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Enhanced Spectrum Access for QoS Provisioning in Multi-Class Cognitive D2D Communication System

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ABSTRACT Integration of Device-to-Device (D2D) communication into the cellular network can greatly enhance the spectrum utilization as well as creating additional communication opportunities. D2D can be combined with cognitive radio to further enhance spectrum utilization and cellular network performance. Unlike the traditional D2D communication approach which employs only cellular spectrum, cognitive D2D can enable sensing and utilizing non-cellular spectrum opportunistically as well, thus allowing to offload cellular base station traffic to non-cellular spectrum such as WiFi, Bluetooth, or TV white-spaces. Cognitive D2D users (cDUs) must vacate channel for primary users and hand-off to another secondary channel which renders it quite challenging to meet Quality of Service (QoS) requirements of multi-class cDUs in the presence of higher primary network load. In this work, an enhanced hybrid spectrum access scheme has been developed based on non-switching spectrum hand-off for multi-class DUs, utilizing both interweave and hybrid interweave underlay spectrum access strategies. Further, lower priority cDUs with non-real-time traffic remains in the system and wait for channels to become available, rather than being dropped from the system due to lack of secondary channels. A Continuous-Time Markov Chain (CTMC) has been developed to analyze the performance of the proposed scheme. For comparison, several cases, ranging from the simple cellular network to complex cellular-cognitive-D2D with hybrid-spectrum-access, have been analyzed. The main focus of the analysis is to compare the efficacy of enhanced hybrid spectrum access scheme with individual interweave and hybrid interweave underlay spectrum access strategies in terms of QoS provisioning for multi-class cDUs. The results depict improvement in throughput, spectrum utilization, and extended data delivery time for the proposed scheme and validate the suitability of the proposed scheme to meet QoS requirements for both delay-sensitive and delay-tolerant users of the multi-class cognitive D2D communication system.

INDEX TERMS Cognitive D2D communication, CTMC, spectrum handoff, hybrid spectrum access, delay-tolerant users, delay-sensitive users, extended data delivery time, throughput, QoS.

I. INTRODUCTION

D2D communication is an integral part of 5G cellular networks [1], [2]. In D2D Communication, devices with closed proximity may opt to establish direct communication link either with or without network assistance. D2D offers many advantages like high data rate, high throughput, and reduced power consumption. D2D Users (DUs) need to perform functions such as device discovery, mode selection, resource allocation, power and interference management. cDUs can

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utilize wireless spectrum more efficiently and independently by sensing cellular network and utilizing unused network resources opportunistically [3]. Cognitive D2D users (cDU) access the primary band opportunistically and ensures no or minimal interference to cellular users (CUs) by switching to a vacant portion of the cellular spectrum and this process is called spectrum handoff [4]. Channel switching in spectrum handoff follows either always staying or always changing approach. In the always-changing approach on the arrival of CU, cDU always switches to the vacant channel. In always staying cDU stay on same spectrum resource which is simple and energy-efficient solution [5]. The only drawback is that it supports low power transmission, fortunately, D2D support very low power communication due to its short distance and thus makes it ideal for D2D communication [6].

Cognitive D2D communication encounters extended delay due to fluctuation in the availability of vacant channels which may lead to higher service delay during higher cellular traffic. To meet QoS requirements DUs are classified into delay-tolerant and delay-sensitive users, where delay-sensitive users are given priority in accessing the vacant portion of spectrum [7]. Spectrum access strategy plays a very important role to mitigate the interference caused by DUs to CUs.

Interweave, in-band and out-band are three basic types of spectrum access strategies [8]. In interweave D2D, DUs and CUs share the same spectrum resource but DU will only use spectrum in the absence of CU. In in-band D2D, DUs can be assigned a portion of spectrum resource called overlay or can use spectrum with low power transmission called underlay. In out-band D2D, DUs will use ISM band for D2D communication either following autonomous, network-assisted or network controlled approach [1], [2], [9]–[13].

In this paper, we have explored cognitive D2D communication for several spectrum access techniques and modeled them using CTMC following non-switching spectrum hand-off. We have developed an enhanced hybrid spectrum access technique building upon interweave, and hybrid interweave underlay spectrum access techniques. our model uses advanced hybrid spectrum access to treat different classes of DU traffic differently. Real-time traffic is given high priority to meet its QoS requirements and non-real-time traffic is given low priority due to its delay-tolerant traffic nature but with reduced drop rate to enhance user experience.

A. CONTRIBUTIONS

The key contributions of this paper are highlighted as follows.

- A unique cellular network with cognitive D2D communication framework for multi-class secondary users with QoS constraints has been considered in this work.
- An enhanced hybrid spectrum access scheme has been developed as part of this work; the scheme involves non-switching spectrum hand-off for multi-class cDUs utilizing both interweave and hybrid interweave underlay spectrum access strategies.
- Lower priority cDUs with non-real-time traffic remains in the system and wait for channels to become available, rather than being dropped from the system due to lack of channels.
- The performance of the proposed scheme has been analyzed using CTMC. Several baseline and advanced access schemes have also been analyzed for comparison of the enhanced hybrid spectrum access scheme in terms of its efficacy in meeting QoS requirements.
- The results for several performance metrics such as throughput, delay, and spectrum utilization gathered through the detailed analysis validate the suitability of the proposed scheme for QoS provisioning to multi-class cDUs.

II. RELATED WORK

Chu *et al.* studied a hybrid-interweave underlay spectrum access system integrated with amplify and forward relaying [14]. A CTMC based model is developed and steady-state probabilities are derived to analyze this cognitive cooperative radio network in terms of outage probability and symbol error rate. Comparison between underlay, hybrid, and hybrid-interweave underlay schemes is provided which shows the hybrid-interweave underlay outperforms the rest.

Wang *et al.* presented a D2D data downloading technique to offload cellular network based on expected available duration metric [15]. The connectivity between D2D pairs is modeled using CTMC and then expected available duration metric rate users based on their social influence, pairwise connectivity, digital object diffusion, and delay tolerance of a user for data download. Based on these ratings the DU will download an object with the smallest values. The model presented in this work is validated with extensive trace-driven simulations and authors claim that their proposed schemes efficiently utilize spectrum and download more data from neighbors comparing to schemes proposed in the existing literature.

Hong *et al.* proposed a blockchain method to fairly distribute resources among DUs [16]. The connectivity and dis-connectivity between two users are modeled using CTMC. Users are divided into several categories based on the computational tasks they perform and it is proposed in this work that users who perform computational tasks will be rewarded with credit points or crypto-currency. The credit points can give users prioritized resource access. Simulation results show the trade-off between task execution time and level of fairness.

Ferdouse *et al.* proposed a throughput efficient sub-carrier allocation method and geometric water filling based optimal power allocation method for multi-class D2D underlying cellular network [7]. The main objective behind the application of both schemes is to increase the data rate of all classes of users in the system with healthy fairness while keeping a check on interference. Simulation results are presented to evaluate the performance of both schemes in terms of throughput, fairness, and data rate of the user.

TABLE 1. Related work comparison to proposed work in terms of in-band cognitive D2D using Markov modeling for better spectrum utilization.

	Cognitive-D2D	Markov Modeling	In - band D2D	Multi-Class Traffic	Spectrum Utilization	Throughput	Delay
Chu *et al.* [14]	✗	✓	✓	✗	✓	✗	✓
Wang *et al.* [15]	✗	✓	✓	✗	✓	✗	✓
Hong *et al.* [16]	✗	✓	✗	✓	✗	✗	✓
Ferdouse *et al.* [7]	✗	✗	✓	✓	✗	✓	✗
Gbenga *et al.* [17]	✗	✓	✓	✗	✓	✓	✓
Kafıloğlu *et al.* [18]	✓	✓	✓	✗	✗	✓	✗
Sultana *et al.* [19]	✓	✗	✓	✗	✓	✗	✗
Algedir *et al.* [20]	✗	✓	✓	✗	✗	✓	✗
Dinh *et al.* [21], [22]	✓	✗	✓	✗	✗	✓	✗
Zhao *et al.* [23]	✓	✗	✓	✗	✗	✓	✗
H.T.Nguyen *et al.* [24]	✓	✗	✓	✗	✗	✓	✗
T.V.Nguyen *et al.* [25]	✓	✗	✓	✗	✗	✗	✗
Shakeel *et al.* [5]	✗	✓	✗	✓	✓	✓	✓
Proposed	✓	✓	✓	✓	✓	✓	✓

Gbenga *et al.* proposed a CTMC based queueing model for D2D enabled cellular network that enhances the throughput of system [17]. Dynamic spectrum access is utilized to optimize the spectrum resource. The authors used CTMC to consider both non-queueing called 6-NQ CTMC and queueing cases called 13-Q CTMC. Numerical simulation is performed and the results show that 13-Q CTMC is a spectrum efficient sharing scheme and provide better network performance by accommodating more DUs, providing better throughput, and causing less delay.

Kafilouglu *et al.* proposed a CTMC based heterogeneous satellite-terrestrial network incorporating cognitive radio and D2D communication [18]. Devices in the satellite spectrum behave as primary users and in the terrestrial network perform opportunistic spectrum access. Popularity aware caching algorithm is proposed in this work and after the integration of popularity aware caching algorithm into this model the simulation results shows that it outperforms random caching algorithm, Least Recently Used (LRU) and First In First Out (FIFO) in-terms of system good-put and high user request rate and energy efficiency.

A CTMC based analytical model for D2D enabled LTE scheduler is presented by Algedir *et al.* to estimate the throughput of the system accurately and quickly [20]. Two-dimensional CTMC is used for throughput estimation and closed-form expressions are derived for the expected number of DUs in dedicated mode and reuse mode. The ISM band is used by DUs in dedicated mode and the cellular band is used in reuse mode. The scheduling algorithms used for estimating throughput are the Max-signal-to-interference-plus-noise ratio and round-robin. Simulation results show that the analytical model is time-efficient, accurate, and closely aligned with simulations.

Sultana *et al.* presented geometric water filling-based algorithm to optimize the energy efficiency of a cognitive D2D communication system for both underlay and overlay spectrum access strategies [19]. Authors model the power allocation problem of a cognitive D2D communication system by maximizing the energy efficiency of DUs subject to minimum rate requirements of both cellular and DUs. This creates a complicated and computationally intractable non-linear fractional optimization problem which is solved using a geometric water filling-based algorithm. The simulation results show that the proposed algorithm performs better in terms of energy efficiency with respect to the already proposed Dinkelbach method and the Dual-based algorithm.

Dinh *et al.* proposed a multi-user cognitive inspired non-orthogonal multiple access (NOMA) scheme which they called CR-NOMA to investigate the performance of secondary network [21], [22]. D2D communication underlying cellular network is considered secondary network in this work to enable close distance communication among NOMA users in down-link and performance evaluation is performed under the assumption of interference received from the primary network. In comparison to existing NOMA schemes that used fixed power allocation, simulation results validate that CR-NOMA performs better in terms of outage and throughput.

