Joint Admission Control, Mode Selection, and Power Allocation in D2D Communication Systems

Muhammad Azam, Mushtaq Ahmad, Muhammad Naeem, *Member, IEEE*, Muhammad Iqbal, Ahmed Shaharyar Khwaja, *Member, IEEE*, Alagan Anpalagan, *Senior Member, IEEE*, and Saad Qaisar, *Senior Member, IEEE*

***Abstract*—Device-to-device (D2D) communications can help in achieving the higher data rate targets in emerging wireless networks. The use of D2D communication imposes certain challenges such as interference with the cellular and D2D users. A well-designed joint admission control, network mode selection, and power allocation technique in a cellular network with D2D capability can improve overall throughput. The proposed technique jointly maximizes the total throughput and number of admitted users in cellular networks under quality-of-service (QoS) and interference constraints. The joint admission control, mode selection, and power allocation problem (JACMSPA) falls into a class of mixed-integer nonlinear constraint optimization problems that are generally NP-hard. Due to the combinatorial nature of the problem, its optimal solution needs exhaustive search of integer variables whose complexity increases exponentially with the number of user pairs. In this paper, we invoke outer approximation approach (OAA)-based linearization technique to solve the JACMSPA. The proposed method gives guaranteed ε-optimal solution with reasonable computational complexity. Simulation results verify the effectiveness of the proposed approach method.**

***Index Terms*—Admission control, device-to-device (D2D) communication, mode selection.**

I. Introduction

DEMAND for higher data rates in future cellular networks is being witnessed globally. Data-hungry applications on mobile devices such as multimedia downloading, video streaming, online gaming, and large file sharing among users are forcing cellular operators to adopt new technologies. These technologies allow the operators to satisfy customer demand for enhanced data rates and increase their revenues. The policy formulating entities and regulators around the globe are also following this trend. Rightly realizing the importance of higher data rates, the Third-Generation Partnership Project has stressed the need to increase the bandwidth requirement of International Mobile Telecommunications-Advanced (IMT-Advanced)[1] systems up to 100 MHz by the incorporation of new technological components [1]. The IMT-Advanced systems promise to improve local area services through efficient utilization of scarce radio resources. Long-Term Evolution (LTE) technologies are designed to provide high data rates [2]–[4]. In [1], the concept of D2D communication in LTE Advanced (LTE-A) was presented to meet higher-data-rate demands.

D2D communication in advanced cellular networks is a very promising technique wherein user equipment shares the same radio resources used by cellular users to enhance the throughput of the cellular systems. According to [5], different techniques are possible for the controlled management of resources by the Evolved Node B (eNB). A nonorthogonal frequency sharing method is more suitable to enhance spectral efficiency. Much work has been done through wireless local area networks and wireless personal area networks. Although technologies such as Bluetooth and ultrawideband provide higher data rates, they require manual peering and have no control over interference. However, in D2D communication, due to the controlled assignment of radio resources by a base station (BS) or an eNB in the licensed band, problems such as manual peering and interference among users are alleviated to a greater extent [1]. According to [5], benefits of D2D communication include: reduction in end-to-end latency due to a reduced number of hops, higher bit rates due to proximity of users, low power consumption thereby enhancing battery life of devices, wireless cellular networks evolving toward the advanced and intelligent architectures to achieve better network capacity, and coverage and quality of service.

The use of D2D communication imposes certain challenges such as interference with cellular and D2D users while reusing the same radio resources with the cellular users. To achieve higher data rate of future wireless networks while simultaneously satisfying the quality of service with power constrained is a challenging task. A well-designed joint admission control, mode selection,[2] and power allocation (JACMSPA) technique in a cellular network with D2D capability can improve overall throughput of cellular network. Various techniques have been suggested in the literature to enhance data rates of future

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M. Azam is with the Department of Electrical Engineering, Foundation University Rawalpindi, Rawalpindi 46000, Pakistan.

M. Ahmad and M. Iqbal are with the Department of Electrical Engineering, COMSATS Institute of Information Technology, Wah Campus, Wah Cantt 47040, Pakistan.

