primary Phase

In Mode 2, the carrier frequency was taken to be 28 GHz (mmWave band). Here, direct communication takes place among the D2D users. Now, let us assume that $R_t$ is the radius of coverage for the D2D users in Zone 2. Thus, from Equation (7), it can be stated that the SINR at the receiver D2D userin Zone 2 should be above the predefined threshold value for seamless operation to take place.

$$\gamma_D^2 = \frac{P_D|h_{D2D}|^2 R_t^{-\alpha}}{P_C|h_{C2D}|^2 d_{C2D}^{-\alpha} + N_0} \geq \gamma_{th}$$
$$\implies R_t^{-\alpha} \geq \frac{(P_C|h_{C2D}|^2 d_{C2D}^{-\alpha} + N_0)\gamma_{th}}{P_D|h_{D2D}|^2} \tag{14}$$
$$\implies R_t \leq \left[\frac{P_D|h_{D2D}|^2}{(P_C|h_{C2D}|^2 d_{C2D}^{-\alpha} + N_0)\gamma_{th}}\right]^{1/\alpha} = R_t^*$$

This equation gives us the expression for the radius of coverage of the D2D users for direct communication in Zone 2 operating in Mode 2.

If $R_t \leq R_t^*$, direct communication takes place among D2D users in Mode 2.

If $R_t > R_t^*$, mode switching takes place from Mode 2 to Mode 3 and communication between D2D users in Mode 3 occurs through the aid of the two-way DF relay node. The operation of D2D communication in Mode 3 through the assistance of the DF relay node is elaborated in the following subsection.

#### 3.2.2. Secondary Phase

In this phase, D2D users are able to communicate with each other through the two-way DF relay node bidirectionally. The operation happens in two time slots, $T1$ and $T2$, as shown in Figure 2. In time slot $T1$, the D2D users $D1$ and $D2$ transmit messages $x_1$ and $x_2$ respectively to the relay node simultaneously. The relay node is also affected by the interference from the cellular users. The received signal at the DF relay node is expressed as follows,

$$Y_R^2 = \sqrt{P_{AR}} h_{AR} d_{AR}^{-\alpha/2} x_1 + \sqrt{P_{BR}} h_{BR} d_{BR}^{-\alpha/2} x_2 + \sqrt{P_{CR}} h_{CR} d_{CR}^{-\alpha/2} x_3 + n_R \tag{15}$$

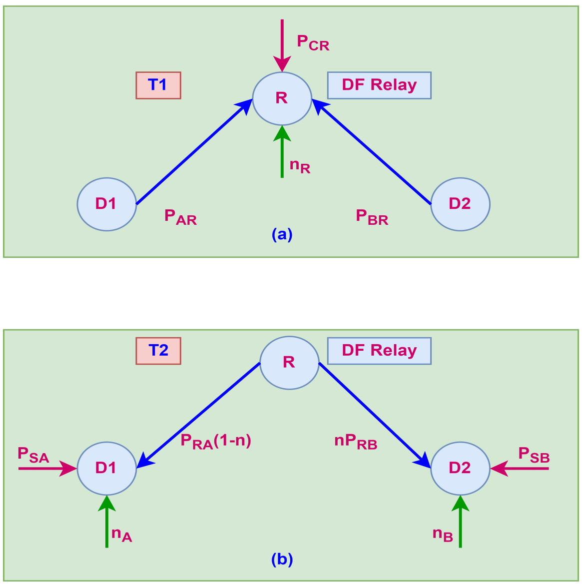


**Figure 2.** Line diagram representing the bidirectional exchange of information between $D1$ and $D2$ through the DF relay in the presence of interference and noise in different time slots. (**a**) time slot $T1$ and (**b**) time slot $T2$.

