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Rate and Outage Trade-Offs for OFDMA Based Device to Device Communication Frameworks

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ABSTRACT This paper presents the rate and outage tradeoffs for orthogonal frequency division multiple access-based device-to-device (D2D) communication frameworks, wherein multiple D2D users coexist with the cellular users in the same cell. Analytical expressions for outage probability for three D2D frameworks, namely underlay, overlay, and cooperative D2D (C-D2D) have been derived. Specifically, for underlay framework, a minimum value of angle θ (an angle between a cellular link and D2D interference link) is derived, for which the target rate and outage probability constraint of both cellular and D2D users are satisfied. For overlay and C-D2D frameworks, an optimal subcarrier sharing scheme is proposed, which not only helps the cellular users to achieve the target quality-of-service but also helps the D2D users to communicate with each other. In addition to above, benefits involved in employing one framework over other have also been investigated. Our results show that for a higher outage probability constraint of the cellular user, the C-D2D framework outperforms the underlay and overlay frameworks.

INDEX TERMS Device-to-device (D2D) communication, orthogonal frequency division multiple access (OFDMA), outage probability, decode-and-forward (DF) relaying.

I. INTRODUCTION

Past few decades have seen a phenomenal growth in wireless multimedia and data applications leading to increasing demand to further boost the capacity of next generation cellular networks.[1] One of the suggested solution to increase the capacity is to reduce the cell size, giving birth to the notion of small cell networks (e.g., micro-base station (BS), femto-BS) [1]. In small cell networks, reducing the cell size leads to increase in spectrum reuse, thus more capacity. However, there are some pertinent issues with the small-scale architecture based on interference, construction, and maintenance cost (e.g., the backhaul bottleneck) [2].

Recently, the concept of D2D communication has been proposed for cellular networks [3], [4] to avail the high capacity benefits to cellular users with minimal constraints on maintenance and construction. In a generic D2D framework, two cellular users living in proximity can form a direct link for data transmission without routing it through the base station (BS). However, control or signaling information between the users is still carried out by the BS. Traditionally, D2D technologies were restricted to short-range communication networks such as WiFi-Direct and Bluetooth working on unlicensed 2.4 GHz band [5]. The unlicensed bands are crowded with a large number of interferers; thus traditional D2D technologies do not provide the Quality-of-Service (QoS) and security as expected in the cellular networks. Several applications of D2D like proximity-based services, emergency communication, cellular traffic offloading, Internet-of-things (IoT) enhancement, etc. make it a viable candidate for next-generation 4.5G and 5G cellular networks [6], [7].

The most common D2D communication frameworks for the cellular networks are underlay and overlay D2D communication [8]. In underlay D2D communication, both cellular and D2D users simultaneously share the licensed cellular spectrum while maintaining the interference threshold, analogous to underlay cognitive radio communication [9]. However, in a D2D scenario, unlike cognitive radio, a D2D user belongs to the same cellular network, so it may not necessarily have low priority. In underlay D2D framework, the biggest concern is to manage the interference caused by the cellular to D2D user and vice-versa. In [10], authors studied the interference management for underlay D2D framework in long term evolution-advanced (LTE-A) cellular networks. In [11], the resource sharing between the D2D user and the cellular user is optimized while satisfying the individual power

[1] Such as Long Term Evolution (LTE)-Advanced Pro (comprising LTE Releases 13 and 14) and 5G cellular networks.

constraints. Distance constrained resource sharing criteria for underlay D2D cellular network is considered in [12]. Specifically, authors have formulated an analytical approach to find an optimum distance between the cellular user and D2D receiver to mitigate D2D interference. Compared to underlay, in overlay D2D communication, BS allocates dedicated spectrum or time slots to D2D link as long as the QoS of the cellular user is not compromised [13]. Although this eliminates the mutual interference between cellular and D2D link, however, it results into the inefficient utilization of available spectrum resources. A spectrum sharing protocol for D2D communication overlaying cellular mode is proposed in [14]. According to [14], the D2D users can assist bi-directional communication between the cellular users and BS, and at the same time communicate through a direct link with each other. Further, improved sum-rate derivation with power control mechanism for the cellular and D2D users are provided. A stochastic geometry approach to evaluate the performance of the D2D network over generalized fading channels is proposed in [15]. Closed-form expressions for spectral efficiency and outage probability are derived for the overlaid D2D network. However, the analysis in [14] and [15] is limited to the D2D communication overlaying cellular networks. Comparison with underlay and other frameworks has not been discussed.

Underlay and overlay D2D frameworks are studied extensively in the literature, whereas, the cooperative D2D (C-D2D) framework is yet to be thoroughly investigated. Cooperative relaying [16], [17] has been recently proposed for D2D communication in the cellular networks [18]. In the C-D2D framework, one or more D2D users are used to improve the performance of a cellular network via spatial diversity. In [18], authors introduce an adaptive mode selection scheme for D2D communication to ensure performance improvement for both cellular and D2D users. A cooperative beamforming and relay selection strategy to facilitate D2D communication in case of failure of communication infrastructure is proposed in [19]. However, the analysis in [18] and [19] is limited to numerical results. Closed-form expression of outage probability is not derived.

Besides, most of the previous works on D2D communication have been restricted to only one framework; tradeoff involved in employing one framework over other has often been overlooked. Motivated by above, in this work we analyze the underlay, overlay and C-D2D frameworks for the cellular network. Specifically, we assess the benefits involved in selecting one D2D framework over another when multiple D2D users coexist with the cellular users in the same cell. The proposed system architecture consists of a circular cell with a BS in the center of a cell operating on a licensed frequency band. Orthogonal frequency division multiple access (OFDMA) has been used as an access technology through which allocated spectrum is divided into a number of orthogonal subcarriers with same subchannel bandwidth. Each cellular link (from BS to CU or vice versa) has been assigned a number of subcarriers (e.g., N) for its communication. It is assumed that BS supports operator controlled D2D communication [20], wherein apart from the cellular links between mobile users and BS, there exist couples of mobile users which when given an opportunity would like to communicate directly via D2D link [10]. In the present context, mobile user in a cellular link is denoted by the cellular user (CU), and two mobile users which would like to do D2D communication are denoted as D2D transmitter (DT) and D2D receiver (DR) respectively. DT-DR exists as a D2D pair. On a specified time-frequency resource block, one D2D pair can share the spectrum of the CU by one of the specified frameworks i.e. underlay, overlay or C-D2D. It is worth mentioning that BS is still responsible for peer discovery, link establishment and subcarrier allocation to the D2D user over D2D link [18].

The major contributions of the proposed work are summarized as follows:

- Investigate the rate and outage trade-offs of OFDMA based underlay, overlay, and C-D2D communication frameworks.
- Specifically,
  - For underlay framework, we proposed an angle constrained D2D communication for which the optimal distance between the CU and BS as well as the minimum value of angle θ (an angle between a cellular link and D2D interference link) is derived. It has been shown that as long as the angle between the cellular link and D2D interference link is greater than the optimal value of θ, the target rate and outage probability constraint of both the cellular and D2D users will be satisfied. Further, the simulation results also show that for fixed ζ_{c_iB} (distance between a CU and BS), D2D outage probability decreases with increase in θ, whereas cellular outage probability is independent of θ. By leveraging the above results, BS can select the CU which facilitates DT-DR communication while maintaining its QoS.
  - For overlay and C-D2D framework, an optimal subcarrier sharing scheme is proposed, which not only helps the cellular user to achieve the target QoS but also helps the D2D users to communicate with each other. Our results show that the proposed subcarrier sharing scheme leads to considerable performance improvement for both cellular and D2D users.
- The impact of CU-BS distance, angle θ, and cellular user outage probability constraint on different frameworks have been investigated. Through the obtained results it has been shown that for high cellular outage probability constraint and large CU-BS distance, C-D2D framework attains less D2D outage probability as compared to underlay and overlay frameworks. These results can be utilized by the BS to select an optimal D2D framework while satisfying the outage probability constraint of cellular and D2D users.

- The performance of all the three frameworks has been quantified by obtaining closed-form expressions of outage probability for cellular and D2D users.

The remainder of this paper is organized as follows. Section II discusses the system model. Rate and outage probability expressions for cellular and D2D links with proposed scheme are given in Section III. Simulation results are provided in Section IV, and finally, the conclusion is drawn in Section V.