Zhao *et al.* presented a system containing single-antenna primary and multi-antenna D2D system which is sharing spectrum opportunistically [23]. A joint time division and power splitting-based three-phase information and energy cooperation algorithm are proposed in this work for a cognitive D2D communication system. In the first phase, DU will simultaneously receive information and energy from the primary user using the power splitting technique. In the second phase, DU will forward the primary user signal and also harvest energy as half-duplex relays using the beam-forming technique. In the third and last phase, DUs can communicate directly on the licensed spectrum using the remaining harvested energy. The focus of this work is to design time-division ratios, power splitting ratios, and beam-forming vectors in order to maximize the data rate of the D2D system to meet QoS requirements of the primary system, and increase D2D systems energy harvesting capability and reduce energy consumption which simulations suggests that authors achieved.

T.H. Nguyen *et al.* considered a cognitive-communication network consisting of an air-born base station deployed by an unmanned aerial vehicle which can serve multiple ground terminals and underlying ground terminals are several D2D devices [24]. To make sure ground terminals achieve maximum throughput and D2D devices achieve QoS, a joint design of D2D assignment, bandwidth, and power allocation is proposed in this work. to show the advantage of the cognitive network a non-cognitive network is also studied in detail. To solve this difficult and complex optimization problem a new solver is developed with low computational complexity. Numerical simulations are performed and their results show that the solution provided in this research provides high throughput for ground terminals while maintaining the required QoS of underlying D2D devices.

T.V. Nguyen *et al.* proposed a scheduling algorithm to improve outage performance of wireless powered multi-hop cognitive D2D communication in wireless sensor network [25]. The exact closed-form expressions are derived from the optimization problem for benchmark, Dual-hop scheduling (DHS), and Best-path scheduling (BPS) schemes. The outage performance is analyzed for interference tolerant and interference-limited cases. Simulation results show that the proposed schemes are very promising to enhance system performance and extend network coverage.

A CTMC based analytical model for cognitive radio networks is developed by Shakeel *et al.* which contains multi-class secondary users and non-switching spectrum hand-off scheme following hybrid interweave underlay spectrum access [5]. The study shows the impact of a hybrid interweave underlay spectrum access scheme on multi-class secondary users to meet QoS requirements of delay-sensitive traffic. Simulation results show improvements in spectrum utilization, throughput, and extended data delivery time.

To improve spectrum utilization and D2D user experience, we have developed an enhanced hybrid spectrum access scheme which is elaborated in the rest of the work and its organization is as follows: Section III presents a system model for enhanced hybrid spectrum access for multi-class cDUs. Section IV presents an enhanced hybrid spectrum access mechanism. Section V presents CTMC modeling and steady-state analysis to examine the relation between CUs and multi-class cDUs. Analysis of different scenarios is performed with steady-state probabilities. Section VI discuss results and conclusion is given in section VII.

III. SYSTEM MODEL

We considered an in-band cognitive D2D communication system underlying the cellular network where CUs and DUs share the same cellular resource for communication. To ensure QoS of CUs, DUs use cellular resources only when CUs are not using them thanks to the cognitive capabilities of DUs. DUs are further categorized into two categories, DU with high priority due to real-time traffic (DU_{hp}) and DU with low priority (DU_{lp}) based on non-real-time traffic requirements. The traffic arrival of CU is following exponentially distributed inter-arrival time which is considered an independent Poisson process [8]. The Preemptive Resume Priority (PRP) based service queuing discipline is considered between CU and DU, Which means CU can preempt DU of any priority, and similarly, DU_{hp} can preempt DU_{lp}. We are using a non-switching spectrum hand-off policy to conserve the battery of DUs, so DUs will have to keep the channel and wait for CU to vacate the channel to resume its communication.

With limited power to make the most of underlay and interweave spectrum access techniques we assume a cognitive D2D communication following enhanced hybrid spectrum access scheme which is based on spectrum access of hybrid interweave-underlay [26]. A user Γ where $\Gamma \in \left\{CU, DU_{hp}, DU_{lp}\right\}$ can achieve a maximum data rate (R) using interweave spectrum access with full channel utilization is given by [27]:

$$R = W\log_2(1 + \frac{P_\Gamma G_\Gamma}{N}), \tag{1}$$

where, communication bandwidth is W, the transmission power of the user Γ is P_Γ, channel gain is G_Γ, and power of Additive White Gaussian Noise (AWGN) is N.

DU has to keep its interference to CU below a specific threshold by limiting its transmission power in underlay access. it limits the data rate R_u^Γ of DU which is given by:

$$R_u^\Gamma = W\log_2(1 + \frac{P_\Gamma G_\Gamma}{N + P_c G_{c\Gamma}}), \tag{2}$$

where, Channel gain from CU transmitter to Γ receiver is $G_{c\Gamma}$, transmission power of the CU is P_c, the transmission power of user Γ is P_Γ which is operating in the underlay.

The behavior of multi-class In-band cognitive D2D communication is shown in Figure. 1, where DU_{hp} or DU_{lp}

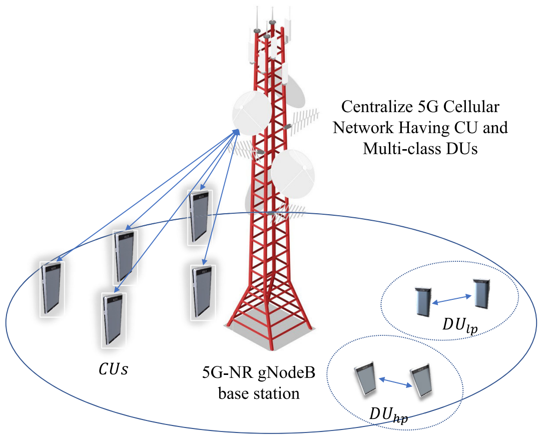

FIGURE 1. **System model of multi-class hybrid interweave in-band D2D communication.**

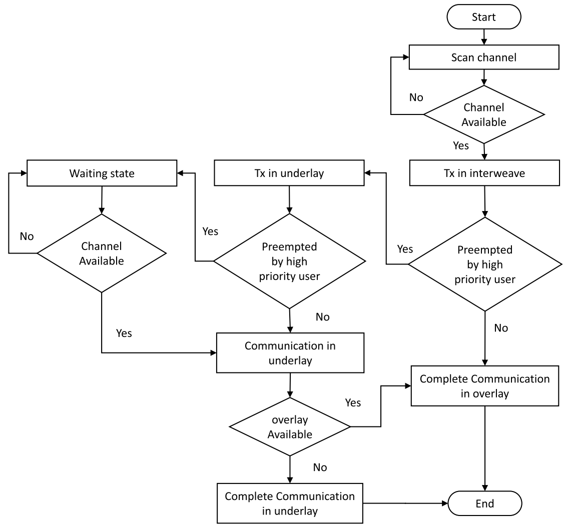

FIGURE 2. **Spectrum access mechanism.**

performs hops between underlay and interweave spectrum access. when DU enters the network it will sense spectrum to detect the presence of CU. If it finds an idle channel it starts transmission using interweave spectrum access for the rest of the time frame. If CU is present on the channel it will use underlay spectrum access and transmit.

The received signal $x(t)$ represents the channel state following binary hypothesis H_0 and H_1, where busy state is represented by H_1 and idle state is represented by H_0 [28], [29].

$$x(t) = \begin{cases} n(t) & H_0 \\ c(t) + n(t) & H_1, \end{cases} \tag{3}$$

Here, the received signal is represented by $x(t)$, AWGN signal is represented by $n(t)$ and transmitted signal of the CU is represented by $c(t)$, missed detection and false alarm are ignored by assuming perfect sensing results.

IV. PROPOSED SPECTRUM ACCESS MECHANISM

In this section, an enhanced hybrid spectrum access scheme is presented. This enhanced hybrid spectrum access mechanism involves non-switching spectrum hand-off for multi-class cDUs utilizing both interweave and hybrid interweave underlay spectrum access strategies. The lower priority cDUs with non-real-time traffic remains in the system and wait for channels to become available, rather than being dropped from the system due to lack of secondary channels. This leads to significantly improved QoS support to multi-class cDUs.

Figure 2 shows the working of the proposed channel access mechanism. It starts with the cDU scanning spectrum for the availability of free channels and upon obtaining an unused channel it starts transmission in interweave mode. In case of an arrival of high priority user, the low-priority user will opt for underlay mode and reduce its communication power. Even in an underlay mode if there is an arrival of a high priority user on the same channel the low priority user will not terminate its communication session and went into a waiting state, upon the departure of any high priority user the waiting user will regain channel and resume its communication. The performance of the proposed enhanced hybrid spectrum access scheme is analyzed using CTMC and compared with several baseline and advanced access schemes in the subsequent sections.

V. STEADY STATE ANALYSIS USING CTMC MODELING

This section presents the evolution of the analytical model for multi-class in-band cognitive D2D communication which is developed based on the study of CUs and DUs in different scenarios using CTMC modeling as shown in Figure. 3. we start with the traditional cellular network without any D2D communication. Then we consider a cognitive D2D communication-enabled cellular system with a single type of DU traffic and two different types of spectrum access strategies separately. In the third step, we consider a cognitive D2D communication system with multi-class DUs following interweave spectrum access and analyzed the effect of CU traffic intensity on multi-class DUs in terms of throughput and transmission delay. In the fourth phase, we consider

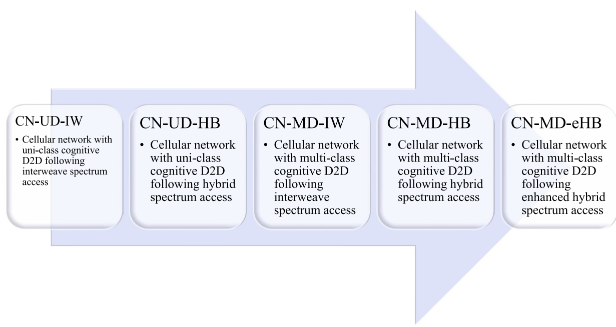

FIGURE 3. **Cases developed for CTMC model.**

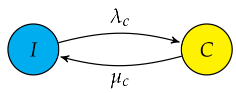

FIGURE 4. State transition diagram of CN-ONLY.

a multi-class cognitive D2D communication system with hybrid interweave underlay spectrum access and analyzed the effect of CU traffic intensity on multi-class DUs in terms of throughput and transmission delay. In the fifth and final phase, we introduced enhanced Hybrid Interweave underlay spectrum access to fulfill the QoS requirements of DUs. Performance evaluation of all these cases is performed using steady-state analysis.

A. CELLULAR NETWORK WITHOUT D2D (CN-ONLY)

A traditional cellular network is considered without any D2D communication and whose state transition diagram is shown in Figure. 4. The only CU is utilizing the channel and CTMC for this case consists of two states, state C and state I, where state I shows idle state and state C shows CU is present. The arrival and departure of CU is a Poisson process with exponentially distributed arrival and departure rates λ_c and μ_c. Initially, the system is in state I, and on the arrival of CU, the system will make a transition with rate λ_c and enters a state C. After completion of its communication session, CU will depart the system with rate μ_c, and the system will make a transition back to the I state. The CTMC is represented as "CN-ONLY" and denoted by $S = \{I, C\}$.