In time slot $T2$, the relay node then recovers the received messages $x_1$ and $x_2$ through maximum likelihood detection. After recovering the messages, it forms an encoded signal

$(x_1 \bigoplus x_2)$ through the bitwise binary XOR operation. After this operation, the relay node transmits the encoded signal to the respective D2D users.

$$x_R = \sqrt{\eta} x_1 + \sqrt{1-\eta} x_2 \tag{16}$$

Here, the relay uses an average transmit power of $\eta P_{RA}$ in the forward direction and $(1-\eta)P_{RB}$ for the backward direction, where $\eta$ is the power dividing factor. The BS also sends messages to the cellular link, which interfere with the received message at users $D1$ and $D2$, respectively. After applying the self-cancellation technique, the received signal at the respective D2D users can be expressed as follows,

$$Y_A^2 = \sqrt{P_{RA}(1-\eta)} d_{RA}^{-\alpha/2} h_{RA}(x_1 \bigoplus x_2) + \sqrt{P_{SA}} h_{SA} d_{SA}^{-\alpha/2} x_4 + n_A \tag{17}$$

and:

$$Y_B^2 = \sqrt{P_{RB}\eta} d_{RB}^{-\alpha/2} h_{RB}(x_1 \bigoplus x_2) + \sqrt{P_{SB}} h_{SB} d_{SB}^{-\alpha/2} x_4 + n_B \tag{18}$$

Now, in time slot $T1$, the SINR at the respective $D1 - R$ and $D2 - R$ links can be expressed as follows,

$$\gamma_{AR}^2 = \frac{P_{AR}|h_{AR}|^2 d_{AR}^{-\alpha}}{P_{CR}|h_{CR}|^2 d_{CR}^{-\alpha} + N_0} = \frac{\gamma_1}{I_R + 1} \tag{19}$$

and:

$$\gamma_{BR}^2 = \frac{P_{BR}|h_{BR}|^2 d_{BR}^{-\alpha}}{P_{CR}|h_{CR}|^2 d_{CR}^{-\alpha} + N_0} = \frac{\gamma_2}{I_R + 1} \tag{20}$$

where,

$$\gamma_1 = \frac{P_{AR}|h_{AR}|^2 d_{AR}^{-\alpha}}{N_0} \tag{21}$$

$$\gamma_2 = \frac{P_{BR}|h_{BR}|^2 d_{BR}^{-\alpha}}{N_0} \tag{22}$$

and:

$$I_R = \frac{P_{CR}|h_{CR}|^2 d_{CR}^{-\alpha}}{N_0} \tag{23}$$

Therefore, the sum SINR at the relay node can be given by,

$$\gamma_{XR}^2 = \frac{P_{AR}|h_{AR}|^2 d_{AR}^{-\alpha} + P_{BR}|h_{BR}|^2 d_{BR}^{-\alpha}}{P_{CR}|h_{CR}|^2 d_{CR}^{-\alpha} + N_0} \tag{24}$$

For time slot $T2$, the SINR at the respective $R - D1$ and $R - D2$ links can be expressed as follows,

$$\gamma_{RA}^2 = \frac{P_{RA}(1-\eta)|h_{RA}|^2 d_{RA}^{-\alpha}}{P_{SA}|h_{SA}|^2 d_{SA}^{-\alpha} + N_0} = \frac{\gamma_3}{I_{RA} + 1} \tag{25}$$

and:

$$\gamma_{RB}^2 = \frac{P_{RB}\eta|h_{RB}|^2 d_{RB}^{-\alpha}}{P_{SB}|h_{SB}|^2 d_{SB}^{-\alpha} + N_0} = \frac{\gamma_4}{I_{RB} + 1} \tag{26}$$

The notations $\gamma_3$, $\gamma_4$, $I_{RA}$, and $I_{RB}$ in the above Equations (25) and (26) can be represented as follows,

$$\gamma_3 = \frac{P_{RA}(1-\eta)|h_{RA}|^2 d_{RA}^{-\alpha}}{N_0} \tag{27}$$

$$\gamma_4 = \frac{P_{RB}\eta|h_{RB}|^2 d_{RB}^{-\alpha}}{N_0} \tag{28}$$

$$I_{RA} = \frac{P_{SA}|h_{SA}|^2 d_{SA}^{-\alpha}}{N_0} \tag{29}$$

and:

$$I_{RB} = \frac{P_{SB}|h_{SB}|^2 d_{SB}^{-\alpha}}{N_0} \tag{30}$$

### 3.3. Performance Analysis

#### 3.3.1. Coverage Probability of D2D Users

In this subsection, the expressions for the coverage probability of the D2D users are derived by using stochastic geometry as an analytical tool. The message transmitted from users $D1$ and $D2$ to the relay node are encoded and broadcast towards the receiver D2D users. Therefore, the coverage probability of the D2D users should be above a certain threshold value for seamless communication to occur, as well as to maintain the QoS constraints. Thus, the coverage probability of the D2D users in the presence of the DF relay can be expressed as follows,

$$P_{cov} = 1 - \mathbb{P}(\gamma_{AR}^2 \geq \gamma_{th})\mathbb{P}(\gamma_{BR}^2 \geq \gamma_{th})\mathbb{P}(\gamma_{RA}^2 \geq \gamma_{th})\mathbb{P}(\gamma_{RB}^2 \geq \gamma_{th}) \tag{31}$$