Notations: In this paper, a circularly symmetric complex Gaussian random variable x with mean μ and variance σ^2 is denoted as $x \sim \mathcal{CN}(\mu, \sigma^2)$. Expectation is denoted by $E\{.\}$, whereas an exponential random variable z with mean ζ^l is denoted by $z \sim \exp\left(\zeta^{-l}\right)$.

II. SYSTEM MODEL AND PROTOCOL DESCRIPTION

The system model for underlay, overlay, and C-D2D frameworks are shown in Fig. 1, 2 and 3 respectively. The system model consists of a small cell of radius R. The cell has a BS located at the center, M cellular users, and R D2D (or DT-DR) pairs. Specifically, a cellular user is denoted as CU_i, where $i = 1, 2, .., M$ and a DT-DR pair is denoted as DT_j-DR_j, where $j = 1, 2, .., R$. In line with LTE-A cellular standard, OFDMA has been used as an access technology through which the available spectrum is divided among the M cellular users by allocating each of them N orthogonal subcarriers.[2] A D2D pair may through one of the above frameworks utilizes the same spectrum as allocated to a cellular user CU_i. Channels over the nodes are modeled as frequency non-selective Rayleigh fading with $\Psi_{xy,k} \sim \mathcal{CN}(0, \zeta_{xy}^{-l})$, where ζ_{xy} is the distance between the respective transmitter 'x' and receiver 'y', and l is path loss exponent. $x \in \{c_i, t_j\}$, $y \in \{B, t_j, r_j\}$; $i = 1, 2, .., M, j = 1, 2, .., R$, where c_i denotes the i_{th} cellular user i.e. CU_i, B denotes BS, t_j and r_j denote j^{th} D2D pair i.e. DT_j and DR_j respectively. ζ_{c_iB} denotes the distance between CU_i-BS. Similarly, the distance between CU_i-DT_j, DT_j-BS and DT_j-DR_j is denoted by $\zeta_{c_it_j}$, ζ_{t_jB} and $\zeta_{t_jr_j}$ respectively. In line with conventional D2D communication, it is assumed that the distance between DT_j and DR_j is negligible as compared to the distance between CU_i and DT_j, i.e. $\zeta_{t_jr_j} \ll \zeta_{c_it_j}$, thus CU_i is equidistant from DT_j and DR_j i.e. $\zeta_{c_it_j} = \zeta_{c_ir_j}$. The channel coefficient corresponds to CU_i-BS link is $\Psi_{c_iB,k}$ over subcarrier $k(1 \leq k \leq N)$. Similarly, channel coefficient between CU_i-DT_j, DT_j-BS, and DT_j-DR_j is denoted by $\Psi_{c_it_j,k}$, $\Psi_{t_jB,k}$, $\Psi_{t_jr_j,k}$ respectively. The instantaneous channel gain for each subcarrier is defined as $\gamma_{xy,k} = |\Psi_{xy,k}|^2$. The additive white Gaussian noise (AWGN) at each receiver BS, DT_j and DR_j is denoted as $n_{B,k}, n_{t_j,k}, n_{r_j,k} \sim \mathcal{CN}(0, \sigma_j^2)$. The cellular and D2D user's signals transmitted on k^{th} subcarrier are denoted as $s_{c_i,k}$ and $s_{d_j,k}$ respectively with zero mean and $E\{s^*_{c_i,k}s_{c_i,k}\} = E\{s^*_{d_j,k}s_{d_j,k}\} = 1$.

[2]Although the results have been illustrated assuming OFDMA as a multiple access technique, the results can be easily extended to SC-FDMA whereby assuming that subcarrier mapping for the cellular users occurs after Discrete Fourier transform (DFT).

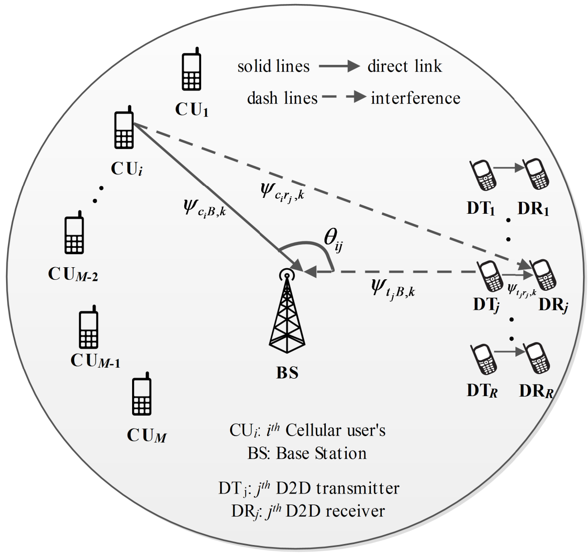

FIGURE 1. System model (underlay framework).

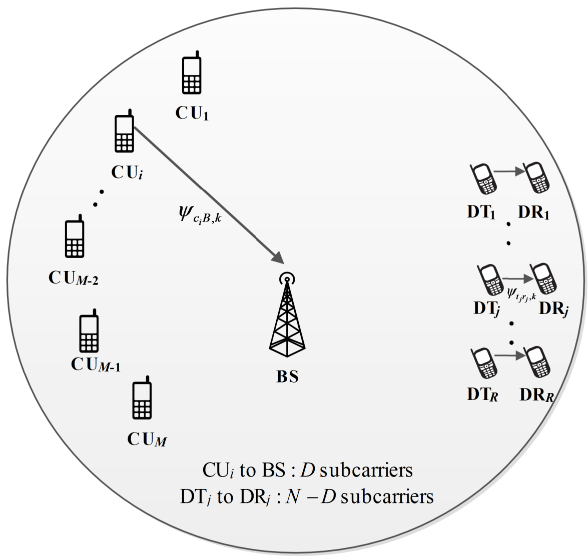

FIGURE 2. System model (overlay framework).

The links between DT_j-BS and CU_i-BS are separated by angle θ_{ij} as shown in the Fig. 1. Hence the distance $\zeta_{c_it_j}$ can be defined in terms of ζ_{c_iB}, ζ_{t_jB}, and angle θ_{ij} as [21],

$$\zeta_{c_it_j} = \sqrt{\zeta_{c_iB}^2 + \zeta_{t_jB}^2 - 2\zeta_{c_iB}\zeta_{t_jB}\cos\theta_{ij}}. \quad (1)$$

In underlay framework, each cellular user can transmit N subcarriers to BS via $\Psi_{c_iB,k}$ link for uplink transmission as shown in the Fig. 1. Since the cellular user and a D2D user share the same spectrum (or same set of resource blocks), BS allows a $\text{DT}_j - \text{DR}_j$ pair to do D2D communication using the spectrum allocated to the cellular user as long as interference threshold requirement of both the cellular and D2D users are satisfied. BS and DR_j will receive interference signals from DT_j and CU_i through $\Psi_{t_jB,k}$ and $\Psi_{c_ir_j,k}$ links respectively.

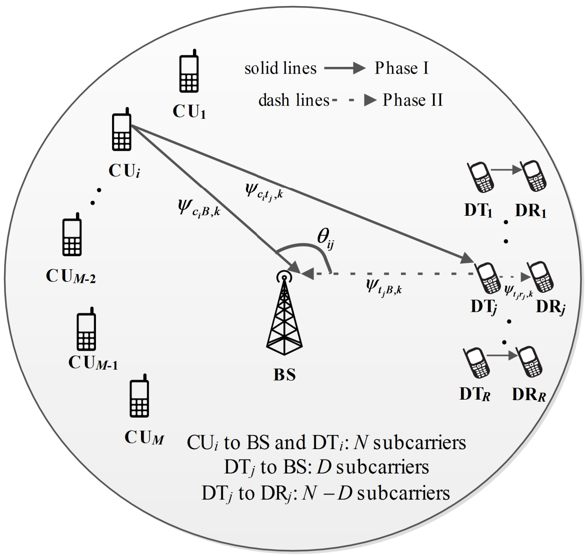

FIGURE 3. System model (C-D2D framework).

However, as $\zeta_{t_j r_j} \ll \zeta_{c_i B}$, the transmission power requirement for the D2D user will be less as compared to the cellular user. Therefore the amount of interference at BS from DT_j will be considerably less than that from CU_i to DR_j. This framework has been evaluated by deriving the outage probability and optimal value of θ_{ij} for various $\zeta_{c_i B}$. Thus from $\zeta_{c_i B}$ and θ_{ij}, BS can find a cellular user that can coexist with DT_j-DR_j pair.