M. Naeem is with the Department of Electrical Engineering, COMSATS Institute of Institute of Information Technology, Wah Campus, Wah Cantt 47040, Pakistan, and also with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON M5B 2K3, Canada (e-mail: mnaeem@rnet.ryerson.ca).

A. S. Khwaja and A. Anpalagan are with WINCORE Laboratory, Ryerson University, Toronto, ON M5B 2K3, Canada (e-mail: alagan@ee.ryerson.ca).

S. Qaisar is with the School of Electrical Engineering and Computer Science, National University of Sciences and Technology, Islamabad 44000, Pakistan.

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[1] IMT-Advanced is a requirement issued by the International Telecommunication Union for future-generation mobile phones and Internet access services.

[2] Mode selection determines whether the user pair will communicate directly in a point-to-point fashion or communicate with the help of cellular eNB.

cellular networks. Currently, local services prefer to reuse the spectrum to increase the system throughput. Unlike the traditional cellular network, D2D can establish a direct link in user equipment by sharing the same resource blocks with other cellular users, thereby improving spectral efficiency. However, cellular users experience interference from the D2D transmitters. To control the interference level efficiently, eNB will be in charge of assigning the resource blocks to the D2D devices. A literature review and some design challenges related to resource allocation and spectrum sharing between cellular and D2D users to enhance the efficiency of network is discussed in the following.

II. Literature Review

In [10], a greedy algorithm and successive interference cancelation (SIC) is proposed, which allows the coexistence of three pairs of D2D user equipment and cellular users in a channel. The SIC approach maximizes the performance of D2D links and reduces the interference from D2D users to cellular users. Fractional frequency reuse is used to reduce the interference with cochannel cells [11]. It was suggested that if user equipment is in the outer cell region, then D2D and cellular user equipment experiences tolerable interference. In [22], power allocation and channel allocation are investigated using a greedy method. In [12], it is suggested that the spectrum utilization be improved and the performance be optimized by maximizing the weighted sum rate of D2D and cellular users. Several efficient algorithms were analyzed based on complexity and overall performance. To optimize different parameters of future cellular networks, power control is considered in [13] and [21], whereas in [14], both admission and power control in D2D and cellular networks are examined. A distance-dependent mode selection is investigated in [23]. In orthogonal frequency-division multiple-access (OFDMA)-based systems, to guarantee quality-of-service (QoS), in [24], a resource allocation scheme is proposed, while considering signal-to-interference-plus-noise ratio threshold value for cellular users. The scheme is divided into two steps: In the first step, subcarriers are assigned under the premise of ensuring the minimum data rate of the D2D multicast groups, and the second step involves QoS of cellular users.

Literature review and some design challenges related to spectrum sharing between cellular and D2D users to enhance the energy efficiency are discussed in [25]. In [26], a new spectrum sharing protocol is proposed. It allows the D2D user equipment to communicate bidirectionally with one another while supporting two-way communications between the BS and cellular users. In [27], the resource reusing mechanism is investigated in more than one D2D pair, allowing to share the multiple resource blocks to obtain higher sum rates. Mode selection is also performed based on an evolutionary algorithm. In [28], a distributed implementation is presented. The sum rate of the D2D system is maximized by maximizing the transmission rate using game theory. An interference management strategy is proposed in [29] to increase the overall capacity of cellular users and the D2D system. A conventional technique is used that limits maximum transmit power of the D2D transmitter so that it does not generate harmful interference from the D2D user to cellular users. In D2D communication, the decision to assign a part of resource to downlink or uplink is very important. It should be done on priority to enable the reuse of resources for higher system capacity. In [30], interference control in downlink mode is proposed to limit the BS interference to D2D user equipment by selecting cellular users that are closer to the BS. To improve the QoS of both D2D and cellular users, a three-step scheme is proposed in [31], which involves admission control and subsequent power allocation for each selected D2D pair and its potential cellular user partners. D2D needs intelligent resource sharing as suggested in [32] to optimize the spectrum utilization. In [33], a resource sharing issue is investigated to optimize the system performance in D2D communication in cellular networks from a cooperative and distributive perspective. In this scheme, the utility function is maximized for each user and provides incentive to cooperate with other users to form a strong group to increase the likelihood of winning its preferred spectrum resource.

