Drone assisted device to device cooperative communication for critical environments

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Abstract
This paper proposes drone assisted device-to-device cooperative communication (DA-DDCC) for critical situations during post-disaster management. The proposed network utilizes the autonomous mode of D2D communication for setting up the link in the absence of a central node. This network incorporates cooperative communication using drone in D2D session for improving reliability of the overall system. A probability-based statistical channel model for such networks is proposed by taking the statistical independence of links into consideration. Unlike the existing air-to-ground (A2G) channel models that use either Rayleigh or Rician distribution for uplink (UL) and downlink (DL) channel modelling, our approach takes the probability of occurrence of line of sight (LoS) into account while predicting the appropriate channel distribution for UL and DL separately. For performance evaluation of the proposed network, average outage probability and average capacity are derived using the proposed channel model. Monte Carlo simulations are conducted to verify our analysis. Moreover, a multi-cluster DA-DDCC scenario is also being analyzed through simulations from an interference perspective to justify the usefulness of the proposed channel model. Results obtained through this investigation can be utilized in selecting various crucial system parameters judiciously for enhanced performance during post-disaster scenario.

1 | INTRODUCTION

In recent years, fifth-generation (5G) and beyond 5G (B5G) technologies are being developed to increase the data rates and network capacity for conventional cellular networks. Multiple input multiple output (MIMO) and network traffic offloading techniques are used for achieving such objectives [1–3]. Equipping multiple antennas needs more hardware, cost, and size. Consequently, these methods are not preferred for most of the battery operated tiny devices. To enhance the cellular network performance, traffic offloading techniques are also used in literature. Traffic offloading may be achieved mainly by two methods, one is through small cell (micro/pico/femto) deployment in macro-cells and the other is using device-to-device (D2D) communications [4]. However, the first method may be inconvenient due to a lack of dynamism that occurs because of fixed access points while in second approach flexible offloading can be achieved with(out) support of infrastructure network. In D2D communication, two devices in proximity of each other establish a direct link for data transmission. D2D communication can be accomplished in two modes, namely inband and outband. Inband and outband modes are further divided into groups of two submodes each as underlay, overlay, and controlled, autonomous, respectively [4]. Out of these four submodes, underlay, overlay, and controlled modes require the assistance of base station (Figure 1(a)) while autonomous mode can be executed in the absence of base station as well (Figure 1(b)) [5]. Our proposal is based on this peculiar characteristic of the D2D technique. Often communication systems become non-functional due to disruption of base station/eNB (evolved node B) after natural/man-made calamities. Under such circumstances, autonomous mode of the D2D technique

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can be harnessed to set-up communication links among various nearby users. For example, this kind of ad-hoc link set-up can be very useful in search and rescue missions during post-disaster management operations. Rescue groups and victims can easily communicate, and the recovery process can speed up. Various works related to the D2D communication can be found in [6–8]. However, existing literature does not harness the autonomous mode of the D2D communication technique thoroughly.

Inherent limitations of the D2D communication technique (such as device size, limited range, battery constraint) call for an association of suitable method to take care of random nature of channel effects. Therefore, use of unmanned aerial vehicle (UAV) or drone in D2D links is proposed to incorporate cooperative communication (CC) for increased reliability by combating the effect of deep fades. This provides an additional path (diversity) between devices for improving the performance of the network along with accuracy in crucial decisions. To the best of our knowledge, this is the first attempt to integrate CC with D2D links in autonomous mode. UAVs/drones are an emerging use cases for next-generation wireless networks. By adjusting the position of drone, the probability of LoS can be increased. Facebook [9] and Google [10] have been deploying a large number of drones for providing better services to rural areas. Amazon [11] is making use of small drones for service delivery purposes. On the one hand, drones can be used as temporary aerial base stations in a cellular network [12], on the other hand, drones can also be used as aerial relays [13] for establishing cooperation between remote sensors and the base station. Further, the introduction of a drone in D2D set-up brings cooperation which provides robust and reliable communication in critical operations like rescue missions. Drone-based CC has been discussed in [14] with fixed channel distributions and without using D2D communication. UAV-assisted D2D network in underlay mode is discussed in [15] and authors derived outage probability using Rayleigh fading for A2G links. UAV-assisted D2D network in underlay mode using large scale fading is discussed in [16]. Cellular based D2D network in semi-autonomous mode using Rayleigh fading is discussed in [17]. In [18] an autonomous mode selection scheme for underlay D2D communication using Rayleigh fading is discussed. However, none of the existing works address the use of drone assisted D2D links in autonomous mode for critical situations.

In existing drone-related works, while modelling the channel between user and drone (relay) or vice-versa, either Rayleigh or Rician distribution is assumed for both the links, based on the non-line-of-sight (NLoS) or LoS conditions [19–21]. Authors in [22] used the Nakagami-m fading channel for modelling A2G links to derive coverage probability. In [23], Nakagami-m faded channel is used for two-hop energy harvesting UAV relay assisted communication. Secrecy outage probability and secrecy diversity gains of the UAV assisted relay cognitive network under Nakagami-m channel are discussed in [24]. In [25], the authors considered unmanned aircraft as a relay node between ground stations without taking the direct link between ground stations and derived outage probability by assuming A2G links as Rician distributed. In [26], communication between ground users (GUs) are considered via UAV, without considering the direct link between them. The authors analyze the outage probability by considering Nakagami-m fading between A2G links. All these works assume the same ‘m’ parameter for UL and DL. UAV assisted underlay mode of D2D communication is discussed in [27], and the authors analyzed coverage and rate by considering A2G links as Rayleigh fading channel. UAV based relaying, scheduling, and trajectory optimization are discussed in [28] without considering the direct link between GUs. Authors in [29] analyzed the secrecy rate by adopting free space path loss model for both uplink and downlink.