In overlay framework, a part of the cellular spectrum is allocated for D2D communication as shown in Fig. 2. For instance, if QoS requirement of a cellular user 'CU_i' can be satisfied by few subcarriers (say $D < N$), then BS allocates D subcarriers to CU_i for transmission via $\Psi_{c_i B,k}$ link while remaining $N - D$ subcarriers can be used for D2D communication between DT_j and DR_j. It is quite obvious that there will be no interference between cellular and D2D links, as both use orthogonal sets of subcarriers. BS is still responsible for mapping of DT_j- DR_j and CU_i.

In a C-D2D framework, a D2D user helps a cellular user to achieve the desired QoS by acting as a relay in exchange for accessing the cellular spectrum. Specifically, by utilizing spatial diversity, a D2D user helps a cellular user to achieve the desired target rate, and as quid pro quo D2D user is allowed to access the cellular user spectrum. From proposed analysis, BS discovers an optimal CU_i which can form a C-D2D framework with a DT_j- DR_j to facilitate D2D communication while satisfying the QoS of both the cellular and D2D user. As shown in Fig. 3, for C-D2D framework, the total transmission is divided into two phases.[3] In Phase I, CU_i broadcasts signal to BS via $\Psi_{c_i B,k}$ link, which is overheard by DT_j via $\Psi_{c_i t_j,k}$ link. DT_j attempts to decode the cellular signal received in Phase I. If the decoding is successful,[4] it helps the cellular user by allocating few subcarriers (for instance D) for uplink transmission via $\Psi_{t_i B,k}$ link. The number of subcarriers, D, to be allocated for DT_j to BS transmission is selected based on the QoS requirement of CU_i. The remaining subcarriers $(N - D)$ can be used by DT_j to transmit its signal to DR_j. Hence, a C-D2D framework represents a mutually beneficial scenario for both cellular and D2D user. D2D user assists the cellular user in exchange for accessing the cellular spectrum. We have quantified the performance of C-D2D framework by deriving the exact number of subcarriers ($D \leq N$) that needs to be allocated for DT_j to BS transmission to fulfill the target QoS of the cellular user.

[3] Control protocol involved in C-D2D framework is in line with[22]–[24].

[4] If DT_j is not able to decode cellular subcarrier in Phase I, then outage will occur, and no retransmission of cellular signal would be possible in Phase II. However, particular subcarrier can be used by DT_j for D2D communication.

III. RATE AND OUTAGE PROBABILITY

In this section, closed-form expressions for the rate and outage probability of the cellular and D2D user for the three frameworks have been derived.

A. RATE AND OUTAGE PROBABILITY WITH UNDERLAY FRAMEWORK

1) CELLULAR RATE AND OUTAGE PROBABILITY

In underlay framework, a cellular user CU_i transmits N allocated subcarriers to BS. Signal $s_{c_i,k}$ is transmitted by CU_i, and is received by BS on $\Psi_{c_i B,k}$ link. During the same time, signal $s_{d_j,k}$ is transmitted by DT_j to DR_j on $\Psi_{t_j r_j,k}$. The received signal at BS over subcarrier k is denoted as ϕ_k^{BS} and is given by,

$$\phi_k^{BS} = (p_{cu,k})^{\frac{1}{2}} \Psi_{c_i B,k} s_{c_i,k} + (p_{d_j,k})^{\frac{1}{2}} \Psi_{t_j B,k} s_{d_j,k} + n_{B,k}; \quad 1 \leq k \leq N, \quad 1 \leq i \leq M, \; 1 \leq j \leq R \quad (2)$$

where, $p_{cu,k}$ denotes cellular signal power, whereas, $p_{dt,k}$ denotes D2D power on k^{th} subcarrier.

The instantaneous rate received at BS will be,

$$R_{cu}^{under} = \sum_{k=1}^{N} \log_2 \left(1 + \frac{p_{cu,k} \gamma_{c_i B,k}}{\sigma_j^2 + p_{dt,k} \gamma_{t_j B,k}} \right). \quad (3)$$

If the target rate for CU_i to BS is R_{th}^c, then outage occurs when $R_{cu}^{under} < R_{th}^c$. Thus, outage probability for the cellular transmission for underlay framework can be defined as,

$$P_{cu,out}^{under} = \Pr\{R_{cu}^{under} < R_{th}^c\}. \quad (4)$$

Without loss of generality, it is assumed that the power and channel gain are uniformly distributed across all the subcarriers [23],

$$p_{cu,k} = p_{cu}, \forall k; p_{dt,k} = p_{dt}, \forall k; \; \gamma_{xy,k} = \gamma_{xy}, \forall k. \quad (5)$$

Thus, from (3) and (5), (4) can be defined as,

$$\begin{aligned} P_{cu,out}^{under} &= \Pr\left\{ N \log_2 \left(1 + \frac{p_{cu} \gamma_{c_i B}}{\sigma_j^2 + p_{dt} \gamma_{t_j B}} \right) < R_{th}^c \right\} \\ &= \Pr\left\{ \frac{\gamma_{c_i B}}{\sigma_j^2 + p_{dt} \gamma_{t_j B}} < \frac{2^{\frac{R_{th}^c}{N}} - 1}{p_{cu}} \right\} \\ &= \Pr\left\{ \gamma_{c_i B} < \mu \left(\sigma_j^2 + p_{dt} \gamma_{t_j B} \right) \right\}, \end{aligned} \quad (6)$$

where,

$$\mu = \frac{2^{\frac{R_{th}^c}{N}-1}}{p_{cu}}. \tag{7}$$

As $\gamma_{t_jB} \sim \exp\left(\zeta_{t_jB}^l\right)$, thus,

$$\mu\left(\sigma_j^2 + p_{dt}\gamma_{t_jB}\right) > 0. \tag{8}$$

To solve (6), we need to find out joint probability density function (pdf) of independent and exponential random variables γ_{c_iB} and γ_{t_jB} which can be represented as,

$$\zeta_{c_iB}^l e^{-\zeta_{c_iB}^l\gamma_{c_iB}}\zeta_{t_jB}^l e^{-\zeta_{t_jB}^l\gamma_{t_jB}}. \tag{9}$$

Proposition 1: The closed form expression for cellular outage probability with underlay framework can be given as:

$$P_{cu,out}^{under} = 1 - \frac{\zeta_{t_jB}^l e^{-\zeta_{c_iB}^l\mu\sigma_j^2}}{\left(\zeta_{t_jB}^l + \mu p_{dt}\zeta_{c_iB}^l\right)}. \tag{10}$$

Proof:

$$\begin{aligned} P_{cu,out}^{under} &= \int_{\gamma_{t_jB}=0}^{\infty}\int_{\gamma_{c_iB}=0}^{\mu\left(\sigma_j^2+p_{dt}\gamma_{t_jB}\right)} \\ &\quad\times \zeta_{c_iB}^l e^{-\zeta_{c_iB}^l\gamma_{c_iB}}\zeta_{t_jB}^l e^{-\zeta_{t_jB}^l\gamma_{t_jB}}\, d\gamma_{c_iB}\, d\gamma_{t_jB} \\ &= 1 - \zeta_{t_jB}^l e^{-\zeta_{c_iB}^l\mu\sigma_j^2}\int_{\gamma_{t_jB}=0}^{\infty} e^{-\gamma_{t_jB}\left(\zeta_{t_jB}^l+\mu p_{dt}\zeta_{c_iB}^l\right)}. \end{aligned} \tag{11}$$

After simplifying (11), we obtain (10).

Corollary 1: ζ_{c_iB}, for a fixed cellular outage probability constraint and fixed p_{cu},

We can rewrite (10) as,

$$\begin{aligned} &P_{cu,out}^{under}(\zeta_{t_jB}^l + \mu p_{dt}\zeta_{c_iB}^l) = \zeta_{t_jB}^l + \mu p_{dt}\zeta_{c_iB}^l - \zeta_{t_jB}^l e^{-\zeta_{c_iB}^l\mu\sigma_j^2} \\ &\zeta_{c_iB}^l(\mu p_{dt}(P_{cu,out}^{under})) + \zeta_{t_jB}^l e^{-\zeta_{c_iB}^l\mu\sigma_j^2} = \zeta_{t_jB}^l(1 - P_{cu,out}^{under}). \end{aligned} \tag{12}$$

From (12), ζ_{c_iB} is given as,

$$\zeta_{c_iB}^l = \frac{C_4 + \frac{C_1}{C_3}W\left(-\frac{C_2C_3}{C_1}e^{-\frac{C_3C_4}{C_1}}\right)}{C_1}, \tag{13}$$

where,

$$\begin{aligned} C_1 &= \mu p_{dt}(P_{cu,out}^{under} - 1), \\ C_2 &= \zeta_{t_jB}^l, \\ C_3 &= \mu\sigma_j^2, \\ C_4 &= \zeta_{t_jB}^l(1 - P_{cu,out}^{under}). \end{aligned}$$

and W(.) is a Lambert W function [25].