A. Contributions

Based on the literature review and a closed look at Table I reveal that a joint user and mode selection with power allocation is an open area of research. Some papers in the literature claim joint admission control and power allocation, but they always try to solve the user selection and power allocation separately. Since user selection and power allocation are not separable and in addition to joint user selection and power allocation, we are also jointly determining the mode selection. In [16]–[20], different joint admission and power control schemes for wireless systems are proposed. All these studies do not include the mode selection in their formulation. As per the best knowledge of the authors, the literature review reveals that there is no throughput maximization scheme in a cellular network with D2D capability that jointly controls the admission of the users, mode selection (whether to be in cellular or D2D mode), and power allocation under QoS and interference constraints. The existing work focuses on individual aspects, as shown in Table I. The closest possible existing work is done in [27], where a genetic algorithm (GA) is applied for admission control and mode selection. The main difference between the formulation in [27] and ours is joint admission control and mode selection. In [27], a separate admission control and mode selection scheme is proposed, whereas in this paper, we propose a joint admission control and mode selection scheme. For a fair comparison, in this paper, we also compare the results of GA with our proposed algorithm. The scope of this paper fills the gap and tries to maximize the throughput considering the JACMSPA mechanism. The main contributions of this paper are summarized as follows.

1) We formulate a constrained JACMSPA optimization problem that maximizes the overall throughput of the future cellular networks by jointly controlling admission of the users, satisfying mode selection and power control constraints of the users and the BS.
2) The JACMSPA is a class of mixed-integer nonlinear constraint optimization problems, which are generally NP-complete. Due to the combinatorial nature of JACMSPA, the optimal solution needs exhaustive search of integer variables whose complexity increases exponentially with the number of user pairs. In this paper, we apply a linearization technique that uses outer approximation approach (OAA) to solve this NP-complete JACMSPA. The

TABLE I
COMPARISON OF DIFFERENT REFERENCES. AC = ADMISSION CONTROL, MS = MODE SELECTION, PA = POWER ALLOCATION

Ref	Admission Control	Mode Selection	Power Allocation	JACMSPA	Algorithm	Remarks
[6]		✓			Heuristic	Mode selection without the knowledge of perfect CSI
[9]		✓			Heuristic	Graph theory based resource allocation
[10]		✓			Greedy	Radio resource allocation based on greedy algorithm and successive interference cancellation in Device-to-Device (D2D) communication
[11]			✓		Traditional convex optimization techniques	System throughput maximization for cellular network with D2D capability.
[13]		✓	✓		Greedy scheme	Empirical D2D results for underlay WINNNER II project
[14]			✓			Power optimization for orthogonal amd non-orthogonal resource sharing modes between cellular and D2D communication.
[15]			✓			Best-effort Successive Interference Cancelation algorithm, canceling interfering signals.
[16]	✓		✓		Adaptive Approximation Algorithms	This admission control is without mode selection.
[17]	✓		✓		Robust optimization algorithm	Utility Maximization and Admission Control for a MIMO Cognitive Radio Network.
[18]	✓		✓		Linear Programming	This admission control is without mode selection.
[19]	✓		✓		Convex Approximation	This admission control is without mode selection.
[21]	✓		✓		Heuristic	Distributed power control and set based admission control
[22]		✓	✓		Greedy	Channel assignment and mode selection in OFDMA based cellular network.
[24]	✓		✓		Heuristic	Subcarrier allocation for D2D multicast system with OFDMA scheme.
[27]	✓	✓	✓		Evolutionary Algorithm	GA based resource allocation in D2D network.
[29]			✓			Coverage analysis and calculation of erotic capacity in cellular D2D network.
[31]	✓		✓		Heuristic	A bipartite matching based resource allocation.
[33]		✓	✓		Heuristic	Resource allocation as a coalition formation game.
[35]		✓	✓		Heuristic	Resource allocation in cooperative two-way cellular D2D network.

proposed OAA gives guaranteed ε-optimal results with finite convergence. In ε-optimal solution, for any $\varepsilon > 0$, the ε-optimal algorithm guarantee the solution within ε of the optimal. We also compare the OAA algorithm with the GA. The results show that performance of the OAA is much better than the GA.

3) The ε-optimal solution is analyzed in detail with the help of simulation results.