However, it should be noted that in practical scenario source to drone and drone to destination channels are statistically independent as the obstacles present may vary in both the channels. Therefore, both these channels may not belong to the same LoS (NLoS) condition. It may happen that within a cycle of cooperative communication, one of these links may encounter strong LoS while other link may see only NLoS components. One such possible scenario is shown in Figure 2. It may be noted that with the present (or lower) height of drone, the direct path between drone and UE is obstructed while a direct path exists between drone and UE. Therefore, the use of a single distribution for modelling the channel in both the links may not be appropriate. Additionally, in order to obtain better link conditions, if the height of drone increases, channel statistics may further change. In general probability of getting LoS increases with the height of drone. Therefore, the system model must be adaptive enough to take such a dynamic nature of links statistics into account. This observation may be justified analytically with the help of the following argument: For a given height of drone, there exists a probability of occurrence of LoS. Using total probability rule, the probability of occurrence of NLoS can also be found. This implies that a link (source to drone or drone to destination) may confront LoS conditions with a corresponding probability of occurrence of NLoS but at the same time, it may suffer from NLoS conditions also with the probability of occurrence.
of NLoS. Therefore, calculations of any performance metric must be averaged over all the possible channel conditions. As per our knowledge, existing literature assumes the same distribution for both the links and thus does not take link independence into account.

1.1 | Motivation

Autonomous mode of D2D communication is the prime motivation for this work. D2D communication can be exploited in networks in two ways. Under normal environment when the base station is functioning properly, D2D communication (in underlay, overlay, and controlled modes) may be utilized for improving spectrum utilization, data rate, energy efficiency etc. Whereas, during critical situations such as earthquakes, floods, various communication infrastructures like base station which plays an important role in setting up the communication links are disrupted, an autonomous mode can be useful. This mode does not require a base station to set-up the D2D communication link. Thus, disaster management can be executed smoothly.

D2D communication is highly sensitive to channel conditions [30]. MIMO or other complex signal processing techniques cannot be practiced to cope with deleterious effects of bad channel conditions due to power constraint at battery-operated devices. This prompts us to propose the use of cooperative communication in a D2D set-up. Use of cooperative communication increases the reliability of the D2D set-up as an appropriate simpler combining technique may be used at the receiver. With many practical applications (public safety, big smart cities etc.) and challenges (drone deployment, device to relay channel modelling etc.), drone-based D2D communications also stimulate many non-trivial issues. One such critical challenge is the accurate channel modelling between a drone and on-ground devices, which still lacks in-depth study. This motivates us to investigate the probability-based statistical approach for finding suitable distributions for UL and DL individually. For such harsh environmental conditions, the proposed DA-DDCC network gives an on-demand, cost-effective, energy efficient, and reliable solution required for speeding up the recovery process. Moreover, given the recent advancements in drone technologies, using drones as a relay (or full-fledged base station) in rescue operations may be a game-changer.

1.2 | Contributions

Main contributions of this work can be summarized as follows:

(i) Integration of drone in the autonomous mode of D2D communication for enhancing the reliability and accuracy of various services. Introduction of the drone as relay serves the purpose of establishing cooperative communication among devices.

(ii) A generic statistical channel model for better characterization of links between nodes in a DA-DDCC network. Unlike previous works, where A2G (uplink as well as downlink) links were modelled as either Rayleigh or Rician distributed for NLoS or LoS links respectively, this model takes a probability-based statistical approach to decide the link distribution between user equipment (UE) and relay node. The pseudocode of proposed model for simulation purpose is further elaborated in Section 6.

(iii) In contrast to the existing works on cooperation [31–33], where relay remains in the same plane as source and destination, this work proposes and analyses vertical adjustment of the position of drone to get a better LoS link. Hence, drone as relay gives us additional degree of freedom to ameliorate the network performance.

(iv) A model of rescue operation for fire detection is proposed using two clusters DA-DDCC approach. Two clusters DA-DDCC scenario is analyzed taking inter-cluster interference into account. Outage and rate expressions are derived in series form for getting valuable insights into the system.

The rest of this paper is organized as follows. In Section 2, we describe the DA-DDCC system model. Sections 3 and 4 present the outage and capacity analysis, respectively, followed by DA-DDCC multi-cluster scenario in Section 5. Section 6 provides the simulation results, and finally, Section 7 concludes the paper. Notations and symbols used in the paper are shown in Table 1.

2 | DA-DDCC SYSTEM MODEL

Figure 1(b) shows our proposed DA-DDCC model (along with base station assisted typical D2D model in Figure 1(a)). There are UEs/devices communicating with each other in the form
of source-destination pairs. It is assumed that only NLoS link exists between UE working as a transmitter and UE working as a receiver. However, an additional path is introduced between UEs via drone. Nodes working as sources (transmitters) and as destinations (receivers) are represented by UEs and UED, respectively. The drone acts as a relay. For the discussion ahead, cluster representing our proposed DA-DDCC scenario (Figure 1(b)), consists of a pair of devices is considered for description purpose similar to Figure 3. Distance between a source (S) or destination (D) and R can be calculated by using $d = \sqrt{h^2 + r^2}$ as shown in Figure 3. The elevation angle of drone from ground is denoted by theta ($\theta$). 

Channel between $S$ and $R$ or $R$ and $D$ is either Rayleigh or Rician distributed depending on the probability of occurrence of LoS ($P_L$) (or NLoS ($P_{NL}$)) component to be decided by the proposed statistical channel model. The system operates over the principle similar to TDMA scheme. Total of two time-slots are required to complete one session of data transmission. Different time-slots are assigned to UEs and $R$ for transmitting the data. Transmission of a source is received by destination as well as overheard by drone. Drone forwards it to the destination node in successive time-slot by using suitable forwarding schemes such as amplify and forward (AF) or decode and forward (DF). Due to limitations of drone, we are considering AF relaying scheme which requires comparatively less complex circuitry. For achieving diversity, selection combining (SC) is used at destination node keeping battery constraint of devices into account.

In this work, it is assumed that UE nodes ($S, D$) are quasi-static. Vertical movement of the quasi-static drone may be significant between two consecutive communication phases. For better LoS, height of the relay (drone) node may be harmonized from the horizon plane during subsequent communication phases, if required. Since UEs are at ground, the direct link between them may remain obstructed by obstacles most of the time. Hence, a radio link between them is assumed to have NLoS component only. Due to the vertical movement of drone, links among UE to $R$ and $R$ to UE may change significantly. Therefore, these links are modeled individually using the proposed channel model (based on $P_L$ ($P_{NL}$), following the procedure illustrated in Section 6. To model the effect of LoS and NLoS components, Rician and Rayleigh fading are used, respectively. System parameter for Rayleigh faded channel is $\sigma = \frac{1}{\sqrt{2}}$.