Corollary 2: p_{cu}, for a fixed cellular outage probability constraint and fixed ζ_{c_iB},

From (12), the closed form expression of μ is given as :

$$\mu = \frac{A_4 + \frac{A_1}{A_3}W\left(-\frac{A_2A_3}{A_1}e^{-\frac{A_3A_4}{A_1}}\right)}{A_1}, \tag{14}$$

where,

$$\begin{aligned} A_1 &= \zeta_{c_iB}^l p_{dt}\left(P_{cu,out}^{under} - 1\right), \\ A_2 &= \zeta_{t_jB}^l, \\ A_3 &= \zeta_{c_iB}^l\sigma_j^2, \\ A_4 &= \zeta_{t_jB}^l\left(1 - P_{cu,out}^{under}\right). \end{aligned}$$

From (7) and (14),

$$p_{cu} = \frac{\left(2^{\frac{R_{th}^c}{N}} - 1\right)A_1}{A_4 + \frac{A_1}{A_3}W\left(-\frac{A_2A_3}{A_1}e^{-\frac{A_3A_4}{A_1}}\right)}. \tag{15}$$

2) D2D RATE AND OUTAGE PROBABILITY

The received signal at DR$_j$ over subcarrier k is denoted as ϕ_k^{DR} which is equal to,

$$\begin{aligned} \phi_k^{DR} &= (p_{dt,k})^{\frac{1}{2}}\Psi_{t_jr_j,k}s_{d_j,k} + (p_{cu,k})^{\frac{1}{2}}\Psi_{c_it_j,k}s_{c_i,k} + n_{r_j,k}; \\ &\qquad 1 \le k \le N, \quad 1 \le i \le M, \; 1 \le j \le R \end{aligned} \tag{16}$$

where $s_{c_i,k}$ acts as an interference at DR$_j$. The instantaneous rate received at DR$_j$,

$$R_{d2d}^{under} = \sum_{k=1}^{N}\log_2\left(1 + \frac{p_{dt,k}\gamma_{t_jr_j,k}}{\sigma_j^2 + p_{cu,k}\gamma_{c_it_j,k}}\right). \tag{17}$$

The target rate of D2D transmission is R_{th}^d and outage occurs if $R_{d2d}^{under} < R_{th}^d$. Thus, the outage probability for D2D user for underlay framework can be given as,

$$P_{dt,out}^{under} = \Pr\{R_{dt}^{under} < R_{th}^d\}. \tag{18}$$

From (5) and (17), (18) can be rewritten as,

$$\begin{aligned} P_{dt,out}^{under} &= \Pr\left\{N\log_2\left(1 + \frac{p_{dt}\gamma_{t_jr_j}}{\sigma_j^2 + p_{cu}\gamma_{c_it_j}}\right) < R_{th}^d\right\} \\ &= Pr\left\{\gamma_{t_jr_j} < \beta\left(\sigma_j^2 + p_{cu}\gamma_{c_it_j}\right)\right\}, \end{aligned} \tag{19}$$

where, $\beta = \frac{2^{\frac{R_{th}^d}{N}-1}}{p_{dt}}$. As $\gamma_{c_it_j} \sim \exp\left(\zeta_{c_it_j}^l\right)$, thus,

$$\beta\left(\sigma_j^2 + p_{dt}\gamma_{c_it_j}\right) > 0. \tag{20}$$

Proposition 2: Following the steps of (10), the D2D outage probability with underlay framework can be derived as,

$$P_{dt,out}^{under} = 1 - \frac{\zeta_{c_it_j}^l e^{-\zeta_{t_jr_j}^l\beta\sigma_j^2}}{\left(\zeta_{c_it_j}^l + \beta p_{cu}\zeta_{t_jr_j}^l\right)}. \tag{21}$$

Corollary 3: θ_{ij} which will satisfy a fixed D2D outage probability constraint. We can rewrite (21) as,

$$P^{under}_{dt,out}(\zeta^l_{c_it_j} + \beta p_{cu}\zeta^l_{t_jr_j}) = \zeta^l_{c_it_j} + \beta p_{cu}\zeta^l_{t_jr_j} - \zeta^l_{c_it_j}e^{-\zeta^l_{t_jr_j}\beta\sigma_j^2}, \tag{22}$$

$$\zeta^l_{c_it_j} = \frac{\beta p_{cu}\zeta^l_{t_jr_j}(1 - P^{under}_{dt,out})}{P^{under}_{dt,out} - 1 + e^{-\zeta^l_{t_jr_j}\beta\sigma_j^2}}, \tag{23}$$

$$\zeta^l_{c_it_j} = Z(\text{let}) \tag{24}$$

where Z is $\frac{\beta p_{cu}\zeta^l_{t_jr_j}(1-P^{under}_{dt,out})}{P^{under}_{dt,out}-1+e^{-\zeta^l_{t_jr_j}\beta\sigma_j^2}}$. Substituting (24) in (1), we obtain θ_{ij} as,

$$\theta_{ij} = \cos^{-1}\frac{\zeta^2_{c_iB} + \zeta^2_{t_jB} - Z^{\frac{2}{l}}}{2\zeta_{c_iB}\zeta_{t_jB}}. \tag{25}$$

θ_{ij} is a very useful parameter. For fixed ζ_{c_iB}, D2D outage probability decreases with increase in θ_{ij}, whereas cellular outage probability is independent of θ_{ij}. It helps the BS to select the CU_i which can facilitate DT_j-DR_j communication with minimal interference to each other.

Lemma 1: Estimating the range of $\zeta_{c_it_j}$

Since, $\cos(\theta_{ij})$ ranges from [-1,1], hence (25) can be written as,

$$-1 \le \frac{\zeta^2_{c_iB} + \zeta^2_{t_jB} - Z^{\frac{2}{l}}}{2\zeta_{c_iB}\zeta_{t_jB}} \le 1 \tag{26}$$

$$-2\zeta_{c_iB}\zeta_{t_jB} \le \zeta^2_{c_iB} + \zeta^2_{t_jB} - Z^{\frac{2}{l}} \le 2\zeta_{c_iB}\zeta_{t_jB}$$
$$|\zeta_{c_iB} - \zeta_{t_jB}| \le Z^{\frac{1}{l}} \le |\zeta_{c_iB} + \zeta_{t_jB}|. \tag{27}$$

From (24),

$$|\zeta_{c_iB} - \zeta_{t_jB}| \le \zeta_{c_it_j} \le |\zeta_{c_iB} + \zeta_{t_jB}|. \tag{28}$$

B. RATE AND OUTAGE PROBABILITY WITH OVERLAY FRAMEWORK

1) CELLULAR RATE AND OUTAGE PROBABILITY

In overlay framework, BS allocates a part of the cellular spectrum to the D2D user as long as QoS of the cellular user is not compromised. To determine whether a part of the cellular spectrum (or set of subcarriers) can be allocated to the D2D user, BS calculates R_N (maximum achievable data rate) of the cellular link by assuming that all subcarriers participated in CU_i to BS communication, and no subcarriers were allocated to the D2D user. If $R_N > R^c_{th}$, where R^c_{th} denotes target rate of the cellular system, then BS assigns few subcarriers (e.g., D) to the cellular user, which helps in maintaining the desired QoS with acceptable outage probability constraint. The remaining $N-D$ subcarriers are allocated for D2D communication.