The last expression in Equation (31) is obtained by applying the independent property of random variables. As it is evident that $\gamma_j$ where $\{j\epsilon 1, 2, \ldots, 4\}$ is an exponentially distributed random variable, the PDF of $\gamma_j$ can be expressed as,

$$f_{y_1}(\theta) = \frac{1}{\bar{\gamma_1}} exp(-\frac{\theta}{\bar{\gamma_1}}) \tag{32}$$

where $\theta > 0$ and the value for $\bar{\gamma_1}$ is given by,

$$\bar{\gamma_1} = \frac{P_{AR} \nu h_{AR} d_{AR}^{-\alpha}}{N_0} \tag{33}$$

Here, $\nu$ represents the parameter of the exponential distribution of random variables. Similarly, from Equation (10), we obtain,

$$\bar{\gamma_{th}} = \frac{P_C \nu h_{C2B} d_{C2B}^{-\alpha}}{N_0} \tag{34}$$

Now, the probability of different SINR terms involved in Equation (31) can be expressed as follows,

$$\begin{aligned}
\mathbb{P}(\gamma_{AR}^2 \leq \gamma_{th}) &= 1 - \mathbb{P}[\frac{\gamma_1}{I_R + 1}] \\
&= 1 - \int_0^\infty \mathbb{P}[I_R \leq \frac{\gamma_1}{\gamma_{th}} - 1] f_{y_1}(\theta) d\theta \\
&= 1 - \int_0^\infty [\frac{1}{\bar{I_R}} \int_0^{(\frac{\theta}{\gamma_{th}} - 1)} exp(\frac{-y}{\bar{\gamma_{th}}}) dy] f_{y_1}(\theta) d\theta \\
&= 1 + \frac{1}{\bar{\gamma_1}} \int_0^\infty [exp(\frac{1 - \frac{\theta}{\gamma_{th}}}{\bar{\gamma_{th}}}) - 1] exp(-\frac{\theta}{\bar{\gamma_{th}}}) d\theta \\
&= \frac{exp(\frac{1}{\bar{\gamma_{th}}})}{\bar{\gamma_1}(\frac{1}{\bar{\gamma_1}} + \frac{1}{\bar{\gamma_{th}} \gamma_{th}})}
\end{aligned} \tag{35}$$

Similarly, other relations can be obtained as follows,

$$\mathbb{P}(\gamma_{BR}^2 \leq \gamma_{th}) = \frac{exp(\frac{1}{\bar{\gamma_{th}}})}{\bar{\gamma_2}(\frac{1}{\bar{\gamma_2}} + \frac{1}{\bar{\gamma_{th}} \gamma_{th}})} \tag{36}$$

$$\mathbb{P}(\gamma_{RA}^2 \leq \gamma_{th}) = \frac{exp(\frac{1}{\bar{\gamma}_{th}})}{\bar{\gamma}_3(\frac{1}{\bar{\gamma}_3} + \frac{1}{\bar{\gamma}_{th}\gamma_{th}})} \tag{37}$$

and,

$$\mathbb{P}(\gamma_{RB}^2 \leq \gamma_{th}) = \frac{exp(\frac{1}{\bar{\gamma}_{th}})}{\bar{\gamma}_4(\frac{1}{\bar{\gamma}_4} + \frac{1}{\bar{\gamma}_{th}\gamma_{th}})} \tag{38}$$