Rician fading parameter is defined as $M = \frac{r^2}{2\sigma^2}$, where $r^2$ and $2\sigma^2$ denote the average power related to LoS and NLoS link, respectively [34]. Since statistically UE to $R$ and $R$ to UE links are independent, $S$ and $R$ may have different channel state even after having the same value of $P_L$. This is primarily due to the difference in the presence of various obstacles like buildings, trees, hills etc. between UE to $R$ and $R$ to UE nodes. Energy-related issues for the device/drone are not considered here. We assume that all UEs and drone have a single antenna and operate in half-duplex mode. Channel state information (CSI) is known by the receiver nodes ($UE$ and $R$) only. Each transmitting node having the same packet size. It is assumed that coherence time is long enough to complete a packet transmission. However, channels may change independently between two consecutive transmissions. The altitude of UEs, antenna heights of both the users and drone are neglected during the study. Generalized power allocation scheme used in our model is as follows

$$P_S = \Psi_1 P_{1r}, \quad P_R = \Psi_2 P_{2r},$$

where $\Psi_1, \Psi_2 \in [0, 1]$, denote power allocation factors. $P_1$ and $P_2$ denote power transmitted by source and relay node, respectively. Symbol $P_r$ denotes the available power in the network given as $P_S + P_R = (\Psi_1 + \Psi_2)P_r$. 

### TABLE 1 Summary of notations

| Symbol | Definition |
|--------|------------|
| $x_i$  | Signal transmitted by $i$th node |
| $d_{ij}$ | Distance between $i$th and $j$th node |
| $h_{ij}$ | Channel coefficient between $i$th and $j$th node |
| $Q$ | Amplification factor for AF relaying scheme |
| $\eta_j$ | Background noise (AWGN) at $j$th node |
| $\sigma_j^2$ | Variance of background noise at $j$th node |
| $\nu_j$ | Power transmitted by $j$th node |
| $v_{ij}$ | Received signal at $j$th node transmitted by $i$th node |
| $\sigma_v^2$ | Variance of AF-noise at $j$th node |
| $\Gamma_{ij}$ | Signal to noise ratio between $i$th and $j$th node |
| $\alpha$ | Path loss exponent |
| $\theta$ | Angle between $d$ and $r$ |
| $b_D$ | Vertical height from drone to ground plane |
| $\Psi_j$ | Power allocation factor |
| $\lambda$ | Rate parameter for exponentially distributed signal |

### FIGURE 3 System model for DA-DDCC, showing vertical movement of drone for changing the link quality along with establishing cooperative communication
TABLE 2 Environment parameters [39, 40]

| Environment type   | a    | b    |
|--------------------|------|------|
| Suburban           | 4.88 | 0.43 |
| Urban              | 9.61 | 0.16 |
| Dense urban        | 12.08| 0.11 |
| High-rise urban    | 27.23| 0.08 |

FIGURE 4 (a) $P_L$ in different environments, (b) $P$ w.r.t $h_D$ and $M$

2.1 Effect of drone height over A2G channel model

In order to develop the analytical framework for the proposed network model, it is imperative to investigate the effect of drone height on various system statistics. In this subsection, we describe the effect of drone height on the probability of occurrence of LoS (NLoS). The probability of occurrence of LoS ($P_L$) is given as [38]

$$P_L = \frac{1}{1 + ae^{b} e^{-i^2}}$$

where $\Theta = \frac{180}{\pi} \tan^{-1} (\frac{\lambda}{\delta})$, and $a, b$ are constant values depending upon the environment type given in Table 2.

The probability of occurrence of NLoS ($P_{NL}$) can be calculated by using $P_L + P_{NL} = 1$. Figure 4(a) shows the variation of $P_L$ w.r.t drone height and horizontal distance for different environments. From Figure 4(a), it may be observed that $P_L$ is high in an urban environment as compared to a high-rise urban environment for any combination of $(r, h_D)$. In an urban environment, increasing the distance between low altitude drone and UEs increases the probability of having more and more obstacles between drone and UEs. Therefore, for low values of $h_D$, $P_L$ decreases with an increase in $r$. However, at very high altitudes, obstacles do not affect the LoS significantly. So, for high values of $h_D$, $P_L$ remains almost constant with $r$. For high-rise urban environments, even moderate heights of drone $(\approx 40m)$ are unlikely to clear obstructions among drone and UEs. Therefore, increment in $r$ decreases the $P_L$.

The average received signal power ($\hat{P}$) at node can be written by cramming the effects of both LoS and NLoS components as

$$\hat{P} = P_{ij}P_{ij}^{L} + P_{ij}P_{ij}^{NL},$$

where $P_{ij}^{L}$, $P_{ij}^{NL}$ denote average received power corresponding to LoS and NLoS links when signal propagates from $i$ to $j$ node $(i, j) \in \{(S, R), (R, D)\}$, respectively. Further, parameters $P_{ij}^{L}$ and $P_{ij}^{NL}$ may be found by using the equations given below

$$P_{ij}^{L} = P_{ij}^{L}d_{ij}^{-\alpha}E\left(|h_{ij}^{R_{ij}}|^{2}\right)$$

$$P_{ij}^{NL} = P_{ij}^{NL}d_{ij}^{-\alpha}E\left(|h_{ij}^{S_{ij}}|^{2}\right),$$

where $P_{ij}$, $d_{ij}$, $h_{ij}$, $R_{ij}$, and $Ray$ denote transmitted power by node $i$, distance between $i$ and $j$ node, channel coefficient between $i$ and $j$ node, Rician and Rayleigh fading, respectively. It may be noted that $P_{ij}$ includes the effect of both large scale as well as small scale fading.

Figure 4(b) shows average received power at drone (calculated using (3)) w.r.t drone height $(h_D)$ and Rician factor $(M)$. From Figure 4(b), it may be observed that for given $h_D$, the average received power at drone increases with $M$ and for given $M$ it increases up to an optimum drone height due to increase in $P_L$, then decreases due to an increase in path loss.