Suppose signal $s_{c_i,k}$ is transmitted by CU_i, and received by BS. The received signal at BS over subcarrier k is denoted as ϕ^{BS}_k which is equal to,

$$\phi^{BS}_k = (p_{cu,k})^{\frac{1}{2}}\Psi_{c_iB,k}s_{c_i,k} + n_{B,k}; \quad 1 \le k \le N,\ 1 \le i \le M \tag{29}$$

BS first calculates R_N by assuming that CU_i is transmitting all N subcarriers to BS.

$$R_N = \sum_{k=1}^{N}\log_2\left(1 + \frac{p_{cu,k}\gamma_{c_iB,k}}{\sigma_j^2}\right), \tag{30}$$

If $R_N > R^c_{th}$, CU_i will transmit D subcarriers to BS. The instantaneous rate with D subcarriers is given as,

$$R^{over}_{cu} = \sum_{k=1}^{D}\log_2\left(1 + \frac{p_{cu,k}\gamma_{c_iB,k}}{\sigma_j^2}\right), \tag{31}$$

The target rate of uplink transmission is R^c_{th} and outage occurs if $R^{over}_{cu} < R^c_{th}$. From (5) and (31), the outage probability for the cellular transmission can be derived as,

$$P^{over}_{cu,out} = 1 - \exp\left(-\frac{\sigma_j^2(2^{R^c_{th}/D} - 1)\zeta^l_{c_iB}}{p_{cu}}\right). \tag{32}$$

2) D2D RATE AND OUTAGE PROBABILITY

Since for overlay framework subcarrier allocation for cellular and D2D users are orthogonal; hence there is no interference between the cellular and D2D user. Signal $s_{d_j,k}$ is transmitted by DT_j to DR_j. The received signal at DR_j over subcarrier k is denoted as ϕ^{DR}_k which is equal to,

$$\phi^{DR}_k = (p_{dt,k})^{\frac{1}{2}}\Psi_{t_jr_j,k}s_{d_j,k} + n_{r_j,k};$$
$$N - D \le k \le N,\ 1 \le j \le R, \tag{33}$$

where $p_{dt,k}$ denotes D2D signal power for k^{th} subcarrier. The instantaneous rate for $N-D$ subcarriers is given as,

$$R^{over}_{d2d} = \sum_{k=1}^{N-D}\log_2\left(1 + \frac{p_{dt,k}\gamma_{t_jr_j,k}}{\sigma_j^2}\right). \tag{34}$$

The target rate of D2D transmission is R^d_{th} and outage occurs if $R^{over}_{d2d} < R^d_{th}$. From (5) and (34), the outage probability for D2D transmission can be defined as,

$$P^{over}_{d2d,out} = 1 - \exp\left(-\frac{\sigma_j^2(2^{R^d_{th}/(N-D)} - 1)\zeta^l_{t_jr_j}}{p_{dt}}\right). \tag{35}$$

C. RATE AND OUTAGE PROBABILITY WITH C-D2D

1) CELLULAR RATE AND OUTAGE PROBABILITY

In the C-D2D framework, DT_j acts as a decode-and-forward (DF) relay between CU_i and BS to provide spatial diversity to the cellular user. In return, BS allows D2D user to access the cellular spectrum. The C-D2D communication is achieved by adopting the following two-phase transmission protocol [22], [26]. In Phase I, CU_i broadcasts N subcarriers to BS which is overheard by DT_j. Signal received by DT_j is,

$$\phi^{DT_j,1}_k = (p_{cu,k})^{\frac{1}{2}}\Psi_{c_it_j,k}s_{c_i,k} + n_{t_j,k};$$
$$1 \le K \le N, \quad 1 \le i \le M,\ 1 \le j \le R. \tag{36}$$

The instantaneous rate at DT_j can be given as,

$$R^{cu-dt}_N = \frac{1}{2}\sum_{k=1}^{N}\log_2\left(1 + \frac{p_{cu,k}\gamma_{c_it_j,k}}{\sigma_j^2}\right). \tag{37}$$

From (5), (37) can be deduced to,

$$R_N^{cu-dt} = \frac{N}{2}\log_2\left(1 + \frac{p_{cu}\gamma_{c_it_j}}{\sigma_j^2}\right), \quad (38)$$

where the factor $\frac{1}{2}$ is due to the fact that the whole transmission is divided into two phases. DT_j attempts to decode the cellular data received from CU_i in Phase I. If the decoding is successful, DT_j allocates D subcarriers to cellular data while remaining $N - D$ subcarriers are allocated for DT_j to DR_j communication.[5] The instantaneous rate at BS after maximal ratio combining (MRC) of two phases transmission with a condition of successful decoding of cellular signal $s_{c_i,k}$ at DT_j is,

$$R_{cu}^{coop} = \frac{1}{2}\sum_{k=1}^{D}\log_2\left(1 + \frac{p_{cu,k}\gamma_{c_iB,k}}{\sigma_j^2} + \frac{p_{dt,k}\gamma_{t_jB,k}}{\sigma_j^2}\right) + \frac{1}{2}\sum_{k=1}^{N-D}\log_2\left(1 + \frac{p_{cu,k}\gamma_{c_iB,k}}{\sigma_j^2}\right). \quad (39)$$

From (5), (39) can be rewritten as,

$$R_{cu}^{coop} = \frac{D}{2}\log_2\left(1 + \frac{p_{cu}\gamma_{c_iB}}{\sigma_j^2} + \frac{p_{dt}\gamma_{t_jB}}{\sigma_j^2}\right) + \frac{N-D}{2}\log_2\left(1 + \frac{p_{cu}\gamma_{c_iB}}{\sigma_j^2}\right). \quad (40)$$

In a case of unsuccessful decoding at DT_j, there will be no transmission from DT_j to BS in Phase II. However, BS may still be able to receive the cellular signal from CU_i-BS link. Thus, the cellular outage probability with C-D2D is,

$$P_{cu,out}^{coop} = \Pr(R_N^{cu-dt} > R_{th}^c)\Pr(R_{cu}^{coop} < R_{th}^c) + \Pr(R_N^{cu-dt} < R_{th}^c)\Pr(\frac{1}{2}R_N < R_{th}^c), \quad (41)$$

where R_N can be found from (30).

$$\Pr\left(\frac{1}{2}R_N < R_{th}^c\right) = \Pr\left(\gamma_{c_iB} < \frac{\rho_1\sigma_j^2}{p_{cu}}\right) = 1 - e^{-\frac{\zeta_{c_iB}^l\sigma_j^2}{p_{cu}}\rho_1}. \quad (42)$$

$$\Pr(R_N^{cu-dt} < R_{th}^c) = \Pr\left(\gamma_{c_it_j} < \frac{\rho_1\sigma_j^2}{p_{cu}}\right) = 1 - e^{-\frac{\zeta_{c_it_j}^l\sigma_j^2}{p_{cu}}\rho_1}, \quad (43)$$

where, $\gamma_{c_iB} \sim \exp\left(\zeta_{c_iB}^l\right)$, $\gamma_{c_it_j} \sim \exp\left(\zeta_{c_it_j}^l\right)$, and $\rho_1 = 2^{\frac{2R_{th}^c}{N}} - 1$.

Similarly,

$$\Pr(R_N^{cu-dt} > R_{th}^c) = \Pr\left(\gamma_{c_it_j} > \frac{\rho_1\sigma_j^2}{p_{cu}}\right) = e^{-\frac{\zeta_{c_it_j}^l\sigma_j^2}{p_{cu}}\rho_1}. \quad (44)$$

[5] It is obvious that $D \leq N$, for the cases where $D = N$, DT_j will be pure relay [26].

Further,

$$\Pr(R_{cu}^{coop} < R_{th}^c) = \Pr\left(\left[1 + \frac{p_{cu}\gamma_{c_iB}}{\sigma_j^2} + \frac{p_{dt}\gamma_{t_jB}}{\sigma_j^2}\right]^D \times \left[1 + \frac{p_{cu}\gamma_{c_iB}}{\sigma_j^2}\right]^{N-D} < 2^{2R_{th}^c}\right). \quad (45)$$

Let, $\sigma_j^2 = \sigma^2; \forall j$, and $\frac{p_{cu}\gamma_{c_iB}}{\sigma^2} + \frac{p_{dt}\gamma_{t_jB}}{\sigma^2} \gg \sigma^2$, we can rewrite (45) as,

$$\begin{aligned} &= \Pr\left(\left(p_{cu}\gamma_{c_iB} + p_{dt}\gamma_{t_jB}\right)^D \left(p_{cu}\gamma_{c_iB}\right)^{N-D} < 2^{2R_{th}^c}\sigma^{2N}\right) \\ &= \Pr\left(\left(p_{cu}\gamma_{c_iB} + p_{dt}\gamma_{t_jB}\right) < \frac{\left(2^{2R_{th}^c}\sigma^{2N}\right)^{\frac{1}{D}}}{\left(p_{cu}\gamma_{c_iB}\right)^{\frac{N-D}{D}}}\right) \\ &= \Pr\left(\gamma_{t_jB} < \frac{\Gamma^{\frac{1}{D}}}{p_{dt}\left(p_{cu}\gamma_{c_iB}\right)^{\frac{N-D}{D}}} - \frac{p_{cu}\gamma_{c_iB}}{p_{dt}}\right), \end{aligned} \quad (46)$$

where, $\Gamma = 2^{2R_{th}^c}\sigma^{2N}$.