Throughout this paper, we use $\boldsymbol{A}$, $\boldsymbol{a}$, and a to represent matrix, vector, and an element of a vector, respectively. This paper is organized as follows: The system model and problem statement are described in Section III. In Section IV, we present the JACMSPA solution technique using the OAA method. The simulation results are analyzed in Section V, and finally, we conclude this paper in Section VI.

III. System Model and Problem Formulation

We consider a cellular network having D2D communication capability as shown in Fig. 1. There are two possible modes of communication: 1) cellular mode and 2) D2D mode. We assume that the users selected for D2D communication use nonorthogonal sharing mode. In this mode, the D2D users will reutilize cellular network resources. Let $\mathcal{K}$ be the set of user pairs that want to communicate with one another. We denote by p_k^{ul}, p_k^{dl}, and p_k^d, the kth user's transmitted power in uplink (to eNB), respectively, the kth user's transmitted power in downlink (to the kth receiver), and the kth user power in D2D mode. The channel gain between the kth user pair is g_k. We denote h_k and f_k as the channel gains between transmitting user–eNB link (uplink) and eNB– receiving user (downlink), respectively. Let the antenna gain be G_o and $\xi = 10^{\tilde{\xi}_o/10}$ be the lognormal shadowing, where $\tilde{\xi_o}$ is zero-mean Gaussian random variable with standard deviation σ [36]. The channel h_k is modeled as [38]

$$h_k = \tilde{h_k} \xi G_o \left(\frac{d_o}{d}\right)^{\alpha} \tag{1}$$

where d_o and d are the antenna far-field reference distance and the distance between the receiver and transmitter, respectively. The path-loss exponent is denoted by α and $\tilde{h}_k$ is the Rayleigh random variable. The channel capacity of the kth user is defined as $C_k = \log(1 + (p_k h_k/N_0))$. A summary of symbol notations is shown in Table II. In cellular mode, the eNB will act like a relay, and the communication between the cellular user pair needs two time slots. The possible rate of the kth user in cellular mode is $C_k^c = 1/2 \min(C_k^{\mathrm{ul}}, C_k^{\mathrm{dl}})$. The rate for the kth pair in D2D communication is $C_k^d = \log(1 + (p_k^d g_k/N_0))$. For mode

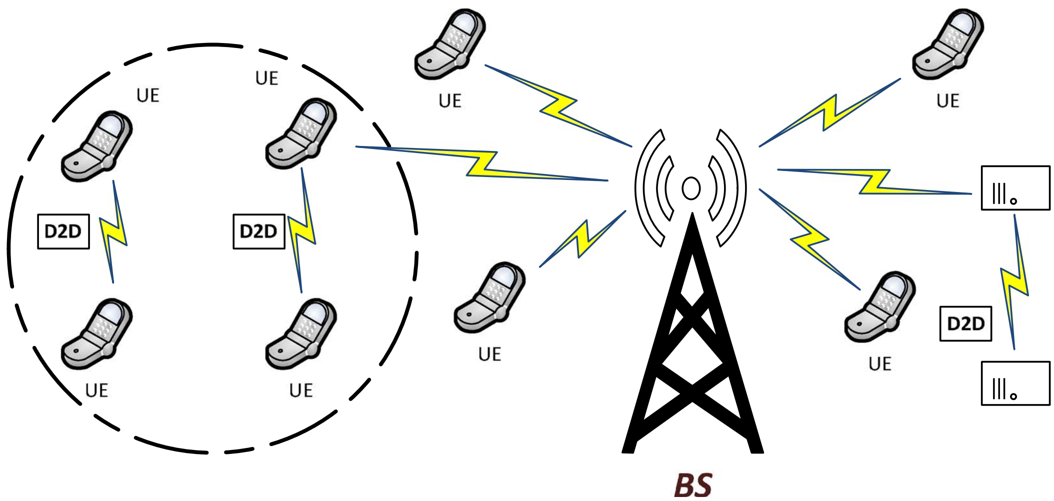

Fig. 1. Cellular system with D2D capability.