2.2 Description of DA-DDCC

For description purpose, the model shown in Figure 3 is considered. In $1^{st}$ time-slot, $S$ transmits the signal to $D$ which is overheard by $R$ also. Signal received at $D$ and $R$ can be modelled as

$$Y_{SD}^{Ray} = \sqrt{P_{SD}^{R_{SD}}h_{SD}^{Ray}} + \eta_{SD}$$

$$Y_{SR}^{h} = \sqrt{P_{SR}^{R_{SR}}h_{SR}^{Ray}} + \eta_{SR}$$

where $\eta_{ij}$ denotes AWGN noise with $\mathcal{N} \in (0, \sigma^2_{ij})$, $l_1$ is either $Ray$ (with $P_{NL}$) or $Rice$ (with $P_{L}$), the method for deciding $l_1$ is explained in Section 6. Relay uses AF scheme to forward the signal towards destination node in $2^{nd}$ time-slot which can be written as

$$Y_{RD}^{h} = \left(Q^{h}Y_{SR}^{h}\right)\sqrt{d_{RD}^{-\alpha}h_{RD}^{Ray}} + \eta_{RD}$$

where both $l_1$ and $l_2 \in \{Ray, Rice\}$. It may be noted that during a particular transmission cycle, $l_1$ and $l_2$ may belong to different distributions also depending upon the obstacles present in the $S$-$R$ and $R$-$D$ channels. Effect of various combinations of $l_1$, $l_2$ on system performance is discussed in Section 3. $Q^{h}$ is known.
as amplification factor given by [31]

\[ Q^h = \sqrt{\frac{P_R}{P \sigma^2 |h_{SR}^h|^2 + \sigma_{SR}^2}}. \]  

(8)

Another copy of the desired signal at destination node can be found by using (6) and (7) as follows

\[ \mathcal{N}_R^{h_{RD}} = Q^h \left( \sqrt{P \sigma^2 |h_{SR}^R|^2} \right) \sqrt{d_{RD}^{-\alpha} |h_{RD}^h|^2} + \mathcal{N}_R^{h_{RD}}, \]  

(9)

where \( \mathcal{N}_R^{h_{RD}} \) denotes AF-noise component at \( D \), given by

\[ \mathcal{N}_R^{h_{RD}} = \eta_{RD} + Q^h \sqrt{d_{RD}^{-\alpha} |h_{RD}^h|^2}. \]  

(10)

Assuming average channel gain remains constant for the duration of a packet (for a given drone height) and average noise power at \( D \) and \( R \) are same \( (\sigma^2 = \sigma_{RD}^2 = \sigma_{SR}^2) \). Mean of the AF-noise is zero and the variance of AF-noise component at node \( D \) becomes [40]

\[ \sigma_{h_{RD}}^2 = \sigma^2 \left[ 1 + (Q^h)^2 d_{RD}^{-\alpha} |h_{RD}^h|^2 \right]. \]  

(11)

### 2.3 AF-noise for Statistical Channel Model

Effective values of \( \mathcal{N}_R^{h_{RD}} \) and \( \sigma_{h_{RD}}^2 \) in case of statistical channel model can be found by averaging (10) and (11) over all the four possible cases (as discussed in Section 3) of various combinations of \( l_1, l_2 \) as:

\[ \mathcal{N}_{\text{avg}} = \sum_{j=1}^{4} \left[ \left( \prod_{i=1}^{2} P_{m_i} \right) \mathcal{N}_R^{h_{RD}} \right]_j \]  

(12)

\[ \sigma_{\text{avg}}^2 = \sum_{j=1}^{4} \left[ \left( \prod_{i=1}^{2} P_{m_i} \right) \sigma_{h_{RD}}^2 \right]_j, \]  

(13)

where \( (m_1, m_2) \in \{L, NL\} \) and \( j \in \{Ray, Rice\} \). Here \( L \) corresponds to \( Rice \) and \( NL \) corresponds to \( Ray \) channel.

Figure 5 shows the average magnitude of AF-noise w.r.t drone height. It may be observed from Figure 5 that average magnitude of AF-noise is different. The average magnitude of AF-noise for Rayleigh \( (l_1 = l_2 = Ray) \) and Rician \( (l_1 = l_2 = Rice) \) models are calculated using (10) and for the proposed probabilistic channel model by using (12). For the hybrid model, \( h_{SR} \) and \( h_{RD} \) are assumed Rayleigh distributed below an optimum drone height \((h_{D0} \approx 18-22m\) as shown in Figure 4(a)) and Rician distributed above \( h_{D0} \).

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5 Rayleigh (Rician) model represents the system where UEs-R and R-UEs both the links are modelled using Rayleigh (Rician) distribution.
where $T$ denotes pre-decided threshold value. Using (14) and (17), we can write

$$P_{Out} = P \left( Y_{SR}^{Ray} < T \right) P \left( Y_{SD}^{Ray} < T \right).$$

(18)

We need to calculate the 1\textsuperscript{st} and 2\textsuperscript{nd} terms separately for obtaining the outage probability. Solution of the 1\textsuperscript{st} term can be obtained as [40]

$$P \left( Y_{SR}^{Ray} < T \right) = 1 - e^{-\lambda_{SR}T},$$

(19)

where $\lambda_{SR} = \frac{\sigma_{SR}^2}{P_{d_{SR}}}$ and $\lambda_{RD} = \frac{\sigma_{RD}^2}{P_{d_{RD}}} \text{and} \hat{P}_{S} = \delta \hat{P}_{S}$. Using (19) and (23) in (18), outage probability for case 1 can be obtained as

$$P \left( Y_{SD}^{Ray} < T \right) = 1 - e^{-\lambda_{SD}T}.$$  

(24)

3.2 | Case 2

Another possible instance may occur when $S$ to $R$ and $R$ to $D$ links are Rayleigh and Rician faded, respectively as shown in Figure 7. Assuming independent links, the probability of occurrence of this case can be calculated by $P_{NL}P_{L}$. Putting $l_1 = Ray$ and $l_2 = Rice$ in (22), solution of the 3\textsuperscript{rd} term can be written as

$$P \left( \hat{Y}_{SR}^{Ray} > T \right) = e^{-\lambda_{SR}T},$$

(25)

and the 4\textsuperscript{th} term can be rewritten as

$$P \left( \hat{Y}_{RD}^{Rice} > T \right) = 1 - P \left( \hat{Y}_{RD}^{Ray} < T \right).$$