To show transitions among various states of vector S, the state transition matrix Q of CN-ONLY is given in (4).

$$\mathbf{Q} = \begin{array}{c} \\ Idle \\ C \end{array} \begin{array}{c} \begin{array}{cc} Idle & C \end{array} \\ \begin{bmatrix} -\lambda_c & \lambda_c \\ \mu_c & -\mu_c \end{bmatrix} \end{array} \tag{4}$$

For CN-ONLY, The rate of transition out of state $\beta \in S$ becomes equal to rate of transition into state $\beta \in S$ which is the flow balance equation [30] and is given by:

$$\pi_i \lambda_c = \pi_c \mu_c, \tag{5}$$

The normalization condition is given as:

$$\sum_{\beta \in S} \pi_\beta = 1, \tag{6}$$

by solving (5) and (6) we obtain steady state probabilities π_i and π_c, are given by:

$$\pi_i = \frac{\mu_c}{\lambda_c + \mu_c}, \tag{7}$$

$$\pi_c = \frac{\lambda_c}{\lambda_c + \mu_c}. \tag{8}$$

The steady state probabilities π_β where $\beta \in S$ for different values of ρ (load of cellular users), is shown in Figure. 5. it is evident from the graph that even at peak value of load there is a room for D2D devices to opportunistically utilize cellular network.

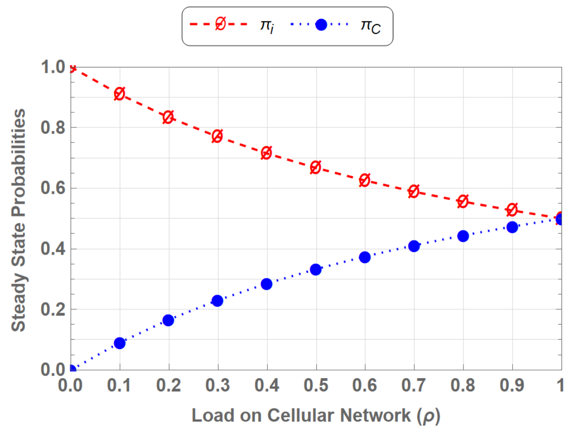

FIGURE 5. Stationary probabilities for CN-ONLY.

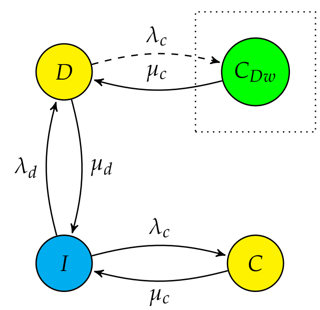

FIGURE 6. State transition diagram of CTMC CN-UD-IW.

B. CELLULAR NETWORK WITH UNI-CLASS cDUs FOLLOWING INTERWEAVE SPECTRUM ACCESS (CN-UD-IW)

The CN-ONLY is extended with the introduction of cognitive D2D communication in 5G cellular networks having uni-class DU traffic. DU accesses the cellular spectrum opportunistically without creating interference for CU traffic. The traffic arrival follows an independent Poisson process for both CU and DU with rate λ_c and λ_d respectively and exponentially distributed service time with departure rate μ_c and μ_d respectively. Figure. 6 shows state transition diagram, where state I shows idle state, the system will move to state C after the arrival of CU with rate λ_c and will move to state D when DU arrive with rate λ_d in the spectrum if there is an arrival of CU when DU is using the spectrum system will move to C_{Dw} which is shown in Figure. 6 with a dashed line and DU will get interrupted by CU, DU will remain in waiting state until CU release the spectrum with rate μ_c and the system will be back in D state and DU can resume its communication session on the spectrum and depart with rate μ_d after its completion. $S = \{I, C, D, C_{Dw}\}$ is the state space vector and as given in (9) where Q is the transition rate matrix. Here we represent this CTMC as CN-UD-IW.

$$\mathbf{Q}= \begin{array}{c} \\ I \\ C \\ D \\ C_{Dw} \end{array} \begin{array}{c} \begin{array}{cccc} I & C & D & C_{Dw} \end{array} \\ \begin{bmatrix} -(\lambda_c+\lambda_d) & \lambda_c & \lambda_d & 0 \\ \mu_c & -\mu_c & 0 & 0 \\ \mu_d & 0 & -(\lambda_c+\mu_d) & \lambda_c \\ 0 & 0 & \mu_c & -\mu_c \end{bmatrix} \end{array} \tag{9}$$

CN-UD-IW flow balance equations are represented as:

$$\begin{aligned} \pi_i(\lambda_c+\lambda_d) &= \pi_c\mu_c+\pi_d\mu_d, \\ \pi_c\mu_c &= \pi_i\lambda_c, \\ \pi_d(\lambda_c+\mu_d) &= \pi_i\lambda_d+\pi_{Cdw}\mu_c, \\ \pi_{c_{dw}}\mu_c &= \pi_d\lambda_c, \end{aligned} \tag{10}$$

solving the normalization equation (6) with set of equations derived in (10), we get steady state probabilities of π_i, π_c, π_d and $\pi_{c_{dw}}$ as follows:

$$\begin{aligned} \pi_i &= \frac{\mu_c\mu_d}{(\lambda_c+\mu_c)(\lambda_d+\mu_d)}, \\ \pi_c &= \frac{\lambda_c\mu_d}{(\lambda_c+\mu_c)(\lambda_d+\mu_d)}, \\ \pi_d &= \frac{\lambda_d\mu_c}{(\lambda_c+\mu_c)(\lambda_d+\mu_d)}, \\ \pi_{c_{dw}} &= \frac{\lambda_c\lambda_d}{(\lambda_c+\mu_c)(\lambda_d+\mu_d)}. \end{aligned} \tag{11}$$

For varying ρ, the steady-state probabilities of CN-UD-IW are shown in Figure. 7. The presence of CU in the system is shown with steady-state probability π_C, As CU is using the channel in both C and C_{dw} states so we can infer that π_C is the sum of π_c and π_{cdw}. Similarly, the presence of DU in the system with steady-state probability π_D is only in D state which has π_d steady-state probability. It is worth noting that with comparison to CN-ONLY section V-A, values of π_C do not change, this means that introduction of cDUs does not affect CUs due to opportunistic spectrum access. On the other hand, spectrum utilization is improved as π_i decreases, and idle time of spectrum is utilized by DUs in absence of CUs.

It is also evident from Figure. 7 that by increasing ρ, π_{cdw} also increases and this reduces the number of opportunistic access possibilities for DUs which is evident from the trend of π_D, At Maximum load i.e. $\rho = 1$. π_{cdw} is also at the highest value due to high interruption caused by CU reappearance probability. This leaves π_D at minimum as there is a very limited number of opportunistic spectrum access possibilities.

C. CELLULAR NETWORK WITH UNI-CLASS cDUs FOLLOWING HYBRID INTERWEAVE UNDERLAY SPECTRUM ACCESS (CN-UD-HB)

CN-UD-IW is extended in this section, we have used hybrid interweave underlay spectrum access with uni-class cDUs. DU instead of going in a waiting state will reduce its power and keep using spectrum with a lower data rate. the departure rate from underlay will be lower and is represented as μ_{du}.

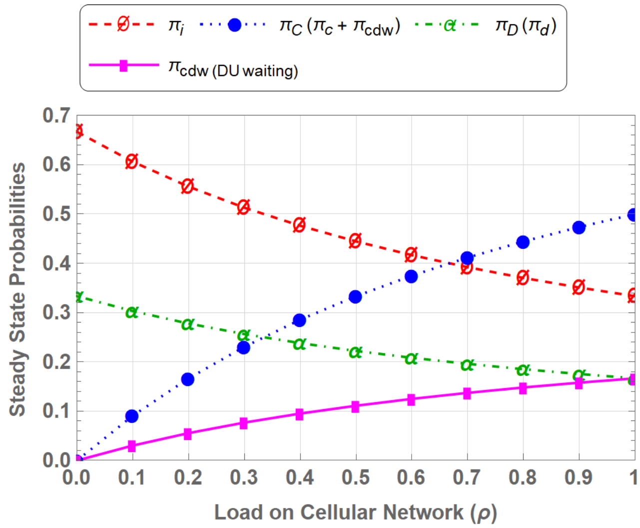

FIGURE 7. Stationary probabilities for CN-UD-IW.

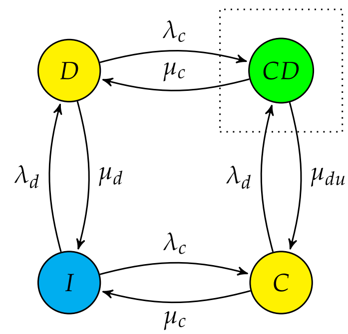

FIGURE 8. State transition diagram of CTMC CN-UD-HB.

$$\mathbf{Q}= \begin{array}{c} \\ I \\ C \\ D \\ CD \end{array} \begin{array}{c} \begin{array}{cccc} I & C & D & CD \end{array} \\ \begin{bmatrix} -(\lambda_c+\lambda_d) & \lambda_c & \lambda_d & 0 \\ \mu_c & -(\lambda_d+\mu_c) & 0 & \lambda_d \\ \mu_d & 0 & -(\lambda_c+\mu_d) & \lambda_c \\ 0 & \mu_{du} & \mu_c & -(\mu_c+\mu_{du}) \end{bmatrix} \end{array}$$

FIGURE 9. CN-MD-HB Q transition rate matrix.

Figure. 8 shows the state transition diagram of CTMC CN-UD-HB.

$S = \{I, C, D, CD\}$ is the state space vector and as given in Figure. 9 matrix Q is transition rate matrix. This CTMC is represented as CN-UD-HB.