Thus, substituting these values into Equation (31), we obtain the expression for the coverage probability of the D2D users as follows,

$$\begin{aligned} P_{cov} = 1 - \{1 - \frac{exp(\frac{1}{\bar{\gamma}_{th}})}{\bar{\gamma}_1(\frac{1}{\bar{\gamma}_1} + \frac{1}{\bar{\gamma}_{th}\gamma_{th}})}\} \times \{1 - \frac{exp(\frac{1}{\bar{\gamma}_{th}})}{\bar{\gamma}_2(\frac{1}{\bar{\gamma}_2} + \frac{1}{\bar{\gamma}_{th}\gamma_{th}})}\} \\ \times \{1 - \frac{exp(\frac{1}{\bar{\gamma}_{th}})}{\bar{\gamma}_3(\frac{1}{\bar{\gamma}_3} + \frac{1}{\bar{\gamma}_{th}\gamma_{th}})}\} \times \{1 - \frac{exp(\frac{1}{\bar{\gamma}_{th}})}{\bar{\gamma}_4(\frac{1}{\bar{\gamma}_4} + \frac{1}{\bar{\gamma}_{th}\gamma_{th}})}\} \end{aligned} \tag{39}$$

### 3.3.2. Relay Selection

In Mode 3, while a D2D user, $D1$, communicates with another D2D user, say $D2$, it is assisted by a two-way DF relay node. However, the most prominent task is choosing the best relay node. Thus, there should be a procedure for selecting the relay for overall D2D communication to prevail. This subsection portrays a dynamic relay selection (DRS) method for selecting the best relay node for D2D communication at a frequency of 28 GHz while satisfying the QoS constraints. The steps for the selection of the relay node for two D2D users, $D1$ and $D2$, to communicate with each other in the presence of $R_{ij}$ relays, where $i, j \epsilon \mathbb{R}$, are given as follows:

(1) The transmitter D2D user $D1$ sends a request to all of the relays in its proximity. The respective relay nodes receive the signal and decode it;
(2) The receiver relay sends back the acknowledge signal to user $D1$ along with the information of the instantaneous sum SINR at the relay node, the path loss attenuation, and the distance between the relay node and D2D users $D1$ and $D2$. The instantaneous sum SINR at the relay node from Equation (24) can be expressed as follows,

$$\gamma_{ij}^{in} = \frac{P_i |h_i|^2 d_i^{-\alpha} + P_j |h_j|^2 d_j^{-\alpha}}{P_{CR} |h_{CR}|^2 d_{CR}^{-\alpha} + N_0} \geq \gamma_{th} \quad ; \quad i, j \epsilon \mathbb{R}; \tag{40}$$

(3) User $D1$ sorts the relays based on the distance between the relay node and D2D users $D1$ and $D2$ in increasing order through a binary search method. The relay link exhibiting a higher sum SINR, a lower distance, and higher channel gain is chosen as the relay for D2D communication in Mode 3 as follows,

$$argmax\{\gamma_{ij}^{in}\} \tag{41}$$

## 4. Numerical Results and Discussion

This section presents the simulation results of the proposed scheme to evaluate its performance. A single-cell mmWave network scenario was considered for the simulation. The operating frequency was taken to be 28 GHz for the mmWave band in Mode 2 and Mode 3. The considered path loss model for signal propagation was in accordance with Release 15 [20] of the 3rd Generation Partnership Project (3GPP) as per Equations (1) and (2). The path loss exponents considered for the simulation were 2, 2.5, and 3. A higher system bandwidth of 1 GHz was chosen for the simulation. The simulations were performed in the MATLAB R2021a (version) software developed by MathWorks. The simulation parameters are listed in Table 2.

**Table 2.** List of notations.

| Sl. No. | Symbols | Significance |
|---|---|---|
| 1 | Cell radius | 500 m |
| 2 | Bandwidth $\Omega$ | 1 GHz |
| 3 | Frequency (mmWave mode) | 28 GHz |
| 4 | Thermal noise density | −174 dBm/Hz |
| 5 | Cellular power $P_c$ | 30 dB |
| 6 | D2D power (relay mode) $P_r$ | 20 dB |
| 7 | Circuit power $P_C$ | 5 dB |
| 8 | Scattering power $P_S$ | 4 dB |
| 9 | SINR threshold $\gamma_{th}$ | 0–30 dB |

In Figure 3, a graph is plotted showing the variation in the EE with the change of the threshold SNR when varying the path loss exponents, i.e., 2, 2.5, and 3, respectively. The scattering power and circuit power consumption were taken into consideration for the accurate analysis of the EE. It can be observed from the graph that as the SNR value increased, the EE also increased exponentially. Again, the EE was also affected by the path loss exponent. The curve portraying the EE with a lower path loss exponent has a higher efficiency. This was due to the fact that higher path loss exponents encountered more interference due to blockages and fading.