(26)
Further simplification of (26) leads to [32]

\[ P \left( \hat{\gamma}_{RD}^{Rice} > T \right) = Q_1 \left( \sqrt{2M \left( 2T[1 + M] \right)} \frac{\alpha_{RD}}{\eta} \right), \]  

(27)

where \( Q_1(.,.) \) is the first-order Marcum \( Q \) function, and \( \eta = \frac{\rho}{\sigma_{RD}^2} \). Putting (27) and (25) in (22), we can obtain

\[ P \left( \hat{\gamma}_{RD}^{Rice} < T \right) = 1 - e^{-\lambda_{RD} T}. \]  

(28)

Putting (19) and (28) in (18), we can obtain the outage probability for the case 3 as written below

\[ P_{out}^{Rice,Ray} = 1 - \left[ e^{-\lambda_{SD} T} \right] \left[ 1 - e^{-\lambda_{RD} T} \right] \left[ Q_1 \left( \sqrt{2M \left( 2T[1 + M] \right)} \frac{\alpha_{RD}}{\eta} \right) \right]. \]  

(29)

### 3.3 Case 3

Third instance occurs when \( S \) to \( R \) and \( R \) to \( D \) links are Rician and Rayleigh faded, respectively as shown in Figure 8. Assuming independent links, the probability of occurrence of this case can be calculated by \( P_L P_{NL} \). Putting \( l_1 = Rice \) and \( l_2 = Ray \) in (22). Solution of the 3rd term can be written as

\[ P \left( \hat{\gamma}_{SR}^{Rice} > T \right) = Q_1 \left( \sqrt{2M \left( 2T[1 + M] \right)} \frac{\alpha_{SR}}{\eta} \right). \]  

(30)

Solution for the 4th term can be obtained as

\[ P \left( \hat{\gamma}_{RD}^{Ray} > T \right) = e^{-\lambda_{RD} T}. \]  

(31)

Putting (30) and (31) in (22), we can obtain

\[ P \left( \hat{\gamma}_{SR}^{Rice,Ray} < T \right) = 1 - \left[ e^{-\lambda_{RD} T} \right] \left[ Q_1 \left( \sqrt{2M \left( 2T[1 + M] \right)} \frac{\alpha_{SR}}{\eta} \right) \right]. \]  

(32)

Putting (19) and (32) in (18), we can obtain the outage probability for the case 3 as written below

\[ P_{out}^{Rice,Ray} = 1 - \left[ e^{-\lambda_{SD} T} \right] \left[ Q_1 \left( \sqrt{2M \left( 2T[1 + M] \right)} \frac{\alpha_{SR}}{\eta} \right) \right]. \]  

(33)

### 3.4 Case 4

The last possible case occurs when both \( S \) to \( R \) and \( R \) to \( D \) links are Rician faded as shown in Figure 9. Again the probability of occurrence of this case is defined by \( P_L P_L \), taking link independence into account. Putting \( l_1 = l_2 = Rice \) in (22). Solution of the 3rd term can be written as

\[ P \left( \hat{\gamma}_{SR}^{Rice} > T \right) = Q_1 \left( \sqrt{2M \left( 2T[1 + M] \right)} \frac{\alpha_{SR}}{\eta} \right). \]  

(34)

and 4th term can be rewritten as

\[ P \left( \hat{\gamma}_{RD}^{Rice} > T \right) = Q_1 \left( \sqrt{2M \left( 2T[1 + M] \right)} \frac{\alpha_{RD}}{\eta} \right). \]  

(35)
Putting (34) and (35) in (22), we can obtain
\[
P(R_{SRD} < T) = 1 - Q_1\left(\sqrt{2M} \sqrt{2T[1 + M]} \frac{d^2_{SR}}{\eta}\right)
\]
Putting (19) and (36) in (18), we can obtain the outage probability for case 4 as written in (37).

\[
P_{Out}^{Rice, Rice} = (1 - e^{-\lambda_{SP}T}) \left[ 1 - Q_1\left(\sqrt{2M} \sqrt{2T[1 + M]} \frac{d^2_{SR}}{\eta}\right)\right].
\]

Putting (34) and (35) in (22), we can obtain
\[
P(R_{SRD} < T) = 1 - Q_1\left(\sqrt{2M} \sqrt{2T[1 + M]} \frac{d^2_{SR}}{\eta}\right).
\]

5 | INTERFERENCE LIMITED MULTI-CLUSTER DA-DDCC SCENARIO

As a practical use case of our proposed model, a scenario is considered where two non-overlapping clusters are operating adjacent to each other. In real-time, clusters may represent two areas served by two different drones in a post-disaster scenario. Since due to practical constraints, a complete disaster scene cannot be covered by a single drone, therefore multiple drones are required to serve various small areas. However, the optimal number of drones required and coordination among drones are not being considered here. Due to the broadcast nature of the wireless channel, links of one cluster may interfere with other. While improving the performance of the overall network, it becomes imperative to take the interference into account to set various network parameters optimally. This asks for the proper modelling of interference in the network. To the best of our knowledge, drone assisted D2D communication in a cooperative environment has not been analyzed in literature in an interference-limited scenario.

Received interference power is a function of link distribution between nodes also. Interference power may be high if the link consists of LoS component, as compared to the case when only NLoS component is present. As we discussed in the previous section that \(P_L\) is a function of drone height also, this implies that changing the drone height affects the system. As in Figure 10, without loss of generality, a drone (interferer) also, therefore, the amount of interference power received at the destination node. Increasing the drone height affects the system in two ways. Firstly it increases the \(P_L\) for UE\(_3\) (desired transmitter) hence, quality of the desired signal at drone improves. Secondly, it improves the link quality between drone and UE\(_3\) (interferer) also, therefore, the amount of interference power also increases. Moreover, there are two interfering links affected by the drone height. Since interfering links are also statistically independent, they may be Rayleigh distributed with \(P_L\) or Rayleigh distributed with \(P_{NL}\). This justifies the need for a probability-based statistical channel model for modelling such an interference-limited scenario.