CN-UD-HB flow balance equations are represented as:

$$\begin{aligned} \pi_i(\lambda_c+\lambda_d) &= \pi_c\mu_c+\pi_d\mu_d, \\ \pi_c(\lambda_d+\mu_c) &= \pi_i\lambda_c+\pi_{cd}\mu_{du}, \\ \pi_d(\lambda_c+\mu_d) &= \pi_i\lambda_d+\pi_{cd}\mu_c, \\ \pi_{cd}(\mu_c+\mu_{du}) &= \pi_c\lambda_d+\pi_d\lambda_c, \end{aligned} \tag{12}$$

solving the normalization equation (6) with set of equations derived in (12), we get steady state probabilities of

π_i, π_c, π_d and π_{cd} as follows:

$$\pi_i = \frac{\mu_c\left(\mu_d\left(\mu_c+\lambda_d+\mu_{\text{du}}\right)+\lambda_c\mu_{\text{du}}\right)}{\left(\lambda_c+\mu_c\right)\left(\lambda_c\left(\lambda_d+\mu_{\text{du}}\right)+\left(\lambda_d+\mu_d\right)\left(\mu_c+\lambda_d+\mu_{\text{du}}\right)\right)},$$
$$\pi_c = \frac{\lambda_c\left(\mu_{\text{du}}\left(\lambda_c+\lambda_d+\mu_d\right)+\mu_c\mu_d\right)}{\left(\lambda_c+\mu_c\right)\left(\lambda_c\left(\lambda_d+\mu_{\text{du}}\right)+\left(\lambda_d+\mu_d\right)\left(\mu_c+\lambda_d+\mu_{\text{du}}\right)\right)},$$
$$\pi_d = \frac{\mu_c\lambda_d\left(\lambda_c+\mu_c+\lambda_d+\mu_{\text{du}}\right)}{\left(\lambda_c+\mu_c\right)\left(\lambda_c\left(\lambda_d+\mu_{\text{du}}\right)+\left(\lambda_d+\mu_d\right)\left(\mu_c+\lambda_d+\mu_{\text{du}}\right)\right)},$$
$$\pi_{cd} = \frac{\lambda_c\lambda_d\left(\lambda_c+\mu_c+\lambda_d+\mu_d\right)}{\left(\lambda_c+\mu_c\right)\left(\lambda_c\left(\lambda_d+\mu_{\text{du}}\right)+\left(\lambda_d+\mu_d\right)\left(\mu_c+\lambda_d+\mu_{\text{du}}\right)\right)}. \quad (13)$$

For varying ρ, the steady-state probabilities of CN-UD-HB are shown in Figure. 10. The presence of CU in the system is shown with steady-state probability π_C, As $CU = C + CD$ so we can infer that $\pi_C = \pi_c + \pi_{cd}$. Similarly, the presence of DU in the system with steady-state Probability π_D is only in D state which has π_d steady-state probability. Comparison to CN-ONLY and CN-UD-IW, the values of π_C do not change which means that cDUs do not affect CUs in hybrid spectrum access and spectrum utilization is improved as π_i decreases and idle time of spectrum is utilized by DUs. As the value of ρ increases the opportunistic spectrum access possibilities for D2D decreases as evident from π_{cd}.

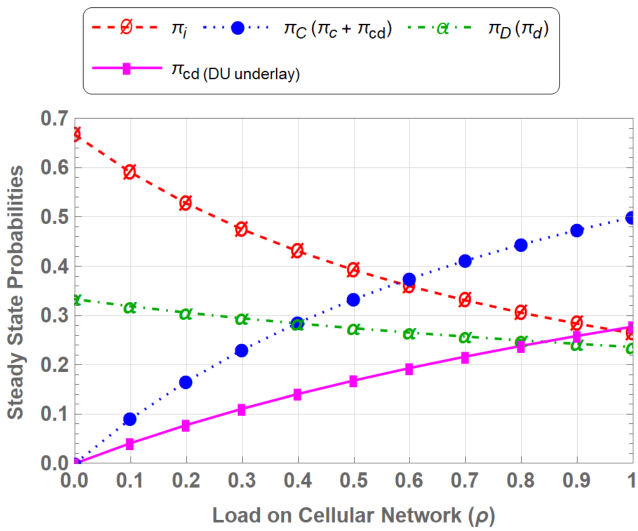

FIGURE 10. Stationary probabilities for CN-UD-HB.

D. CELLULAR NETWORK WITH cDUs HAVING MULTI-CLASS DUs IN INTERWEAVE ONLY SPECTRUM ACCESS (CN-MD-IW)

5G Cellular network having multi-class cognitive D2D communication is introduced in this section. Here cDUs will follow interweave only spectrum access and the state transition diagram is given in Figure. 11. DUs having the real-time or delay sensitive traffic is DU_{hp} and DUs having the non-real-time or delay-tolerant traffic are DU_{lp}. Seven state CTMC model is used to represent the spectrum access procedure here. The idle state of the system is represented with state I and state C shows CU is using the system. state D_H shows DU_{hp} and state D_L shows DU_{lp} is occupying the system resources. State C_{D_Hw} represents that CU is using the spectrum and D_H is in waiting state similarly C_{D_Lw} shows CU in using the spectrum and D_L is in waiting state. D_H and D_L will get the spectrum when CU will depart from the system, here we assumed that only one DU can be in waiting state at any one time instance. State D_HD_Lw indicates that D_H is using the spectrum and D_L is in waiting state.

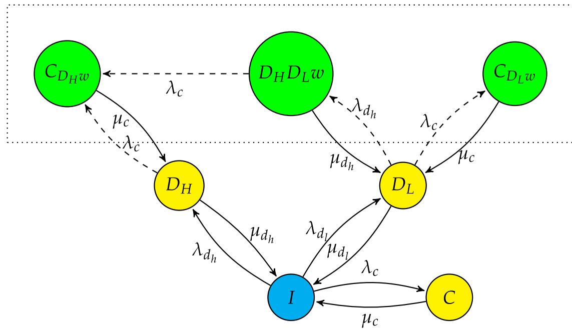

FIGURE 11. State transition diagram of CN-MD-IW.

Let's assume that at the start the system is at state I. There is an arrival of CU with Poisson rate λ_c and system transits into state C, after the departure of CU with exponentially distributed time with rate μ_c the system hops back to state I. DU will only be able to access the system in the absence of CU i.e. interweave spectrum access. System will move to state D_H on arrival of DU_{hp} with arrival rate λ_{d_h} and system will move back to I state when DU_{hp} completes its transmission and departs with rate μ_{d_h}. CU can preempt DU_{hp}, in this case, the system will move to C_{D_Hw} state, DU_{hp} will keep waiting until CU departs. Similarly system will move from I to D_L state on arrival of DU_{lp} with Poisson rate λ_{d_l} and after its departure at rate μ_{d_l} the system will move back to I state. DU_{lp} can be preempted by both CU and DU_{hp} and the system will move to C_{D_Lw} or D_HD_Lw states respectively with arrival rates λ_c and λ_{d_h}. DU_{lp} will keep waiting until the departure of CU with rate μ_c or departure of DU_{hp} with rate μ_{d_h}.

It is worth noting here, that together with μ_c and μ_{d_l} would be a heavy-tailed and slow decaying process but as we have considered separate states for both D_L and C_{D_Lw}, state transition would be Poisson distributed for C_{D_Lw} to D_L and from D_L to I. CU can preempt both DU_{hp} and DU_{lp} as it is licensed user, DU_{hp} can only preempt DU_{lp} to meet its QoS requirements. The interrupted DU has to vacate the spectrum and wait until the spectrum is idle for reuse again. DU_{lp} can only access the system in the absence of DU_{hp} and CU.

Figure. 11 contains four spectrum hand-off events, dashed lines are used to represent them.

- State D_H changes to state $C_{D_H w}$, CU preempts DU_{hp} forces it into waiting state.
- State D_L changes to state $C_{D_L w}$, CU preempts DU_{lp} forces it into waiting state.
- State D_L changes to state $D_H D_L w$, DU_{hp} preempts DU_{lp} forces it into waiting state.
- State $D_H D_L w$ changes to state $C_{D_H w}$, CU preempts DU_{hp}. DU_{hp} having higher priority over DU_{lp} moves to waiting state and DU_{lp} will be dropped from system.

The state space vector of this system is $S = \{I, C, D_H, D_L, C_{D_H w}, C_{D_L w}, D_H D_L w\}$.We denote this CTMC as "CN-MD-IW" and transition rate matrix Q is given as in Figure. 12.

$$\mathbf{Q} = \begin{array}{c} \\ I \\ C \\ D_H \\ D_L \\ C_{D_H w} \\ C_{D_L w} \\ D_H D_L w \end{array} \begin{array}{c} \begin{array}{ccccccc} I & C & D_H & D_L & C_{D_H w} & C_{D_L w} & D_H D_L w \end{array} \\ \begin{bmatrix} -(\lambda_c + \lambda_{d_h} + \lambda_{d_l}) & \lambda_c & \lambda_{d_h} & \lambda_{d_l} & 0 & 0 & 0 \\ \mu_c & -\mu_c & 0 & 0 & 0 & 0 & 0 \\ \mu_{d_h} & 0 & -(\mu_{d_h} + \lambda_c) & 0 & \lambda_c & 0 & 0 \\ \mu_{d_l} & 0 & 0 & -(\lambda_c + \lambda_{d_h} + \mu_{d_l}) & 0 & \lambda_c & \lambda_{d_h} \\ 0 & 0 & \mu_c & 0 & -\mu_c & 0 & 0 \\ 0 & 0 & 0 & \mu_c & 0 & -\mu_c & 0 \\ 0 & 0 & 0 & \mu_{d_h} & \lambda_c & 0 & -(\lambda_c + \mu_{d_h}) \end{bmatrix} \end{array}$$

FIGURE 12. **CN-MD-IW Q-Transition Rate Matrix.**

CN-MD-IW flow balance equations are given by:

$$\begin{aligned} \pi_i(\lambda_c + \lambda_{d_l} + \lambda_{d_h}) &= \pi_c \mu_c + \pi_{d_h} \mu_{d_h} + \pi_{d_l} \mu_{d_l}, \\ \pi_c \mu_c &= \pi_i \lambda_c, \\ \pi_{d_h}(\lambda_c + \mu_{d_h}) &= \pi_i \lambda_{d_h} + \pi_{cd_h w} \mu_c, \\ \pi_{d_l}(\lambda_c + \mu_{d_l} + \lambda_{d_h}) &= \pi_i \lambda_{d_l} + \pi_{cd_l w} \mu_c + \pi_{d_h d_l w} \mu_{d_h}, \\ \pi_{cd_h w} \mu_c &= \pi_{d_h} \lambda_c + \pi_{d_h d_l w} \lambda_c, \\ \pi_{cd_l w} \mu_c &= \pi_{d_l} \lambda_c, \\ \pi_{d_h d_l w}(\lambda_c + \mu_{d_h}) &= \pi_{d_l} \lambda_{d_h}, \end{aligned} \tag{14}$$

solving the normalization equation (6) with set of equations derived in (14), we get steady state probabilities of $\pi_i, \pi_c, \pi_{d_h}, \pi_{d_l}, \pi_{cd_l w}$ and $\pi_{d_h d_l w}$ as follows:

$$\begin{aligned} &\pi_i \\ &= \frac{\mu_{d_h}(\lambda_{d_h}\lambda_c + (\lambda_c + \mu_{d_h})\mu_{d_l})\mu_c}{(\lambda_{d_h} + \mu_{d_h})(\lambda_{d_h}\lambda_c + (\lambda_c + \mu_{d_h})(\lambda_{d_l} + \mu_{d_l}))(\lambda_c + \mu_c)}, \\ &\pi_c \\ &= \frac{\lambda_c \mu_{d_h}(\lambda_{d_h}\lambda_c + (\lambda_c + \mu_{d_h})\mu_{d_l})}{(\lambda_{d_h} + \mu_{d_h})(\lambda_{d_h}\lambda_c + (\lambda_c + \mu_{d_h})(\lambda_{d_l} + \mu_{d_l}))(\lambda_c + \mu_c)}, \\ &\pi_{d_h} \\ &= \frac{\lambda_{d_h}((\lambda_{d_h} + \lambda_{d_l})\lambda_c + (\lambda_c + \mu_{d_h})\mu_{d_l})\mu_c}{(\lambda_{d_h} + \mu_{d_h})(\lambda_{d_h}\lambda_c + (\lambda_c + \mu_{d_h})(\lambda_{d_l} + \mu_{d_l}))(\lambda_c + \mu_c)}, \\ &\pi_{d_l} \\ &= \frac{\lambda_{d_l}\mu_{d_h}(\lambda_c + \mu_{d_h})\mu_c}{(\lambda_{d_h} + \mu_{d_h})(\lambda_{d_h}\lambda_c + (\lambda_c + \mu_{d_h})(\lambda_{d_l} + \mu_{d_l}))(\lambda_c + \mu_c)}, \\ &\pi_{cd_h w} \\ &= \frac{\lambda_{d_h}\lambda_c}{(\lambda_{d_h} + \mu_{d_h})(\lambda_c + \mu_c)}, \\ &\pi_{cd_l w} \\ &= \frac{\lambda_{d_l}\lambda_c \mu_h(\lambda_c + \mu_{d_h})}{(\lambda_{d_h} + \mu_{d_h})(\lambda_{d_h}\lambda_c + (\lambda_c + \mu_{d_h})(\lambda_{d_l} + \mu_{d_l}))(\lambda_c + \mu_c)}, \\ &\pi_{d_h d_l w} \\ &= \frac{\lambda_{d_h}\lambda_{d_l}\mu_f \mu_c}{(\lambda_{d_h} + \mu_{d_h})(\lambda_{d_h}\lambda_c + (\lambda_c + \mu_{d_h})(\lambda_{d_l} + \mu_{d_l}))(\lambda_c + \mu_c)}. \end{aligned} \tag{15}$$