Let,

$$\frac{\Gamma^{\frac{1}{D}}}{p_{dt}\left(p_{cu}\gamma_{c_iB}\right)^{\frac{N-D}{D}}} - \frac{p_{cu}\gamma_{c_iB}}{p_{dt}} = \beta\left(\gamma_{c_iB}\right), \quad (47)$$

where, $\gamma_{t_jB} \sim \exp\left(\zeta_{t_jB}^l\right)$.

Since,

$$\beta\left(\gamma_{c_iB}\right) > 0, \quad (48)$$

$$\frac{\Gamma^{\frac{1}{D}}}{p_{dt}\left(p_{cu}\gamma_{c_iB}\right)^{\frac{N-D}{D}}} - \frac{p_{cu}\gamma_{c_iB}}{p_{dt}} > 0. \quad (49)$$

Simplifying (49), we will get,

$$\gamma_{c_iB} < \frac{\Gamma^{\frac{1}{N}}}{p_{cu}} = \alpha \text{ (let)}. \quad (50)$$

As γ_{c_iB} and γ_{t_jB} are independent exponential random variable, it's joint probability density function is given as (9). Hence,

$$\begin{aligned} &\Pr\left(\gamma_{t_jB} < \beta\left(\gamma_{c_iB}\right)\right) \\ &= \int_{\gamma_{c_iB}=0}^{\alpha}\int_{\gamma_{t_jB}=0}^{\beta(\gamma_{c_iB})} \zeta_{c_iB}^l e^{-\zeta_{c_iB}^l\gamma_{c_iB}}\zeta_{t_jB}^l e^{-\zeta_{t_jB}^l\gamma_{t_jB}} d\gamma_{c_iB}d\gamma_{t_jB} \\ &= \int_{\gamma_{c_iB}=0}^{\alpha} \zeta_1^l e^{-\zeta_{c_iB}^l\gamma_{c_iB}}\left(1 - e^{-\zeta_{t_jB}^l\beta(\gamma_{c_iB})}\right) d\gamma_{c_iB} \\ &= 1 - e^{-\zeta_{c_iB}^l\alpha} - \zeta_{c_iB}^l\Upsilon_1, \end{aligned} \quad (51)$$

where,

$$\Upsilon_1 = \int_{\gamma_{c_iB}=0}^{\alpha} e^{\left(\vartheta_2\gamma_{c_iB} - \frac{\vartheta_1}{\gamma_{c_iB}^{\frac{N}{D}-1}}\right)} d\gamma_{c_iB}, \quad (52)$$

$$\vartheta_1 = \frac{\zeta_{t_jB}^l \Gamma^{\frac{1}{D}}}{p_{dt} p_{cu}^{\frac{N}{D}-1}}, \quad \vartheta_2 = \frac{\zeta_{t_jB}^l p_{cu}}{p_{dt}} - \zeta_{c_iB}^l. \tag{53}$$

(52) is intractable, however, if we substitute, $\vartheta_2 = 0$ i.e. $\frac{\zeta_{c_iB}^l}{\zeta_{t_jB}^l} = \frac{p_{cu}}{p_{dt}}$, (52) can be reduced to,

$$\Upsilon_1 = \int_{\gamma_{c_iB}=0}^{\alpha} e^{-\vartheta_1 \gamma_{c_iB}^{-\left(\frac{N}{D}-1\right)}} d\gamma_{c_iB}. \tag{54}$$

Now, substitute $\gamma_{c_iB}^{-\frac{N-D}{D}} = t$. So (54) reduces to,

$$\Upsilon_1 = \frac{D}{N-D} \int_{\alpha^{-\frac{N-D}{D}}}^{\infty} t^{-\frac{N}{N-D}} e^{-\vartheta_1 t} dt. \tag{55}$$

From [27], (55) can be solved as,[6]

$$\Upsilon_1 = (-1)^{n+1} \vartheta_1^n \frac{Ei(-\vartheta_1 u)}{n!} + \frac{e^{-\vartheta_1 u}}{u^n} \tag{56}$$

where, $n = \frac{D}{N-D}$, $u = \alpha^{-\frac{N-D}{D}}$ and Ei stands for exponential integral.

Hence, from (42),(43),(44),(51), the outage probability for the C-D2D framework can be given as,

$$P_{cu,out}^{coop} = e^{-\frac{\zeta_{c_it_j}^l \sigma^2}{p_{cu}} \rho_1} (1 - e^{-\zeta_{c_iB}^l \alpha} - \zeta_{c_iB}^l \Upsilon_1) + \left(1 - e^{-\frac{\zeta_{c_it_j}^l \sigma^2}{p_{cu}} \rho_1}\right) \left(1 - e^{-\frac{\zeta_{c_iB}^l \sigma^2}{p_{cu}} \rho_1}\right). \tag{57}$$

2) D2D RATE AND OUTAGE PROBABILITY

In Phase II, DR_j will receive $N - D$ subcarriers via $\Psi_{t_jr_j,k}$ link. Hence signal received by DR_j will be,

$$\phi_k^{DR,2} = (p_{dt,k})^{\frac{1}{2}} \Psi_{t_jr_j,k} s_{d_j,k} + n_{r_j,k}; \quad 1 \le K \le N, \ 1 \le j \le R. \tag{58}$$

The instantaneous rate at DR_j is given as,

$$R_{d2d}^{coop} = \frac{1}{2} \sum_{k=1}^{N-D} \log_2 \left(1 + \frac{p_{dt,k} \gamma_{t_jr_j,k}}{\sigma_j^2}\right). \tag{59}$$

If the target rate for D2D communication is R_{th}^d, then the outage will occur when $\Pr(R_{d2d}^{coop} < R_{th}^d)$. From (5) and (59),

$$\Pr(R_{d2d}^{coop} < R_{th}^d) = \Pr\left(\gamma_{t_jr_j} < \frac{\rho_2 \sigma^2}{p_{dt}}\right) = 1 - e^{-\frac{\zeta_{t_jr_j}^l \sigma^2}{p_{dt}} \rho_2}, \tag{60}$$

where $\gamma_{t_jr_j} \sim \exp\left(\zeta_{t_jr_j}^l\right)$ and $\rho_2 = 2^{\frac{2R_{th}^d}{(N-D)}} - 1$.

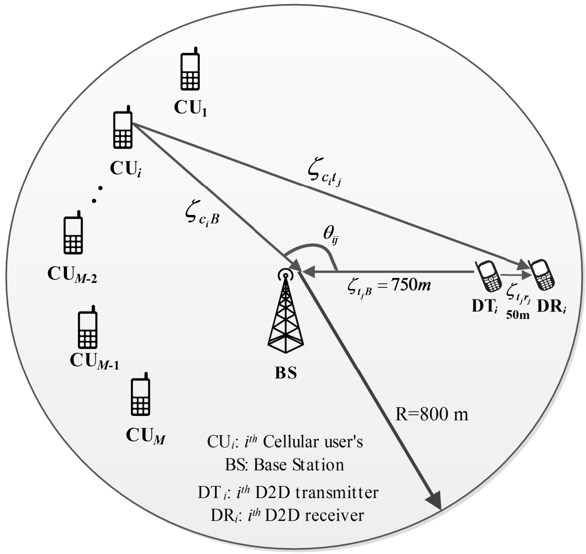

FIGURE 4. Simulation model.

TABLE 1. Simulation parameters.

N	32 subcarriers
R_{th}^c	1 b/s/Hz
R_{th}^d	1 b/s/Hz
σ^2	−120dbm
l	4 (urban area)
ζ_{t_jB}	750m
$\zeta_{t_jr_j}$	50m

IV. SIMULATION RESULTS AND DISCUSSION

In this section, we have plotted the simulation results for the outage probability of cellular and D2D user for the three frameworks. Further, in order to verify the analytical derivations, simulation results have also been compared with theoretical results. Fig. 4 depicts the simulation model. As discussed before, the simulation model consists of a circular microcell of radius R = 800m, where BS is located at the center of the cell. A D2D user[7] lie at the cell boundary, and the distance between DT_j−DR_j is assumed to be 50 meters *i.e.* $\zeta_{t_jr_j} = 50$m. Distance between BS and a D2D user is set to 750 meters *i.e.* $\zeta_{t_jB} = 750$m. The parameters used for simulation are listed in Table I. We have chosen target rate for both cellular and D2D link as $R_{th}^c = R_{th}^d = 1$ b/s/Hz, $N = 32$ is the total number of subcarriers preassigned by BS to CU_i.