TABLE II
NOTATIONS

Symbol	Definition
$\mathcal{K}$	Set of user pairs
c	Cellular mode
d	D2D mode
R	Radius of D2D transmission
C_k^{ul}	Capacity of the kth cellular user in uplink
C_k^{dl}	Capacity of the kth cellular user in downlink
C_k^{c}	Capacity of the kth cellular user pair-i.e., $\frac{1}{2}\ min(C_k^{ul}, C_k^{dl})$
C_k^{d}	Capacity of the kth D2D users
P_{eNB}^{max}	Maximum power of eNB
$P_{c,k}^{max}$	Maximum power of the kth user in cellular mode
$P_{d,k}^{min}$	Minimum power threshold of the kth user in D2D mode outside radius R
p_k^d	Power of the kth in D2D mode
p_k^{ul}	Power of the kth in uplink cellular mode
p_k^{dl}	Power of the kth in downlink cellular mode
x_k	Binary indicator for D2D or cellular mode
C_k^{min}	Minimum rate requirement of the kth user
h_k	Channel gain between the kth user and eNB link (uplink)
f_k	Channel gain between the kth receiver and eNB link (downlink)
g_k	Channel gain between the kth D2D user pair
ϕ^c	Set of selected users in cellular mode
ϕ^d	Set of selected users in D2D Mode
ϕ	Set of all selected Users-i.e.,$\phi^c \cup \phi^d$
d_o	Reference distance for the antenna far field
d	Distance between secondary transmitter and receiver
$\tilde{h}_k$	Rayleigh random variable associated with the kth SU
ξ	Log normal shadowing
$\mathcal{U}$	A utility function to maximize the joint user admission and throughput
$\mathcal{U}_S$	A utility function to maximize the admitted users
$\mathcal{U}_T$	A utility function to maximize the throughput
p_c	Probability of cross over
p_m	Probability of mutation
p_s	Probability of selection

selection, we define a binary mode selection indicator as

$$x_k = \begin{cases} 1, & \text{Cellular mode} \\ 0, & \text{D2D mode.} \end{cases}$$

To meet the QoS of the kth user pair, the pair must satisfy its minimum rate $C_k^{\min}$. For any power constraint, a wireless network satisfying every user's rate requirement is not always possible.[3] Traditional admission control schemes generally select the users that can give higher aggregate throughput. In this paper, we propose a framework for joint admission control and mode selection that not only maximizes the throughput but also maximizes the number of admitted users under the minimum rate and power constraints. Let ϕ be the set of admitted users. One admitted user can only be served either in cellular or D2D mode, and the set of admitted users ϕ is the union of admitted cellular and D2D users. Mathematically, this is written as

$$\begin{aligned} &\phi = \phi^c \cup \phi^d \\ &\phi^c \cap \phi^d = \varnothing. \end{aligned} \tag{2}$$

We introduce a utility function that maximizes admitted users and throughput as

$$\mathcal{U}(\phi, \boldsymbol{x}, \boldsymbol{p^d}, \boldsymbol{p^{\text{ul}}}, \boldsymbol{p^{\text{dl}}}) = \mathcal{U}_S(\phi) \sum_{k\in\phi} \mathcal{U}_T\left(x_k, p_k^d, p_k^{\text{ul}}, p_k^{\text{dl}}\right) \tag{3}$$

where $\mathcal{U}_S = |\phi|/|\mathcal{K}|$ and $\mathcal{U}_T(x_k, p_k^d, p_k^{\text{ul}}, p_k^{\text{dl}}) = x_k C_k^c + (1 - x_k) C_k^d$. The utility function $U(\phi, \boldsymbol{x}, \boldsymbol{p^d}, \boldsymbol{p^{\text{ul}}}, \boldsymbol{p^{\text{dl}}})$ ensures that if cellular mode is selected for any admitted user, then the terms related to D2D mode should be zero and *vice versa*. Mathematically, we can write the JACMSPA-constrained optimization problem as