The steady state probabilities π_β where $\beta \in S$ for varying values of ρ are shown in Figure. 13. The steady state probability π_C that shows presence of CU in system, is sum of π_c, $\pi_{cd_h w}$ and $\pi_{cd_l w}$. DU_{hp} is using the spectrum in states D_H and $D_H D_L w$ so sum of π_{d_h} and $\pi_{d_h d_l w}$ gave us π_{D_H},on the other hand DU_{lp} is usually in waiting state or dropped off from system and using the spectrum in D_L state only so π_{D_L} is reflected only in π_{d_l}. This indicated that π_{D_H} is greater than π_{D_L} due to higher priority of DU_{hp}. Throughout the graph as cellular load increase π_{D_H} dominate π_{D_L} by visible margin, At $\rho = 0$, $\pi_{D_H} = 0.33$ compared to $\pi_{D_L} = 0.22$ with fixed DU traffic load at $\lambda_{d_h} = \lambda_{d_l} = 1$ and $\mu_{d_h} = \mu_{d_l} = 2$.

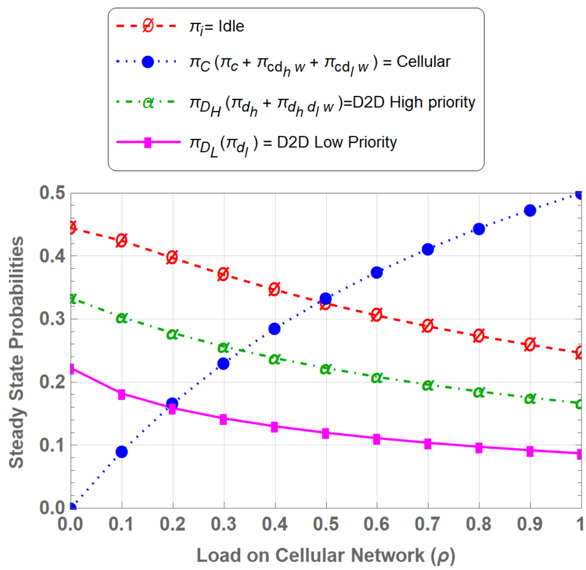

FIGURE 13. **Stationary probabilities for CN-MD-IW.**

E. CELLULAR NETWORK WITH cDUs HAVING MULTI-CLASS DUs IN HYBRID INTERWEAVE UNDERLAY SPECTRUM ACCESS (CN-MD-HB)

D2D communication is mostly for devices in closed proximity, which means DUs can operate on very low power. In CN-MD-HB, DUs will not go in waiting state on the arrival of CU as in case of CN-MD-IW where interrupted DUs have to wait for CU to depart and at higher value of ρ waiting time increase so much that its not possible for DUs to meet QoS, rather they will reduce their transmission power and keep communication session alive i.e hybrid interweave underlay spectrum access. This can only be possible by reducing data rate and keeping interference to CU under the threshold. Hybrid spectrum access suits DUs so both DU_{hp} and DU_{lp} users when using the spectrum at D_H and D_L states will follow hybrid spectrum access and move to CD_H and CD_L states when there is an arrival of CU.

Figure. 14 shows the state transition diagram of CN-MD-HB, Hybrid spectrum access is shown in dotted box. Two states CD_H and CD_L represents the coexistence of CUs and DUs together and state $D_H D_L$ shows coexistence of both

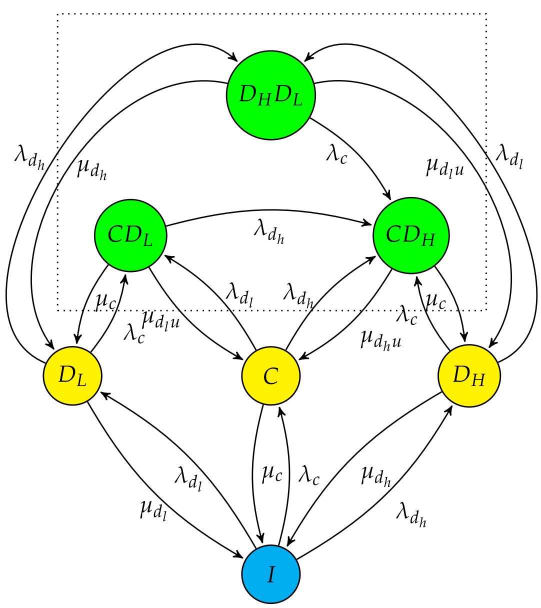

FIGURE 14. State transition diagram of CN-MD-HB.

DU_{hp} and DU_{lp} together. Only one DU can coexist with CU using underlay and due to its QoS constraints DU_{hp} is given preference over DU_{lp}. the detail of each state is as under.

- System at state C and DU_{hp} arrives, system will go to CD_H state, DU_{hp} goes underlay.
- System at state D_H and C arrives, system will go to CD_H state, DU_{hp} goes underlay.
- System at state C and DU_{lp} arrives, system will go to CD_L state, DU_{lp} goes underlay.
- System at state D_L and C arrives, system will go to CD_L state, DU_{lp} goes underlay.
- System at state CD_L and DU_{hp} arrives, system will go to CD_H state, DU_{hp} goes underlay and DU_{lp} got dropped.
- System at state D_L and D_H arrives, system will go to $D_H D_L$ state, DU_{lp} goes underlay.
- System at state $D_H D_L$ and C arrives, system will go to CD_H state, DU_{hp} goes underlay and DU_{lp} got dropped.

DUs operating underlay needs to limit their transmission power in order to control interference, this reduces their data rate and increases time to complete the communication session. Hence, departure rates $\mu_{d_h u}$ and $\mu_{d_l u}$ of DU_{hp} and DU_{lp} from states CD_H and CD_L is reduced. The state space vector of the system in this case is $S = \{I, C, D_H, D_L, CD_H, CD_L, D_H D_L\}$. The transition rate matrix Q is given in 15.

From Figure. 14 the flow balance equations of CN-MD-HB are given by:

$$
\begin{aligned}
\pi_i(\lambda_c + \lambda_{d_l} + \lambda_{d_h}) &= \pi_c\mu_c + \pi_{d_h}\mu_{d_h} + \pi_{d_l}\mu_{d_l},\\
\pi_c(\mu_c + \lambda_{d_l} + \lambda_{d_h}) &= \pi_i\lambda_c + \pi_{cd_l}\mu_{d_l u} + \pi_{cd_h}\mu_{d_h u},\\
\pi_{d_h}(\lambda_c + \mu_{d_h} + \lambda_{d_l}) &= \pi_i\lambda_{d_h} + \pi_{cd_h}\mu_c + \pi_{d_h d_l}\mu_{d_l u},\\
\pi_{d_l}(\lambda_c + \mu_{d_l} + \lambda_{d_h}) &= \pi_i\lambda_{d_l} + \pi_{cd_l}\mu_c + \pi_{d_h d_l}\mu_{d_h},\\
\pi_{cd_h}(\mu_c + \mu_{d_h u}) &= \pi_{d_h}\lambda_c + \pi_c\lambda_{d_h} + \pi_{cd_l}\lambda_{d_h}\\
&\quad + \pi_{d_h d_l}\lambda_c,\\
\pi_{cd_l}(\mu_c + \mu_{d_l u} + \lambda_{d_h}) &= \pi_{d_l}\lambda_c + \pi_c\lambda_{d_l},\\
\pi_{d_h d_l}(\lambda_c + \mu_{d_h} + \mu_{d_l u}) &= \pi_{d_l}\lambda_{d_h} + \pi_{d_h}\lambda_{d_l},
\end{aligned}
\tag{16}
$$

The steady state probabilities for each state π_β ($\beta \in S$) can be found by solving the set of linear equations in (16) and normalization equation (6). The steady state probability π_C is the sum of states where CU operates i.e. π_c, π_{cd_h} and π_{cd_l}. similarly when DU_{hp} access the spectrum in interweave π_{d_h} and $\pi_{d_h d_l}$ will give us steady state probability π_{D_H}. DU_{lp} only access system in interweave in π_{d_l} which gives us π_{D_L}. The steady state probabilities of π_β are presented in Figure. 16. where for complete values of ρ the $\beta \in S$ and only in the absence of CU, DUs will operate using interweave spectrum access and gain in CN-MD-HB case is shown in Figure. 17.

The steady state probability for DU_{hp}, operating in underlay access mode i.e. $\pi_{D_H-Underlay}$, increases by increasing the load on cellular network. The reason behind this behavior is when ρ increases, more CU arrive and preempt DUs, so DUs will have to operate in underlay access mode to complete their communication. Whereas, steady state probability for DU_{lp} in underlay access mode ($\pi_{L-Underlay}$) gradually decrease as increase in ρ. It is because at $\rho = 0$ user DU_{hp} gets maximum opportunities to access the spectrum in the absence of CU and being the higher priority operates in interweave spectrum access while and DU_{lp} operates in underlay access mode coexisting with DU_{hp}. However, when the ρ increases the channel is mostly used by CU, which forces DU_{hp} to operate mostly in underlay access mode and further reduces the DU_{lp} presence in the system.

F. CELLULAR NETWORK WITH cDUs HAVING MULTI-CLASS DUs IN ENHANCED HYBRID SPECTRUM ACCESS (CN-MD-eHB)

In both CN-MD-IW and IN-MD-HB, only two higher category devices access the system simultaneously and whenever all three category devices appear on the system DU_{lp} will be dropped and only CU and DU_{hp} will be compensated in system. In CN-MD-eHB we overcome this limitation as shown in Figure. 18 by introducing $CD_H D_L w$ state and we call it enhanced hybrid spectrum access technique. Rest of the process is same as Figure. 14 only enhancements are as under.