Table 2 shows the upper limit (maximum value) of ζ_{c_iB} (distance between CU_i and BS) for fixed p_{cu} for the underlay framework, below which the given outage probability constraint of a cellular user is always satisfied. It can also be seen from Table 2, that for a particular p_{cu}, ζ_{c_iB} decreases with

[6]In this paper we have solved (52) numerically to obtain the theoretical plots.

[7]For simulation, a D2D pair is considered which can map to an optimal CU_i for subcarrier sharing by BS. However, the analysis presented in the paper is applicable for multiple D2D pairs as each CU_i has its individual N allocated subcarrier for uplink transmission.

TABLE 2. Upper limit of ζ_{c_iB} which satisfies the outage probability constraint of a cellular user for underlay framework.

Fixed p_{cu} to calculate max ζ_{c_iB}				
p_{cu}(in Watts)	$P^{under}_{cu,out} = 10^{-1}$	$P^{under}_{cu,out} = 10^{-2}$	$P^{under}_{cu,out} = 10^{-3}$	$P^{under}_{cu,out} = 10^{-4}$
0.1	*All values*	701.57	393.74	221.41
0.01	714.75	394.52	221.46	124.51
0.001	401.93	221.85	124.53	70.02

TABLE 3. Lower limit of θ_{ij} which satisfies the Outage Probability constraint of a D2D User for a fixed ζ_{c_iB} and $p_{cu} = 0.1$W for underlay framework.

Fixed ζ_{c_iB} and $p_{cu} = 0.1$ to calculate min θ_{ij}				
ζ_{c_iB}(in meters)	$P^{under}_{dt,out} = 10^{-1}$	$P^{under}_{dt,out} = 10^{-2}$	$P^{under}_{dt,out} = 10^{-3}$	$P^{under}_{dt,out} = 10^{-4}$
750	21°	39°	73°	*Nil*
600	19°	41°	81°	*Nil*
300	*All values*	26°	108°	*Nil*
200	*All values*	*All values*	129°	*Nil*

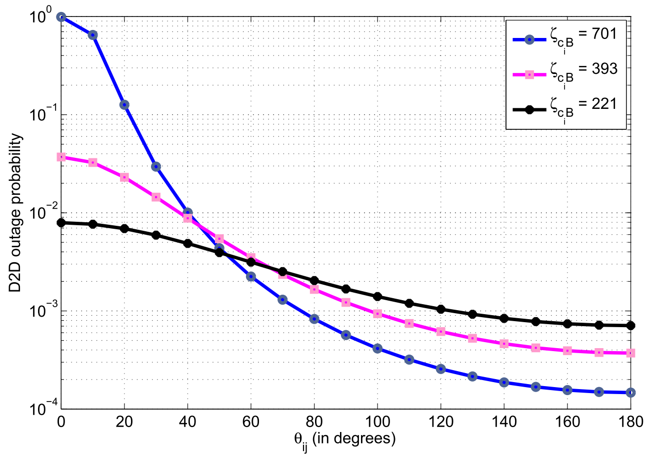

FIGURE 5. D2D outage probability vs angle θ_{ij} for underlay framework.

cellular outage constraint. Essentially, when $p_{cu} = 0.1$W, to satisfy $P^{under}_{cu,out} = 10^{-2}$, $\zeta_{c_iB} \leq 701.57$m.

Table 3 gives the minimum value of angle θ_{ij} (in degrees) which satisfies the given outage probability constraint of cellular and D2D user for fixed value of ζ_{c_iB}. For instance, when $p_{cu} = 0.1$ and $\zeta_{c_iB} = 600$, $\theta_{ij} \geq 41°$ is required to satisfy the D2D outage constraint[8] of 10^{-2}. Hence from Table 2 and 3, BS can select an optimal cellular user for underlaying D2D communication to satisfy the outage constraints for both cellular as well as D2D users. Maximum value (optimal) of θ_{ij} is 180° i.e. when $\theta_{ij} = 180°$, D2D system attains minimum outage probability. In Table 3 , *Nil* signifies that D2D outage constraint will not be satisfied irrespective of the value of θ_{ij}, whereas, *All values* states that D2D outage constraint will always be satisfied irrespective of value of θ_{ij}.

Fig. 5 shows D2D outage probability with respect to θ_{ij} (in degrees) for three distances $\zeta_{c_iB} = 701, 393, 221$ meters for underlay framework. These distances satisfy the cellular

[8] $\zeta_{c_iB} = 600$ satisfies the cellular outage constraint of 10^{-2}, (see Table2)

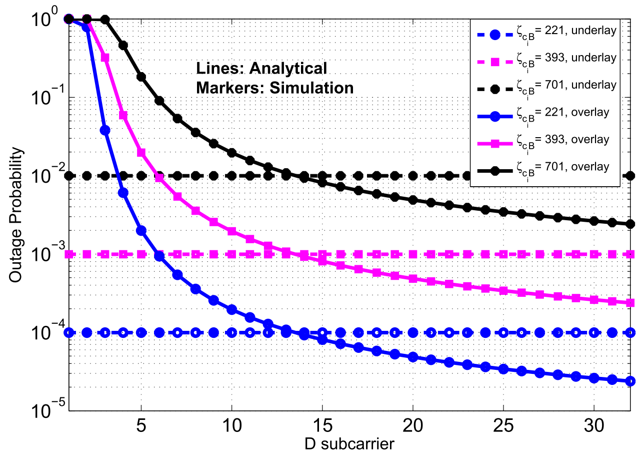

FIGURE 6. Cellular outage probability for underlay and overlay frameworks.

outage constraint of $10^{-2}, 10^{-3}, 10^{-4}$ respectively, when $p_{cu} = 100$ mW (as seen from Table 2). D2D subcarrier power p_{dt} has been set to 1 mW. D2D outage probability decreases with increase in θ_{ij}. This is quite obvious that for fixed ζ_{c_iB}, as θ_{ij} increases, $\zeta_{c_it_j}$ also increases, thus CU$_i$ moves away from DT$_j$ causing less interference at DT$_j$, consequently D2D outage probability decreases. For $\zeta_{c_iB} = 701$, if θ_{ij} ranges from 0 to 50°, the cellular user will be close to DT$_j$−DR$_j$ pair, thus outage probability is comparatively high. If θ_{ij} approaches 180°, ζ_{c_iB} becomes large, consequently, CU$_i$ will cause less interference to D2D user, thus resulting in low outage probability. On the contrary, for $\zeta_{c_iB} = 221$, for low range of θ_{ij}, D2D outage probability is comparatively low. If θ_{ij} varies from 50° to 180°, D2D outage probability is higher as compare to other distances.

Fig. 6 shows the theoretical and simulation results of the outage probability of the cellular user for overlay and underlay frameworks. For overlay framework, D orthogonal subcarriers are used for cellular communication, whereas for underlay framework, all N subcarriers are used for cellular communication. Results have been plotted for different CU$_i$−BS distances, i.e. $\zeta_{c_iB} = 221$m, 393m and 701m, and $p_{cu} = 100$ mW, $p_{dt} = 1$ mW (for underlay) and $\theta_{ij} = 180^0$ (best case for underlay). Overlay outage probability is independent on θ_{ij}. For overlay framework, when number of subcarriers are allocated for CU$_i$ to BS transmission, outage probability decreases, whereas, for underlay framework, outage probability is independent of D. For $\zeta_{c_iB} = 221$m, cellular outage probability for underlay framework is 10^{-4}, whereas, to achieve same outage probability via overlay framework, BS needs to allocate $D \geq 14$ subcarriers for cellular communication. However, remaining $N - D$ i.e. 18 subcarriers can be used for D2D communication. Similar observations can be made for other two distances $\zeta_{c_iB} = 393$, $\zeta_{c_iB} = 701$.