4 | CAPACITY ANALYSIS FOR DA-DDCC

In this set-up, let the bandwidth assigned to each time-slot is \(B\), where \(B\) denotes the bandwidth available in the system. Taking direct (\(S-D\)) and relay path (\(S-R-D\)) into account, rate at \(D\) using SC, can be defined as
\[
C_{Rate}^{h_1, h_2} = \left(\frac{B}{2}\right) I_{D,D-DCC}^{h_1, h_2},
\]

where \(I_{D,D-DCC}^{h_1, h_2}\) mutual information between the direct path (\(S-D\)) and the relay path (\(S-R-D\)), can be defined as
\[
I_{D,D-DCC}^{h_1, h_2} = \log_2 \left(1 + \text{max} \left(\gamma_{SRD}^{Ray}, \gamma_{SRD}^{Rice}\right)\right).
\]

The average capacity also can be found by weighting each case with appropriate probabilities as
\[
C_{Rate}^{h_1, h_2} = (P_{NL}P_{NL}) C_{Rate}^{h_1, h_2} + (P_{NL}P_L) C_{Rate}^{h_1, h_2} + (P_LP_{NL}) C_{Rate}^{h_1, h_2} + (P_LP_L) C_{Rate}^{h_1, h_2}.
\]

5.1 | Multi-cluster DA-DDCC system model

The network model consists of two neighbouring clusters\(^3\) \((C_1, C_2)\) as shown in Figure 10. Without loss of generality \(C_1\) is assumed as the desired cluster. Each cluster consists of a pair of devices \((\text{UE}_{i}^{1}, \text{UE}_{j}^{2})\) and \((\text{UE}_{i}^{3}, \text{UE}_{j}^{4})\) and a drone \((R_1, R_2)\). Similar to our previous framework, communication within a cluster is divided into two time-slots. The direct links among device pairs \((\text{UE}_{i}^{1}, \text{UE}_{j}^{2}), (\text{UE}_{i}^{3}, \text{UE}_{j}^{4})\) are assumed to be Rayleigh distributed due to absence of the LoS component. Rest of the links \((\text{UE}_{i}^{3}, \text{UE}_{j}^{1})\) \((R_1, R_2)\) are Rayleigh distributed with either the cluster of interest or interfering cluster are assumed to be either Rayleigh or Rician distributed determined by the statistical

\(^3\) Unlike Figure 1, here both D2D clusters are operating in DA-DDCC mode (without assistance of base station)
channel model (as explained in Section 6). For modelling purpose, it is assumed that both the clusters are operating in synchronization. Effect of interference from $C_2$ is observed on $C_1$. It is assumed that UE is being served by the drone having best possible radio links towards the UE. For better understanding, drone heights of $R_1$ and $R_2$ are now represented by $h_{D1}$ and $h_{D2}$, respectively.

5.2 Description of inter-cluster interference in DA-DDCC

For the ease of description, nodes UE$_S^1$ and UE$_D^1$ are now represented by $S_1$ and $D_1$, respectively for this section. Without loss of generality $D_1$ is considered as node of interest. In 1st time-slot, $S_1$ and $S_2$ transmit the signal $x_1$ and $x_2$ to $D_1$ and $D_2$, which are overheard by drone $R_1$ and $R_2$, respectively. At the same time, due to inter-cluster synchronization, $R_1$ and $R_2$ receive interfering signal $x_2$ from $S_2$. Channel distributions associated with links $S_1-R_1$ and $S_2-R_1$ depend on $P_L$ ($P_{NL}$)$_4$. Based on $P_L$ ($P_{NL}$)$_4$, 4 ($2^2$) possible cases may occur for the scenarios shown in Figure 11. For example, in 1st time-slot of a particular transmission cycle, one such case may be $\{h_{S_1,R_1}, h_{S_2,R_1}\} = \{Ray, Rice\}$. The signals received at node $R_1$ and $D_1$ in 1st time-slot $T_1$ can be written, respectively as

$$Y_{D1} = \sqrt{P_{S_1} \frac{d^{-\alpha}_{S_1,D_1}}{d^{-\alpha}_{R_1,D_1}}} h_{S_1,D_1} x_1 + \sqrt{P_{S_2} \frac{d^{-\alpha}_{S_2,D_1}}{d^{-\alpha}_{R_1,D_1}}} h_{S_2,D_1} x_2 + \eta_{D1}$$

$$Y_{R1} = \sqrt{P_{S_1} \frac{d^{-\alpha}_{S_1,R_1}}{d^{-\alpha}_{S_1,R_1}}} h_{S_1,R_1} x_1 + \sqrt{P_{S_2} \frac{d^{-\alpha}_{S_2,R_1}}{d^{-\alpha}_{S_1,R_1}}} h_{S_2,R_1} x_2 + \eta_{R1}$$

Destinations node can get another copy of desired signal given in (46) by using (43) in (44).

Taking the direct ($S_1-D_1$) and relay path ($S_1-R_1-D_1$) into account, rate at $D_1$ using SC in the interference-limited scenario

where $l_1$ and $l_2$ are either Rayleigh ($P_{NL}$) or Rice ($P_L$) as decided by the proposed statistical channel model explained in Section 6. The upper subscript $T_1$ in (42) represents the time-slot. Relay $R_1$ and $R_2$ amplify the signals received from $S_1$ and $S_2$ and forward them towards destination nodes $D_1$ and $D_2$, respectively in 2nd time-slot. Again in this synchronized scenario, $D_1$ receives interference signal ($x_3$) from $R_2$. Channel distributions associated with links $R_1-D_1$ and $R_2-D_1$ depend on $P_L$ ($P_{NL}$)$_4$. Based on $P_L$, 4 ($2^2$) possible cases may occur for the scenarios shown in Figure 11. For example, in 2nd time-slot of a particular transmission cycle, one such case may be $\{h_{R_1,D_1}, h_{R_2,D_1}\} = \{Rice, Ray\}$. Signal received at $D_1$ in 2nd time-slot $T_2$ can be written as

$$Y_{D1}^2 = (Q^{l_1,l_2} Y_{R1}) \sqrt{\frac{d^{-\alpha}_{R1,D1}}{d^{-\alpha}_{R1,D1}}} h_{R1,D1} + \sqrt{P_{R2} \frac{d^{-\alpha}_{R2,D1}}{d^{-\alpha}_{R2,D1}}} h_{R2,D1} x_3 + \eta_{D1}$$