- System at state CD_H and DU_{lp} arrives with rate λ_{d_l}, system will go to $CD_H D_L w$ state, DU_{hp} goes underlay and DU_{lp} goes in waiting.
- System at state CD_L and DU_{hp} arrives with rate λ_{d_h}, system will go to $CD_H D_L w$ state, DU_{hp} goes underlay and DU_{lp} goes in waiting.
- System at state $D_H D_L$ and CU arrives with rate λ_C, system will go to $CD_H D_L w$ state, DU_{hp} goes underlay and DU_{lp} goes in waiting.

At $CD_H D_L w$ state CU is using spectrum at Interweave rate and DU_{hp} is using spectrum at underlay and DU_{lp} is

$$
\mathbf{Q} = \begin{array}{c} \\ I \\ C \\ D_H \\ D_L \\ CD_H \\ CD_L \\ D_HD_L \end{array}
\begin{array}{ccccccc}
I & C & D_H & D_L & CD_H & CD_L & D_HD_L \\
\hline
-(\lambda_c+\lambda_{d_h}+\lambda_{d_l}) & \lambda_c & \lambda_{d_h} & \lambda_{d_l} & 0 & 0 & 0 \\
\mu_c & -(\mu_c+\lambda_{d_h}+\lambda_{d_l}) & 0 & 0 & \lambda_{d_h} & \lambda_{d_l} & 0 \\
\mu_{d_h} & 0 & -(\mu_{d_h}+\lambda_c+\lambda_{d_l}) & 0 & \lambda_c & 0 & \lambda_{d_l} \\
\mu_{d_l} & 0 & 0 & -(\lambda_c+\lambda_{d_h}+\mu_{d_l}) & 0 & \lambda_c & \lambda_{d_h} \\
0 & \mu_{d_hu} & \mu_c & 0 & -(\mu_c+\mu_{d_hu}) & 0 & 0 \\
0 & \mu_{d_lu} & 0 & \mu_c & \lambda_{d_h} & -(\mu_c+\lambda_{d_h}+\mu_{d_lu}) & 0 \\
0 & 0 & \mu_{d_lu} & \mu_{d_h} & \lambda_c & 0 & -(\lambda_c+\mu_{d_lu}+\mu_{d_h})
\end{array}
$$

FIGURE 15. CN-MD-HB Q-transition rate matrix.

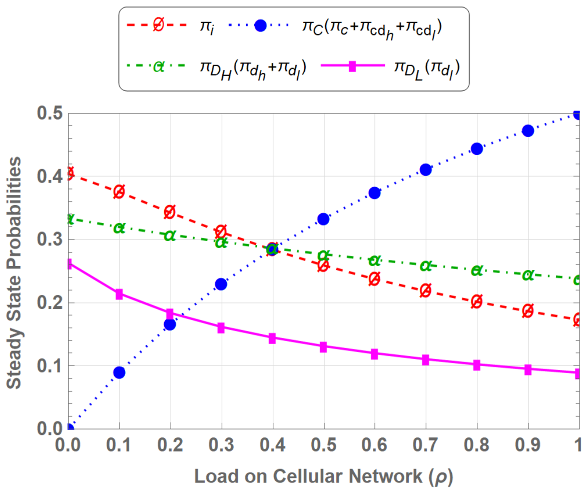

FIGURE 16. DUs operating in interweave access.

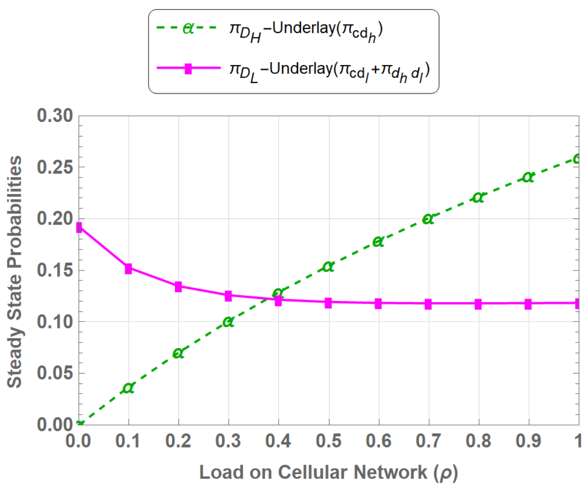

FIGURE 17. DUs operating in underlay access.

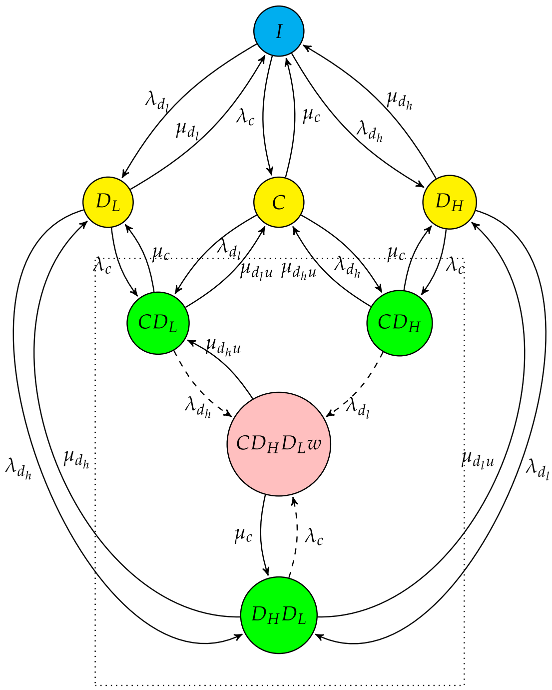

FIGURE 18. State transition diagram of CN-MD-eHB.

at waiting for any of them to complete their transmission. CU will depart with rate μ_c and system will move to D_HD_L state. DU_{hp} will depart with rate $\mu_{d_{hu}}$ and system will move to CD_L state. The state space vector of the system in this case is $S = \{I, C, D_H, D_L, CD_H, CD_L, D_HD_L, CD_HD_Lw\}$. we denote this CTMC as CN-MD-eHB and its state transition matrix Q is given in Figure. 19 we have extracted flow balance equations of CN-MD-eHB from 19

$$
\begin{aligned}
\pi_i(\lambda_c+\lambda_{d_l}+\lambda_{d_h}) &= \pi_c\mu_c+\pi_{d_h}\mu_{d_h}+\pi_{d_l}\mu_{d_l}, \\
\pi_c(\mu_c+\lambda_{d_l}+\lambda_{d_h}) &= \pi_i\lambda_c+\pi_{cd_l}\mu_{d_lu}+\pi_{cd_h}\mu_{d_hu}, \\
\pi_{d_h}(\lambda_c+\mu_{d_h}+\lambda_{d_l}) &= \pi_i\lambda_{d_h}+\pi_{cd_h}\mu_c+\pi_{d_hd_l}\mu_{d_lu}, \\
\pi_{d_l}(\lambda_c+\mu_{d_l}+\lambda_{d_h}) &= \pi_i\lambda_{d_l}+\pi_{cd_l}\mu_c+\pi_{d_hd_l}\mu_{d_h}, \\
\pi_{cd_h}(\mu_c+\mu_{d_hu}+\lambda_{d_l}) &= \pi_c\lambda_{d_h}+\pi_{d_h}\lambda_c+\pi_{cd_hd_lw}\lambda_{d_l}, \\
\pi_{cd_l}(\mu_c+\mu_{d_lu}+\lambda_{d_h}) &= \pi_{d_l}\lambda_c+\pi_c\lambda_{d_l}+\pi_{cd_hd_lw}\mu_{d_{hu}}, \\
\pi_{d_hd_l}(\lambda_c+\mu_{d_h}+\mu_{d_lu}) &= \pi_{d_l}\lambda_{d_h}+\pi_{d_h}\lambda_{d_l}, \\
\pi_{cd_hd_lw}(\mu_c+\mu_{d_hu}) &= \pi_{cd_l}\lambda_{d_h}+\pi_{cd_h}\lambda_{d_l}+\pi_{d_hd_l}\lambda_c,
\end{aligned} \tag{17}
$$

The steady state probabilities for each state π_β ($\beta \in S$) can be found by solving the set of linear equations in (17) and normalization equation (6).

The steady state probability π_C is the sum of states where CU operates i.e. π_c, π_{cd_h}, π_{cd_l} and $\pi_{cd_hd_lw}$. similarly when DU_{hp} access the spectrum in interweave π_{d_h} and $\pi_{d_hd_l}$ will give us steady state probability π_{D_H}. DU_{lp} only access system

$$
\mathbf{Q} = \begin{array}{c} \\ I \\ C \\ D_H \\ D_L \\ CD_H \\ CD_L \\ D_H D_L \\ CD_H D_L w \end{array}
\begin{array}{c}
\begin{array}{cccccccc} I & C & D_H & D_L & CD_H & CD_L & D_H D_L & CD_H D_L w \end{array} \\
\begin{bmatrix}
-(\lambda_c+\lambda_{d_h}+\lambda_{d_l}) & \lambda_c & \lambda_{d_h} & \lambda_{d_l} & 0 & 0 & 0 & 0 \\
\mu_c & -(\mu_c+\lambda_{d_h}+\lambda_{d_l}) & 0 & 0 & \lambda_{d_h} & \lambda_{d_l} & 0 & 0 \\
\mu_{d_h} & 0 & -(\mu_{d_h}+\lambda_c+\lambda_{d_l}) & 0 & \lambda_c & 0 & \lambda_{d_l} & 0 \\
\mu_{d_l} & 0 & 0 & -(\lambda_c+\lambda_{d_h}+\mu_{d_l}) & 0 & \lambda_c & \lambda_{d_h} & 0 \\
0 & \mu_{d_h u} & \mu_c & 0 & -(\mu_c+\mu_{d_h u}+\lambda_{d_l}) & 0 & 0 & \lambda_{d_l} \\
0 & \mu_{d_l u} & 0 & \mu_c & 0 & -(\mu_c+\lambda_{d_h}+\mu_{d_l u}) & 0 & \lambda_{d_h} \\
0 & 0 & \mu_{d_l u} & \mu_{d_h} & 0 & 0 & -(\lambda_c+\mu_{d_l u}+\mu_{d_h}) & \lambda_c \\
0 & 0 & 0 & 0 & 0 & \mu_{d_h u} & \mu_c & -(\mu_c+\mu_{d_h u})
\end{bmatrix}
\end{array}
$$

FIGURE 19. CN-MD-eHB Q-transition rate matrix.

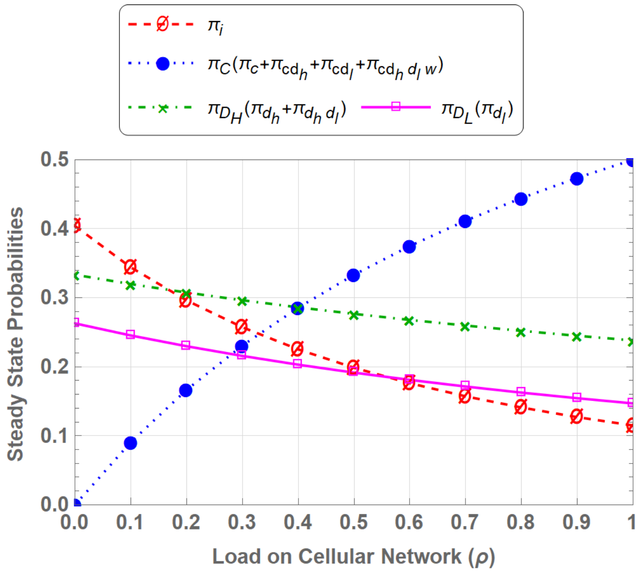

FIGURE 20. DUs Operating in Interweave Access.