Fig. 7 shows the outage probability of CU$_i$-BS link vs number of subcarriers allocated by DT$_j$ under C-D2D framework. Subcarrier power has been set to $p_{cu} = 100$mW. Outage

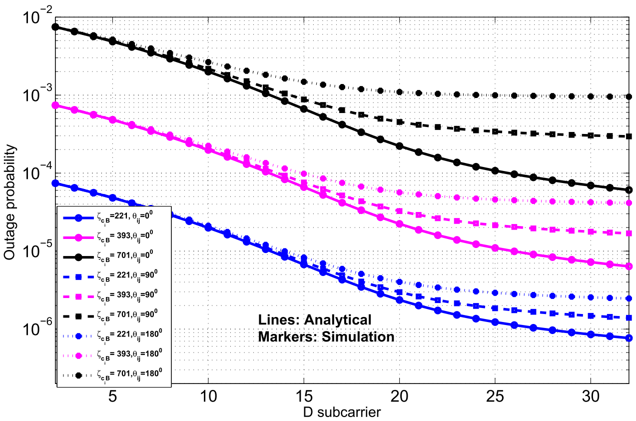

FIGURE 7. Cellular outage probability for C-D2D framework.

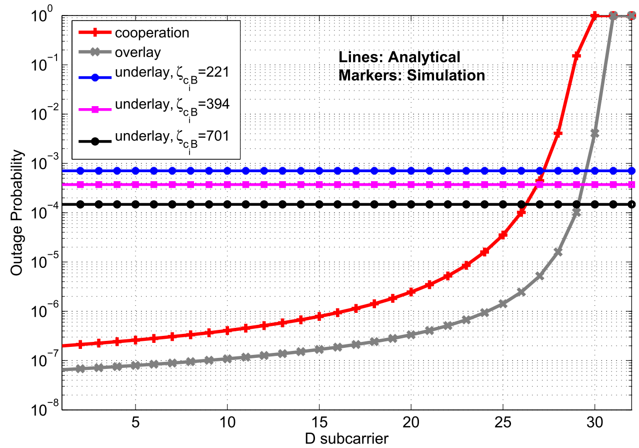

FIGURE 8. D2D outage probability vs subcarriers.

probability has been plotted for three distances, $\zeta_{c_iB} = 221$m, 393m and 701m for different θ_{ij} (0°, 90°, 180°). Outage probability increases with increase in ζ_{c_iB}, and decreases with decrease in θ_{ij}. From Fig. 7, it can be observed that as D increases, outage probability decreases. It is evident as with the increase in D, rate at BS with MRC increases, consequently outage probability decrease. For $\zeta_{c_iB} = 221$, if DT$_j$ forwards only 2 subcarriers to BS, the outage probability achieved is less than 10^{-4}. Hence, remaining $N - D = 30$ subcarriers are available for D2D communication. If we compare Fig. 6 and Fig. 7, it is also evident that C-D2D framework outperforms underlay and overlay frameworks.

Another observation that can be made from Fig. 7 is for $\zeta_{c_iB} = 221$, outage probability is almost constant from $D = 1$ to $D = 13$. This can be explained as follows. For a low value of D, the outage probability with C-D2D mainly depends on direct CU$_i$-BS transmission rather than relayed transmission. As direct CU$_i-$BS distance is fixed to $\zeta_{c_iB} = 221$, therefore changes in θ_{ij} has low impact on outage probability. However, for higher values of D, more subcarriers are relayed by DT$_j$ to BS, whose impact largely reduces the outage probability. Further, as θ_{ij} increases, successful decoding of subcarriers at DT$_j$ becomes the limiting factor, consequently, outage probability increases.

For, $\zeta_{c_iB} = 701$, $\theta_{ij} = 180$, and D $\geq$ 20, outage probability decreases slowly and is almost stagnant. It is due to the fact that at this distance ζ_{c_iB} is quite large, so again successful decoding of subcarriers at DT$_j$ becomes the bottleneck for outage probability.

Fig. 8 shows the outage probability of D2D user for the three frameworks. For overlay and C-D2D frameworks, $N-D$ orthogonal subcarriers can be used for D2D communication, whereas for underlay framework, all N subcarriers can be used for D2D communication. θ_{ij} has been set to its optimal value, i.e. $\theta_{ij} = 180°$. From Fig. 8, it can be seen that, for overlay and C-D2D frameworks, as D increases, outage probability increases, whereas underlay framework is independent of D. For underlay framework, as ζ_{c_iB} increases, D2D outage probability decreases as interference generated by CU$_i$ to DR$_j$ decreases.

Let us assume a scenario in which cellular system would like to maintain an acceptable QoS by putting a constraint on outage probability, i.e. $P_{cu,out} \leq 10^{-4}$. For underlay framework, as observed in Fig. 6, this cellular outage probability constraint will be satisfied when $\zeta_{c_iB} = 221$ and $\theta_{ij} = 180°$. Further, it can be seen from Fig. 8 that D2D user can obtain an outage probability of $\approx 10^{-3}$. With overlay and C-D2D framework, $D \geq 14$ and $D \geq 1$ subcarriers are required respectively to satisfy the cellular outage probability constraint. The D2D outage probability for $D = 14$ (overlay) and $D = 1$ (C-D2D) is 1.51×10^{-7} and 1.98×10^{-7} respectively. Hence, overlay and C-D2D frameworks achieve a significantly lower outage probability for the D2D user as compared to underlay framework.

When $\zeta_{c_iB} = 394$, overlay framework can never satisfy the cellular outage constraint i.e. $P_{cu,out} \leq 10^{-4}$, even if they use all N subcarriers for cellular. A similar observation can be made for underlay framework. However, with C-D2D, only $D \geq 14$ subcarriers are required to achieve the cellular outage constraint. Thus, remaining $N - D$ subcarriers in the C-D2D framework can be used for D2D communication. Similar pattern appears when $\zeta_{c_iB} = 701$. Hence, from above it is evident that, for high cellular outage constraint and large CU$_i-$BS distance, C-D2D framework completely outperforms the other two frameworks.

Table IV compares the D2D outage probability corresponding to the cellular outage probability constraint for underlay, overlay, and C-D2D frameworks. From Table IV, we can observe that,

- For underlay framework, we can achieve the D2D outage probability $= 0.37 \times 10^{-3}$ while satisfying the low cellular outage probability constraint (i.e. $P_{cu,out} \geq 10^{-3}$). However, we can not satisfy the high cellular outage probability constraint (i.e. $P_{cu,out} \leq 10^{-4}$). Hence, D2D outage probability will be 1 for such cases.
- For overlay and C-D2D frameworks, $N - D$ denotes the number of subcarriers available for D2D communication while satisfying the prescribed cellular outage

TABLE 4. **D2D outage probability corresponding to cellular outage probability constraint.**

Cellular outage probability constraint	10^{-2}	10^{-3}	10^{-4}	10^{-5}
Underlay	Satisfied	Satisfied	Not satisfied	Not satisfied
Overlay $(N-D)$	24	18	Not satisfied	Not satisfied
C-D2D $(N-D)$	31	30	18	6
D2D Outage (underlay)	0.37×10^{-3}	0.37×10^{-3}	1	1
D2D outage (overlay)	0.94×10^{-7}	0.15×10^{-6}	1	1
D2D outage (C-D2D)	0.19×10^{-6}	0.21×10^{-6}	0.67×10^{-6}	10^{-4}

probability constraint. For instance, for cellular outage constraint= 10^{-3}, the number of subcarriers available for D2D communication with overlay framework is 18, whereas with C-D2D framework is 30.

- For low cellular outage constraint (i.e. $P_{cu,out} \geq 10^{-3}$), D2D overlay outage probability is slightly less than the C-D2D outage probability. In this case, the overlay framework performs better than the other two frameworks.
- For high cellular outage constraint (i.e. $P_{cu,out} \leq 10^{-4}$), the C-D2D framework completely outperforms the underlay and overlay frameworks. For both frameworks, we can not achieve $P_{cu,out} \leq 10^{-4}$, even if cellular user transmits all N subcarriers to BS.

V. CONCLUSION

This paper investigated the OFDMA based underlay, overlay, and C-D2D communication frameworks in cellular networks. By utilizing one of the above frameworks, a D2D user can share the spectrum of the cellular user. The three frameworks were evaluated by deriving the closed form expressions of the outage probability for the cellular and D2D users. The impact of distance between the BS and cellular users, as well as between the cellular and D2D users was also analyzed on the basis of outage performance of the cellular and D2D users. Results interpret that for high cellular outage constraint, the C-D2D framework outperforms the underlay and overlay D2D frameworks.

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