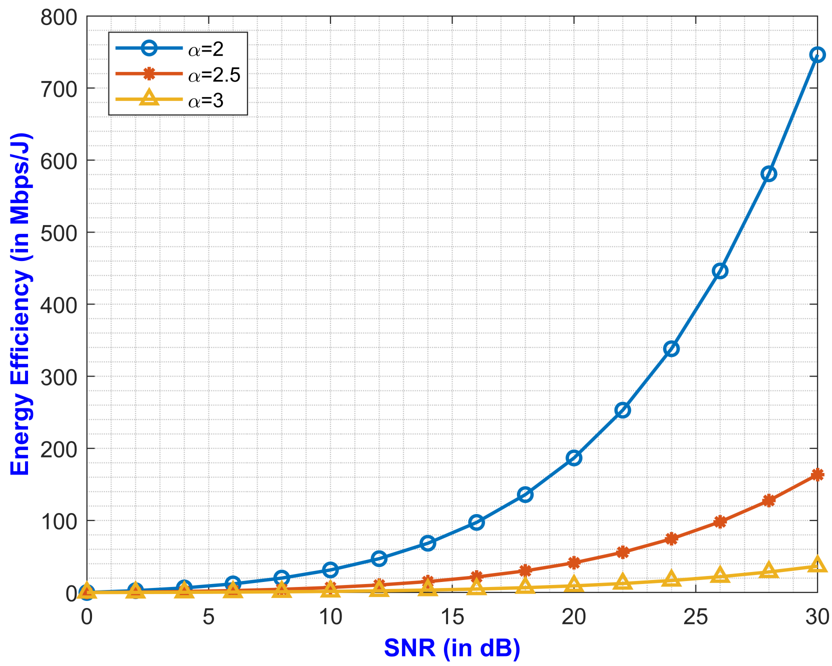


**Figure 3.** EE vs. threshold SNR for varying path loss exponents.

In Figure 4, the coverage probability of the D2D users is portrayed with the variation in the threshold SNR values for varying path loss exponents, i.e., 2, 2.5, and 3, respectively. Equation (39) justifies the curves, which shows that higher path loss exponents have lower coverage. Furthermore, with an increase in the SNR value, the coverage area of the D2D users reduced.

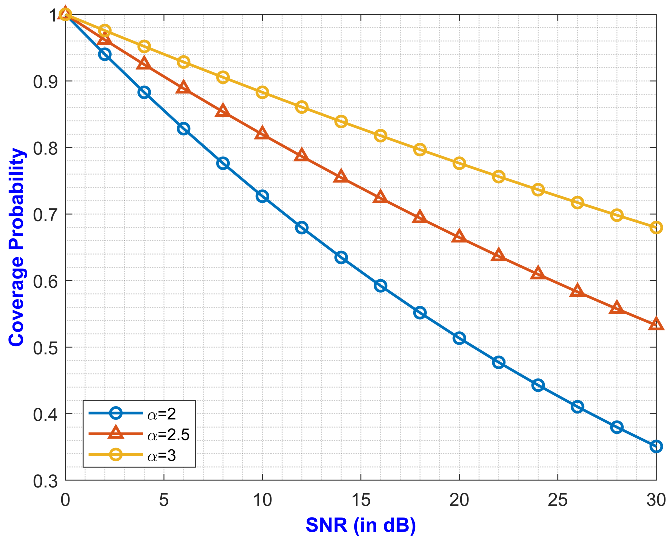


**Figure 4.** Coverage probability vs. threshold SNR for varying path loss exponents.

Figure 5 portrays the graph for the EE for increasing values of the distance between the D2D transmitter and the relay node for varying path loss exponents of 2, 2.5, and 3. Similar to the previous graphs, this graph also shows better performance for lower path loss exponents. However, the EE kept on decreasing as we increased the distance between the D2D transmitter and the relay node. The maximum value of the EE attained in the simulation for DF relay-assisted D2D communication was over 700 Mbps/J.