(44)

$$Y_{R1} = \sqrt{P_{S_1} \frac{d^{-\alpha}_{S_1,R_1}}{d^{-\alpha}_{S_1,R_1}}} h_{S_1,R_1} x_1 + \sqrt{P_{S_2} \frac{d^{-\alpha}_{S_2,R_1}}{d^{-\alpha}_{S_1,R_1}}} h_{S_2,R_1} x_2 + \eta_{R1}$$

(43)

(45)
for D2D pair \((S_1-D_1)\) can be defined as

\[
Y_{R_1,D_1} = Q^K_{\beta,\lambda} \left[ \left( \sqrt{P_L} R_{S_1,R_1}^{\text{desired}} h_{S_1,R_1}^{S_1,R_1} \right) + \left( \sqrt{P_L} R_{S_1,R_2}^{\text{interference}} h_{S_1,R_2}^{S_1,R_2} \right) + \eta_{R_1} \right]
\]

where \(Q^K_{\beta,\lambda}\) is the cumulative distribution function of the standard normal distribution. The desired signal is the received signal at the desired node, the interference signal is the received signal at the destination node from the interfering node, and \(\eta_{R_1}\) is the channel noise at the receiver.

\[
R_{S_1,R_1}^{\text{desired}} = \frac{1}{\left( \sqrt{P_L} \right)^2} \left( \frac{1}{h_{S_1,R_1}^{S_1,R_1}} \right)
\]

The outage probability can be found as

\[
P_{\text{out}} = \max \left( 1 - Y_{R_1,D_1}, Y_{S_1,R_1,D_1} \right)
\]

where \(Y_{S_1,R_1,D_1}\) is the ratio of the desired signal to the interference plus noise ratio (SINR).

\[
C_{\text{rate}} = \frac{R}{\log_2 \left( 1 + Y_{R_1,D_1} \right)}
\]

where \(C_{\text{rate}}\) is the channel capacity. The outage probability and capacity are crucial for evaluating the system performance.

\[\text{TABLE 3: Simulation parameters [40]}\]

| Parameter | Value |
|-----------|-------|
| Transmitted power \((P_t)\) | \(-10 \text{ dBm}\) |
| Noise power | \(-74 \text{ dBm}\) |
| Bandwidth in network \((B)\) | \(100 \text{ MHz}\) |
| Path loss exponent \((\alpha)\) | \(3\) |
| Ricean factor \((M)\) | \(6\) |
| Fading type | Rayleigh, Ricean |
| Vertical height \((h_D)\) | \(0 - 60 \text{ m}\) |
| Effective distance \((d_{eff})\) | \(50 \text{ m}\) |
| Pre-decided threshold \((T_{\text{th}})\) | \(0.1 \text{ dB}\) |
| Multiplicative factor \((\delta)\) | \(0.65\) |
| Environment type | \(a = 9.61, b = 0.16\) |

In Section 6, simulations results are presented. Results for a single cluster are presented first and after that, results for the interference-limited scenario are discussed. Analytical results are compared with simulation results for some representative cases. Parameters used in the simulation are given in Table 3. For simplicity, \(\Psi_1 = \Psi_2 = 0.5\) is considered for simulation purpose. However, the framework is equally applicable for other values also. The flow chart of our proposed approach for channel modeling for drone assisted scenario is shown in Figure 12. The same method is being used during simulations for assigning (probability) distribution to a particular channel. The algorithm needs to be executed twice in one cooperative cycle for the network under consideration, first at UE\(^5\) and then at drone. Thus, two channels being statistically independent may follow two different distributions\(^5\).

Matrices such as the outage probability, rate and required transmitted power are chosen to validate the proposed model. Outage probability \(P_{\text{out}}\) is defined as the probability that received SNR (SINR) is below some pre-decided threshold.

\[P_{\text{out}} = \sum_{i=1}^{2^d} \left( \prod_{j=1}^{4} P_{m_j} \right) P_{\text{out}}^{i_{12},i_{23}} \]

where \(i_{12}=\{l_1, l_2, l_3, l_4\}\) and \(i_{23}=\{l_5, l_6, l_7, l_8\}\). Here, \(L\) corresponds to \(Rice\) and \(NL\) corresponds to \(Ray\) channel.

5When both \(N_1\) and \(N_2\) are either less or greater than \(P_{t_1}\) and \(P_{t_2}\), respectively, this leads to the case when both the channels can be modelled using the same distribution [20, 21].
(\gamma_{th} = 10^{\frac{\text{dB}}{10}}). For simulation purpose, we have used the following equation for calculation of \( P_{\text{out}} \),

\[
P_{\text{out}} = P(\text{SNR} < \gamma_{th}).
\]

Figure 13 gives variation of the \( P_{\text{out}} \) with drone height for our proposed approach along with the two other existing approaches. The proposed approach is represented by probabilistic model while two other approaches are Rayleigh and Rician models used for comparison purpose. For very low drone heights, result of the proposed model is comparable to Rayleigh model and for high values, this approaches towards Rician model. This behaviour may be justified since for low values of \( h_D, P_L(\text{SNR}) \) remains very small (large), therefore channel is dominated by NLoS components and hence, approaching Rayleigh model. On the contrary, for high values of \( h_D, P_L(\text{SNR}) \) becomes very large (small), therefore the channel is dominated by LoS components and hence, approaching the Rician model. Thus, we see that the use of either Rayleigh or Rician model in such an environment either overestimates or underestimates the network performance, respectively. Moreover, unlike Rayleigh and Rician model, the probabilistic model indicates an optimum value of \( h_D \) around \( \approx 18–22 \text{m} \). Intuitively, it is the height where loses due to continuously increasing path loss are exactly balanced by gain due to improving values of probability of LoS. Before this optimum point, due to short distances, losses due to path loss are dominated by probability of LoS that results in a decrement of \( P_{\text{out}} \). After the optimum point, however, path loss increases at a higher rate than probability of LoS that gives rise to high values of \( P_{\text{out}} \).