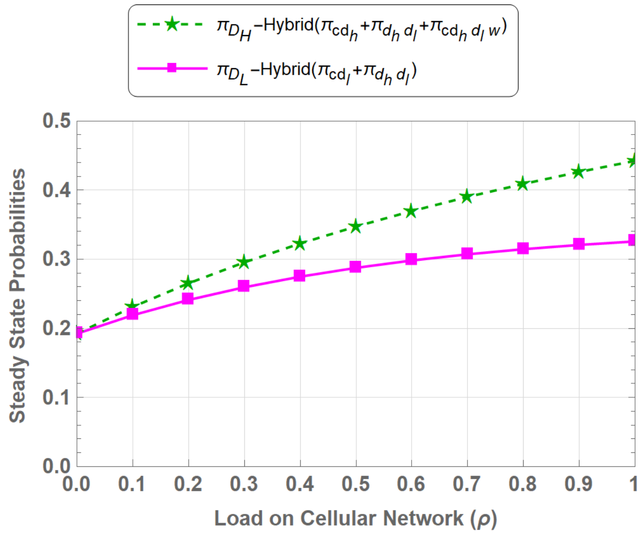

FIGURE 21. DUs Operating in Underlay Access.

in interweave in π_{d_l} which gives us π_{D_L}. Figure. 20 shows the steady state probabilities π_β, where $\beta \in S$ for entire range of ρ, where DUs operate using interweave spectrum access in the absence of CU. It is evident from the graph that CN-MD-eHB outperforms both CN-MD-IW and CN-MD-HB as it reduces steady state probability of π_i and increases π_{d_l} at full load ($\rho = 1$).

The gain in CN-MD-eHB is shown in Figure. 21, where DUs perform enhanced hybrid spectrum access. There is increase of steady state probability for both DU_{hp} and DU_{lp}. the pattern shows healthy increase with increase in load which means this system can accommodate more DUs at high load.

VI. SIMULATION AND RESULTS

Performance evaluation of CN-MD-eHB scheme is performed in this section. Its comparison with CN-ONLY, CN-UD-IW, CN-UD-HB, CN-MD-IW and CN-MD-HB schemes is performed and their numerical results are presented. The evaluation parameters are Throughput, EDDT, Spectrum utilization and steady state probabilities. System parameters used for performance evaluation are shown in Table. 2.

TABLE 2. System parameters.

Symbol	Name	Values
N_{ch}	Number of Cellular Channel	1
ρ	Load on Cellular Network	[0.0 - 1.0]
λ_d	Mean Arrival Rate of DU	2
λ_{d_h}	Mean Arrival Rate of DU_{hp}	1
λ_{d_l}	Mean Arrival Rate of DU_{lp}	1
μ_d	Mean Departure Rate of DU	4
μ_{d_h}	Mean Departure Rate of DU_{hp}	2
μ_{d_l}	Mean Departure Rate of DU_{lp}	2
$\mu_{d_h u}$	Mean Underlay Departure Rate of DU_{hp}	0.01
$\mu_{d_l u}$	Mean Underlay Departure Rate of DU_{lp}	0.01
$Size$	File Size	5 Kb
R_i	Interweave Transmission Rate (IEEE 802.11a)	48 Mbps
R_u	Underlay Transmission Rate (IEEE 802.11a)	18 Mbps
W	Channel Bandwidth (IEEE 802.11a)	22 MHz
λ_c	Mean Arrival Rate of CU	4

A. STEADY STATE PROBABILITIES

Out of total time how much portion of time the spectrum remain occupied by CU or DU in a particular state is called steady state probability. The comparison between steady states for CN-MD-IW, CN-MD-HB and CN-MD-eHB is

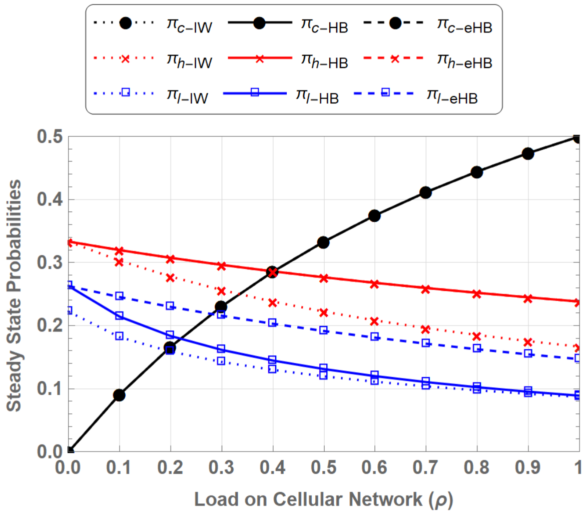

FIGURE 22. Comparison of stationary probabilities.

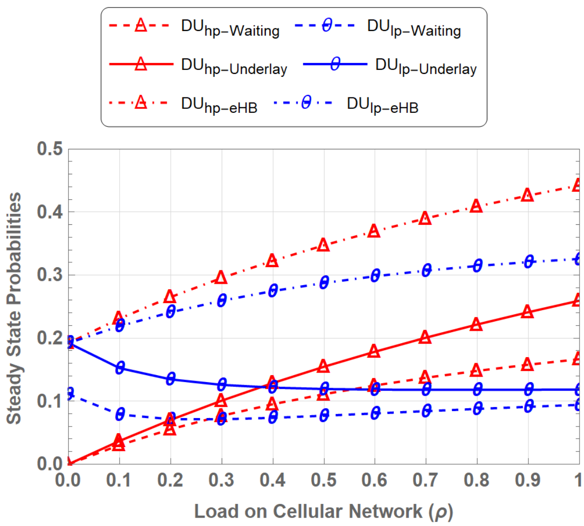

FIGURE 23. Comparison of interrupted DUs waiting vs underlay vs hybrid spectrum access.

shown in Figure. 22. For all values of ρ, the values of π_C remains same which shows that opportunistic access of spectrum by DUs don't interfere CUs. π_{D_H} and π_{D_L} follows same trend in all three cases but CN-MD-eHB spectrum access strategy outperforms CN-MD-IW and CN-MD-HB. This is due to fact that system is not dropping any user.

Results shown in Figure.23 shows the comparison between DU_{hp} and DU_{lp} under waiting, underlay and enhanced hybrid spectrum access schemes. In interweave and underlay access mode there are very limited opportunity for DUs to access the spectrum under increasing value of ρ but in eHB we can see healthy improvement in steady state probability of both DU_{hp} and DU_{lp} even at higher values of ρ.

B. SPECTRUM UTILIZATION

The ratio of active utilization time of spectrum either by CUs or DUs to the total time is called spectrum utilization [31].

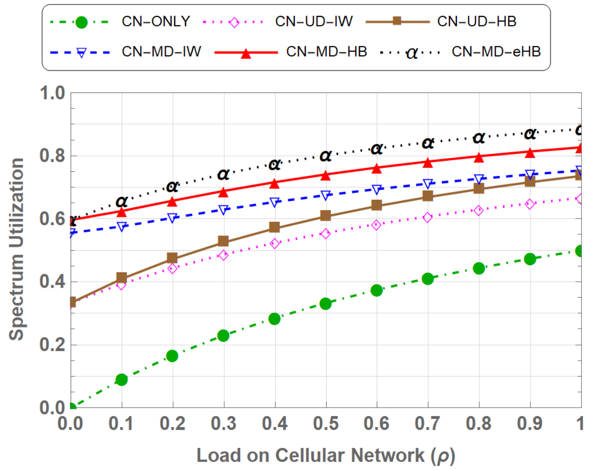

FIGURE 24. Comparison of spectrum utilization.

It increases with increase in active users of the system. In Figure. 24 we show a comparison of spectrum utilization between CN-ONLY, CN-UD-IW, CN-UD-HB, CN-MD-IW, CN-MD-HB and CN-MD-eHB. It is evident from graph that by increasing ρ spectrum utilization increases. CN-ONLY perform worst as it only accommodate cellular users. CN-UD-IW performs better as it provides opportunity for DUs to coexist with CUs and increase number of users to simultaneously utilize spectrum. CN-UD-HB shows improvement as the DUs don't go in waiting state and keep on using spectrum even in the presence of CU. Introduction of categories in DUs further increase spectrum utilization. CN-MD-eHB perform better then CN-MD-IW and CN-MD-HB by accommodating more users as it uses both underlay and waiting spectrum access techniques simultaneously.

Spectral Efficiency of the system, which is Data Bits per Hertz [32] is represented in Figure. 25. At full load ($\rho = 1$) spectral efficiency of CN-MD-IW is 1.6 Mbps/Hz, CN-MD-HB is 2.1 Mbps/Hz which is 31% increase and

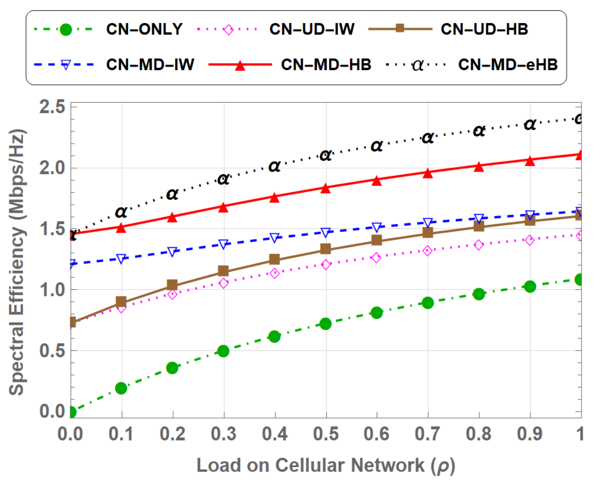

FIGURE 25. Comparison of spectral efficiency.

CN-MD-eHB is at 2.4 Mbps/Hz which is 50% and 14.2% increase respectively.

C. THROUGHPUT

The amount of data passes through a system in unit time is called throughput which is data of both CUs and DUs collectively. In CN-ONLY where only CU is present at spectrum, the average throughput is given by:

$$T_1 = \pi_c r. \tag{18}$$

where, r is the maximum value of data rate. The average throughput of CN-UD-IW and CN-UD-HB, where both CU and DU can access the spectrum is given by:

$$T_2 = (\pi_c + \pi_d) r. \tag{19}$$

For CN-MD-IW, where Multi class DUs operate alongside CUs in interweave only spectrum access, the average throughput is given by:

$$T_3 = (\pi_c + \pi_{d_h} + \pi_{d_l}) r. \tag{20}$$

In CN-MD-HB where priority based multi class DUs are operating in underlay spectrum access opportunistically, the throughput of system is given by:

$$\begin{aligned} T_4 = &(\pi_c + \pi_{d_h} + \pi_{d_l}) r \\ &+ \pi_{cd_h} r_u^{d_h} + (\pi_{cd_l} + \pi_{d_h d_l}) r_u^{d_l}. \end{aligned} \tag{21}$$

where, r and r_u^{Γ} are defined in (1) and (2).