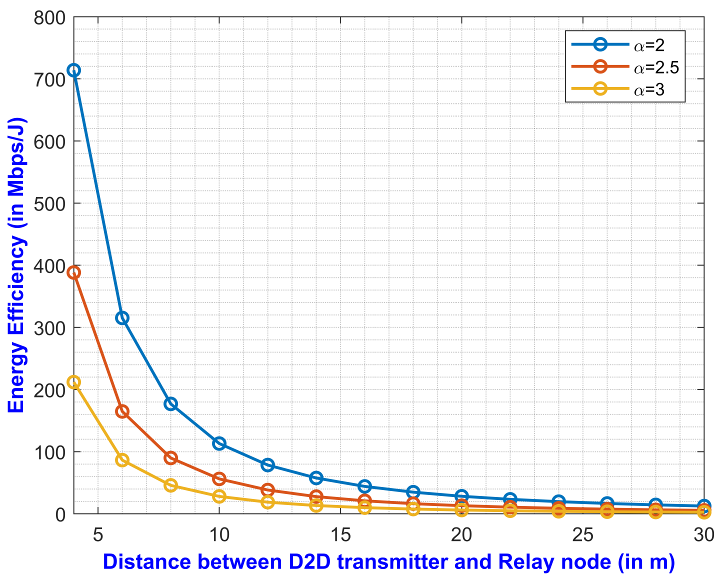


**Figure 5.** EE vs. distance between the D2D transmitter and the relay node for varying path loss exponents.

Again, in Figure 6, a graph is plotted showing the comparison of the proposed DF relay-assisted D2D communication with the AF relay-assisted D2D communication for varying path loss exponents of 2 and 3, respectively. The same environment was considered for the simulation with a carrier frequency of 28 GHz. In a Rician channel, the scheme with the AF relay undergoes much interference at the receiver end due to noise amplification, whereas, in the DF scheme, the interference is canceled due to the encoding of the information at the relay node, and the D2D receiver has a better data rate with a higher SNR. Furthermore, the different modes in the proposed scheme operating at different frequencies helped reduce the co-channel interference. From Figure 6, it is evident that the EE of the proposed work at path loss exponents of 2 and 3 had values of around 750 Mbps/J and 280 Mbps/J, which were better than the AF scheme with values of around 35 Mbps/J and 25 Mbps/J.

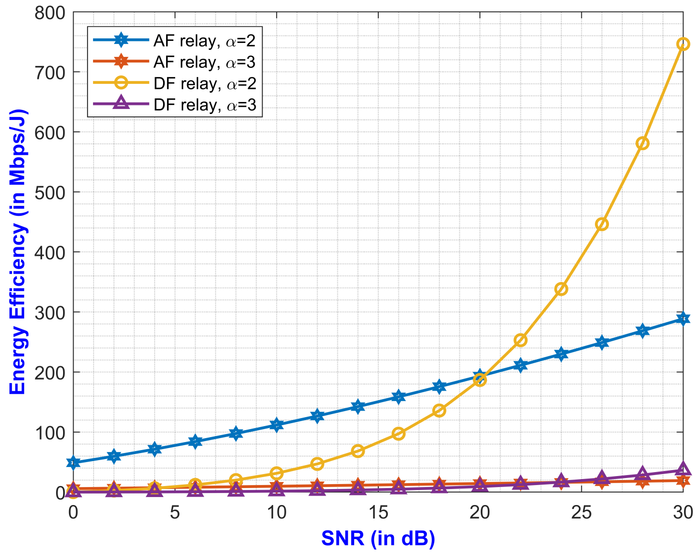


**Figure 6.** Comparison of the EE for the DF and AF relay schemes.

Finally, in Figure 7, we plot a graph showing the comparison of the proposed scheme with the stochastic scheme [3]. The graph depicts the values of the EE while varying the D2D transmit power. The D2D transmit power was taken from 0 mW to 25 mW for varying path loss exponent values, namely 2, 2.5, and 3. From the graph, it can be noted that with the increase in the D2D transmit power, the EE decreased gradually. The EE ranged from around 400 Mbps/J to 80 Mbps/J while varying the D2D transmit power from 0 mW to 25 mW at a path loss exponent of 3. This validated the efficacy of the proposed work, whereby the EE increased with a better coverage probability and higher SINR values.