Figure 14 shows the \( P_{\text{out}} \) w.r.t rate for different channel models. It may be noted that for different values of rates, outcome corresponding to the probabilistic model lies between the two extremes of Rayleigh and Rician models. Degradation in the outage performance with increment in the required rate for all the three models is due to the fact that channel support continuously degrades for the large values of required rate.

Figure 15 shows the required values of drone height (\( Y_1 \)) and rate (\( Y_2 \)) for achieving certain \( P_{\text{out}} \). Simulation and analytical results are in a good match. Expressions in (38) and (41) are used to find an optimum value of drone height and rate for a given required \( P_{\text{out}} \).
Figures 16 and 17 extend the results of Figures 13 and 14 for different threshold values and for different drone heights, respectively. It may be noted from Figure 16 that increasing the value of threshold results in higher $P_{\text{out}}$. Figure 17 shows that increasing the drone height for a fixed value of rate parameter, results in higher values of outage. Increasing the drone height results in better LoS as well as higher path loss. After a certain height of drone, path loss dominates that leads to high values of $P_{\text{out}}$. Simulation and analytical results predict almost similar values.

Figure 18 shows variation of the $P_{\text{out}}$ w.r.t drone height and Rician factor for Rician and probabilistic channel models. It may be observed here that optimum point for small values of $M$ is lower as compared to large values of $M$. It may also be noted that at low value of $h_D$, the probabilistic channel model predicts higher values of the outage probability as compared to Rician channel while at a high value of $h_D$, performances are almost the same for both the models.

Figure 19 shows variation of $P_{\text{out}}$ w.r.t drone height and Rician factor in different environments namely urban and high rise urban. It may be observed that the outage probability is low in the urban environment as compared to the high-rise urban environment for most combinations of $(M, h_D)$. In urban environments, for given $M$ outage decreases up to an optimum value of $h_D$ (which is different for low and high values of $M$) due to the dominance of increment in $P_L$. After an optimum value of $h_D$, path loss starts dominating and results in a higher outage. However, the impact of $M$ on $P_{\text{out}}$ values is more for the urban environment as compared to the high rise urban.

Figure 20 predicts the required transmitted power w.r.t drone height for fixed $P_{\text{out}}$ using different channel models. Behaviour of different slopes may again be explained with the similar
arguments presented earlier for Figure 13. The results obtained in Figure 20 provides very useful insight for minimization of the transmitted power, which is one of the main issues related to D2D or drone-based networks. Here, we also note that up to an optimum height (≈20–22 m) drone saves the energy by transmitting at less power.

Figure 21(a) predicts the suitable horizontal position of drone for different values of transmitted power for the fixed $P_{out}$ using different channel models. It is observed from Figure 21(a) that centre position of drone needs less transmission power as compared to other horizontal position of drone. Behaviour of different slope may be explained with the help of Figure 20. Figure 21(b) gives the required height of drone to achieve a fixed $P_{out}$ as a function of horizontal position of drone. It may also be noted here that for a given $P_{out}$, central position of drone requires the maximum height.

### 6.1 Effect of interference on system performance

In this subsection, we present results for an interference-limited multi-cluster scenario.

Figure 22 shows $P_{out}$ at UE $D_2$ w.r.t drone height ($h_{D_1}$) and rate. It is interesting to note that unlike Figure 13 and Figure 14 of a single cluster scenario, most of the values predicted by our proposed model lies no more in between the other two models. After a certain drone height ($h_{D_1} \approx 7$ m) the proposed channel model predicts less outage as compared to other two existing channel models. Primary reason behind this behaviour is the fact that for this node configuration, interference link $L_{2-R_1}$ comes out to be mostly Rayleigh distributed by following the method explained in Section 6. This results in less interference power and hence, low outage probability.

Figure 23 gives the required value of $h_{D_1}$ for various combinations of the $P_{out}$ and drone height ($h_{D_2}$) of the interfering cluster. Expression found in (51) can be used to achieve an optimum drone height ($h_{D_1}$) for a given required $P_{out}$ and interfering drone height ($h_{D_2}$). It may be noted that required values of $h_{D_1}$ are less affected by variation in $h_{D_2}$ for most values of $P_{out}$, since
signal received at $D_1$ from $R_2$ starts getting fair amount of LoS components after a certain value of $h_{D_2}$ (i.e. a particular height of $R_2$). After that rate of change of increment of LoS does not increase much.

Figure 24 gives variation of the $\mathbb{P}_{\text{out}}$ w.r.t transmitted power for our proposed approach along with two other existing approaches. It may be noted here, the $\mathbb{P}_{\text{out}}$ decreases as transmitted power increases for proposed (a) as well as existing models (b). However, the values predicted by our model are lesser than the values predicted by two other models. The requirement of reduced transmitted power results in high life time of devices (drone).

7. CONCLUSION

We have introduced drone assisted device to device cooperative communication. A probability based generic statistical channel model has been proposed to model links individually in such networks where the height of drone may change in order to enhance the network performance. Results obtained using this proposed model have been compared with two other commonly used channel models namely Rayleigh model and Rician model. It has been observed that the proposed probability-based model gives a better characterization of links in such a dynamic network by taking statistical independence of links into account. Analytical closed-form expression of the outage probability along with capacity using the proposed channel model have been derived and verified with simulation results. Moreover, few more performance metrics have been investigated to get more insight into the system behaviour.

As an application scenario, a multi-cluster network has been discussed from an interference perspective. It has been demonstrated using simulations that use of models other than the probability-based statistical model, may result in non-optimal values of network parameters which may affect system performance and energy consumption drastically. The results show that for a given horizontal node configuration, a specific range of height of drone would result in the better performance. This helps the network designer to choose the optimum height of drone along with other crucial system parameters in various application scenarios and thus to minimize the energy consumption of drone and battery-operated devices. The proposed drone based network provides a cost-effective, temporary recovery solution for setting up a quick communication set-up where an existing cellular base station becomes non-functional. Optimization of drone altitude and field-test of our system model is considered for future work. Integration of Internet of Things (IoT) with this drone-based D2D network to make the system more robust in critical situations may be an exciting research direction. Development of framework for proposed channel model using Nakagami-m distribution may also be an insightful work in future.

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