Finally in CN-MD-eHB where DUs follow Hybrid spectrum access, the throughput is calculated as:

$$\begin{aligned} T_5 = &(\pi_c + \pi_{d_h} + \pi_{d_l}) r + (\pi_{cd_h} + \pi_{c_{d_h d_l}}) r_u^{d_h} \\ &+ (\pi_{cd_l} + \pi_{d_h d_l}) r_u^{d_l}. \end{aligned} \tag{22}$$

The average throughput of the system against $\rho(0-1)$ is shown in Figure. 26 for CN-ONLY, CN-UD-IW, CN-UD-HB, CN-MD-IW, CN-MD-HB and CN-MD-eHB. The average system throughput of CN-MD-eHB is higher compared to all other against $\rho(0-1)$.

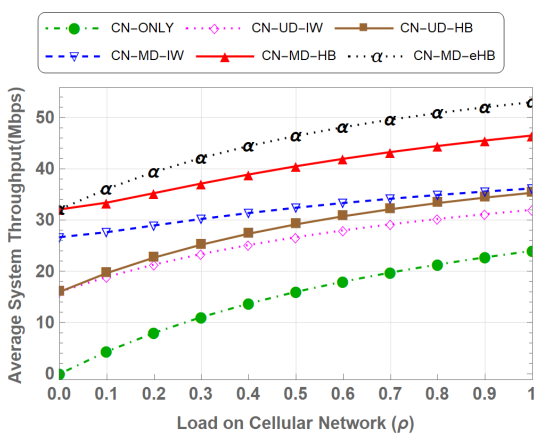

FIGURE 26. **Comparison of average system throughput.**

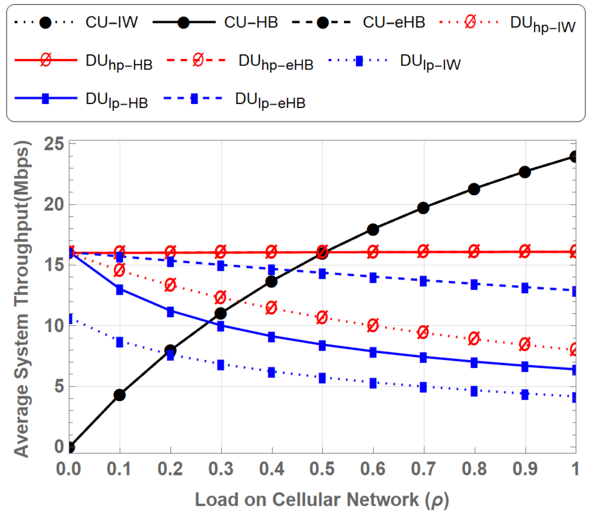

FIGURE 27. **Average system throughput for CUs and DUs.**

The contribution of CUs and multi-class DUs in average system throughput is given in Figure. 27. The average data rate of DU_{hp} at $\rho = 1$ is 8 Mbps for CN-MD-IW but it increases to 16 Mbps for both CN-MD-HB and CN-MD-eHB which is 100% increase. Similarly the average data rate of DU_{lp} at $\rho = 1$ is 4.1 Mbps for CN-MD-IW and 6.4Mbps for CN-MD-HB which is 56% increase, it further increases to 12.9 Mbps for CN-MD-eHB which is 214.6% and 101.5% increase respectively. For DU_{hp} and DU_{lp}, the decaying trend of graph shows that increasing cellular load on system reduces opportunistic access of DUs.

D. EXTENDED DATA DELIVERY TIME

Total time taken by multi-class DU in successfully transmitting its data is called EDDT of DU. It also includes the time DU spend in waiting state during hand-off. As the load on network increases, the waiting time and number of hand-offs also increase, this ultimately results in increased EDDT. The EDDT comparison between CN-MD-IW, CN-MD-HB and CN-MD-eHB is shown in Figure. 28. For DU_{hp}, EDDT at $\rho = 0$ is at 0.31 msec which is same for CN-MD-IW, CN-MD-HB and CN-MD-eHB but at $\rho = 1$ EDDT of CN-MD-IW increases to 0.625 msec which is 101% increase and EDDT of CN-MD-HB and CN-MD-eHB slightly increase to 0.32 msec which is 3.22% increase. As DU_{lp} is low priority user and it had to wait often, there is a visible change in EDDT at different values of ρ. At $\rho = 0$ EDDT of CM-MD-IW = 0.46 msec, EDDT of CN-MD-HB and CN-MD-eHB is 0.31 msec. At $\rho = 1$ EDDT of CN-MD-IW is at 1.2 msec which is 160% increase, EDDT of CN-MD-HB is at 0.775 msec which is 150% increase and EDDT of CN-MD-eHB is at 0.39 msec which is 25.8% increase.

It is evident from the results that among all other spectrum access techniques implemented in this work CN-MD-eHB is most suitable due to its low EDDT increase at maximum load. The Difference between DU_{hp} and DU_{lp} for CN-MD-eHB

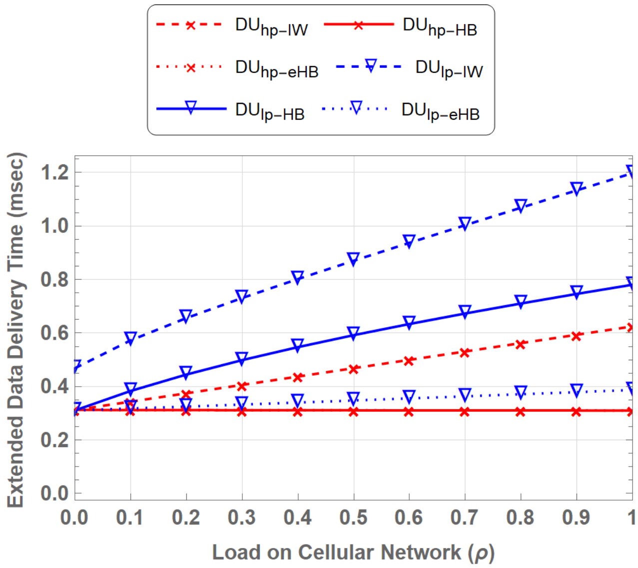

FIGURE 28. Comparison of EDDT.

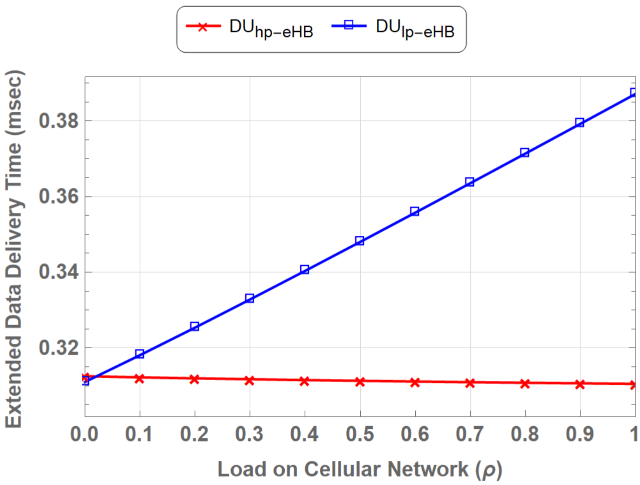

FIGURE 29. EDDT for delay-sensitive vs delay-tolerant traffic in CN-MD-eHB.

is shown in Figure. 29. At Maximum load ($\rho = 1$) there is 22.5% difference between DU_{hp} and DU_{lp}. this is due to priority assigned based on QoS requirements of DU.

E. DROP RATE

The rate at which users are dropped out of system due to unavailability of spectrum resource is called drop rate. In CN-MD-IW as shown in Figure. 11. The state $D_H D_L w$ shows that DU_{hp} using spectrum with DU_{lp} in waiting state and with arrival of CU at rate λ_c the system will move to state $C_{D_H w}$ and DU_{lp} will be dropped from system as shown in Figure.30 the DU_{lp} drop rate is the product of $\pi_{d_h d_l w}$ and λ_c. In CN-MD-HB as shown in Figure. 14 DU_{lp} drop is happening on two states with two different arrival rates, state CD_L with rate λ_{d_h} and state $D_H D_L$ with λ_c. The DU_{lp} drop rate is $\pi_{cd_l}\lambda_{d_h} + \pi_{d_h d_l}\lambda_c$.

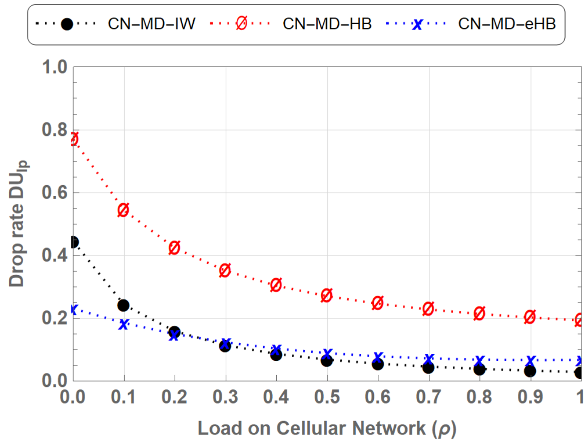

FIGURE 30. DU_{lp} **drop rate CN-MD-IW, CN-MD-UL.**

To overcome this drop we have introduced a state $CD_H D_L w$ in CN-MD-eHB as shown in Figure. 18 and instead of dropping DU_{lp} out of system we compensate it by introducing a waiting state which will greatly benefit the system in two aspects. first DU_{lp} will not be dropped out of system on arrival of CU or DU_{hp} secondly DU_{lp} will be allowed to enter the system when its preoccupied by CU and DU_{hp}. The drop rate of DU_{lp} in CN-MD-eHB is calculated as $1 - (\pi_{cd_l}\lambda_{d_h} + \pi_{d_h d_l}\lambda_c + \pi_{cd_h}\lambda_{d_l})$

VII. CONCLUSION

The primary focus of this work is on a cognitive D2D communication system that is emerging as a promising solution to improve spectrum utilization and meet QoS requirements of multi-class cDUs within the next-generation cellular networks. An enhanced hybrid spectrum access scheme is developed to meet QoS requirements of multi-class cDUs following non-switching spectrum handoff. The performance of the proposed spectrum access scheme is analyzed through CTMC modeling and comparison is also made with several baseline and advanced spectrum access techniques. The results of the analysis indicate that the proposed scheme outperforms interweave and hybrid interweave-underlay spectrum access strategies in terms of spectral efficiency, throughput, and EDDT. The findings of this work demonstrate that with an improved drop-rate, the proposed scheme is well suited to meet the QoS requirements of next-generation dynamic communication systems supporting multi-class cDUs. The proposed framework can further be extended to manage spectrum handoff and QoS provisioning in diverse cognitive D2D communication scenarios involving mobility, varying number of primary channels as well through integration of advanced machine learning and artificial intelligence techniques.

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