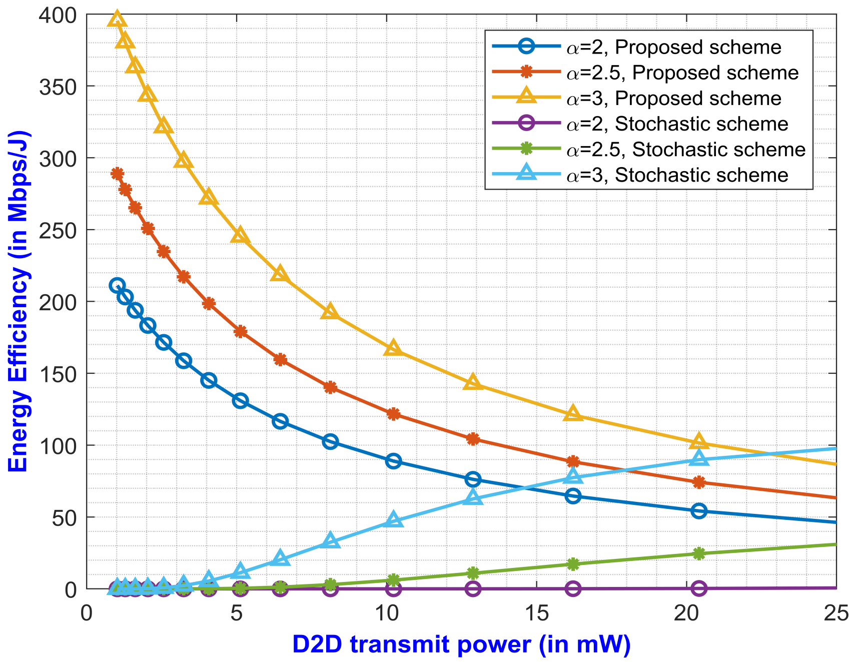


**Figure 7.** Comparison of different schemes with the proposed scheme.

## 5. Conclusions and Future Works

In the proposed work, we introduced three modes for D2D communication to prevail. D2D communication in Mode 1 occurred at a frequency of 2 GHz, which was a direct communication using cellular uplink resources. In Mode 2, D2D communication took place at a carrier frequency of 28 GHz. If the radius of coverage exceeded a certain threshold, it switched to Mode 3. The D2D communication in Mode 3 took place through a DF relay. The bitwise binary XOR operation was executed to encode the message received at the relay node from the D2D transmitter at a carrier frequency of 28 GHz using the uplink Rician fading channel. The radius of coverage was derived for the switching of modes. The coverage probability was also derived to demonstrate the efficacy of the communication system. In addition, the DRS method was proposed for the optimal selection of DF relays based on the higher sum SINR, lower distance, and higher channel gain of the instantaneous SINR of the D2D communication. The simulation results also validated the efficiency of the proposed method. The EE for the DF relay scheme was compared with the AF relay scheme for better understanding and showing the effectiveness of the DF relay over the AF relay. Nevertheless, there is scope for improvement in the coverage area of the D2D users by considering the unknown CSI, which would make the problem statement more realistic in nature. The future works may also consider the dynamics of the interference introduced by the interacting users by applying machine learning and game theory methods.

**Author Contributions:** S.S.S. modeled the system for D2D communication in a 5G mmWave cellular network using an uplink channel through the assistance of a two-way DF relay protocol, implemented the case study, and analyzed the performance of the system under the supervision of R.H. and P.H.J.C. The manuscript was drafted by S.S.S. and was revised and proofread by R.H. and P.H.J.C. All authors have read and agreed to the published version of the manuscript.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| D2D | Device-to-device |
| SE | Spectral efficiency |
| EE | Energy efficiency |
| BS | Base station |
| SINR | Signal-to-interference-plus-noise ratio |
| QoS | Quality-of-service |
| DF | Decode-and-forward |
| AF | Amplify-and-forward |
| FDAF | Full-duplex amplify-and-forward |
| CRS | Cooperative relaying strategy |
| QF | Quantization-and-forward |
| PDF | Probability distribution function |
| PPP | Poisson point process |
| FSPL | Free-space path loss |
| CSI | Channel state information |
| DRS | Dynamic relay selection |

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