$$\begin{aligned} \max_{\phi, \boldsymbol{x}, \boldsymbol{p^d}, \boldsymbol{p^{\text{ul}}}, \boldsymbol{p^{\text{dl}}}} \quad & \mathcal{U}(\phi, \boldsymbol{x}, \boldsymbol{p^d}, \boldsymbol{p^{\text{ul}}}, \boldsymbol{p^{\text{dl}}}) \\ \text{subject to} \quad & \\ & \text{C1}: \mathcal{U}_T\left(x_k, p_k^d, p_k^{\text{ul}}, p_k^{\text{dl}}\right) \geq C_k^{\min} \quad \forall k \in \phi \\ & \text{C2}: p_k^d \leq (1 - x_k) R^\alpha P_{d,k}^{\min} \quad \forall k \in \phi \\ & \text{C3}: p_k^{\text{ul}} \leq x_k P_{c,k}^{\max} \quad \forall k \in \phi \\ & \text{C4}: \sum_{k\in\phi} x_k p_k^{\text{dl}} \leq P_{\text{eNB}}^{\max} \\ & \text{C5}: \phi = \phi^c \cup \phi^d \\ & \text{C6}: \phi^c \cap \phi^d = \varnothing \end{aligned}$$

[3]There are a number of reasons for this, e.g., a channel may be bad, a battery is low, the increase in power may increase interference to others, etc.

$$\begin{aligned}&\text{C7}: x_k \in \{0,1\} \quad \forall\, k \in \mathcal{K}\\ &\text{C8}: p_k^d \geq 0, p_k^{\text{ul}} \geq 0, p_k^{\text{dl}} \geq 0 \quad \forall\, k \in \mathcal{K}.\end{aligned} \tag{4}$$

The objective function in (4) is a max/min problem. By introducing a new variable $t_k, k \in \mathcal{K}$, we can rewrite an equivalent maximization problem as

$$\begin{aligned}\max_{t,\phi,\boldsymbol{x},\boldsymbol{p^d},\boldsymbol{p}^{\text{ul}},\boldsymbol{p}^{\text{dl}}} \quad & \mathcal{U}_t(\boldsymbol{t},\phi,\boldsymbol{x},\boldsymbol{p^d},\boldsymbol{p}^{\mathbf{ul}},\boldsymbol{p}^{\mathbf{dl}})\\ \text{subject to} \quad & \\ & \text{C1-C8 of (4)}\\ & \text{C9}: C_k^{\text{ul}} \geq t_k \quad \forall\, k \in \phi^c\\ & \text{C10}: C_k^{\text{dl}} \geq t_k \quad \forall\, k \in \phi^c\end{aligned} \tag{5}$$

where

$$\mathcal{U}_t(\boldsymbol{t},\phi,\boldsymbol{x},\boldsymbol{p^d},\boldsymbol{p}^{\mathbf{ul}},\boldsymbol{p}^{\mathbf{dl}}) = \mathcal{U}_S(\phi)\sum_{k\in\phi}\mathcal{U}_{T,t}\left(t,x_k,p_k^d,p_k^{\text{ul}},p_k^{\text{dl}}\right) \tag{6}$$

$$\mathcal{U}_{T,t}\left(t,x_k,p_k^d,p_k^{\text{ul}},p_k^{\text{dl}}\right) = x_k t_k + (1-x_k)C_k^d. \tag{7}$$

The utility function in the given optimization problem maximizes the admitted users and total throughput. Constraint C1 is the minimum rate constraint of each user. If any user cannot meet the rate constraint condition, then that user is not selected for transmission. Constraints C2–C4 are power constraints for D2D, cellular uplink, and cellular downlink modes, respectively. Constraint C2 ensures that, in the case of D2D communication, the power experienced by any other cellular or D2D user beyond radius R should be less than threshold power $P_{d,k}^{\min}$. Constraint C3 is the uplink power constraint, and C4 is the downlink sum-power constraint. Constraints C2–C4 ensure that the respective power should be zero if the respective mode is not selected. Constraints C5 and C6 ensure that D2D and cellular users are mutually exclusive.

The formulation in (5) is a nonconvex mixed-integer nonlinear programming problem. To prove the hardness of (5), we can reduce the multiple-choice multiple-dimensional knapsack problem (MCMDKP) to the JACMSPA optimization problem.

Theorem 1: JACMSPA for the D2D cellular network is NP-complete.

Proof: The proof is given in the Appendix.

Due to the NP-complete nature of JACMSPA, determining the optimal solution in polynomial time is not possible. An exhaustive search algorithm (ESA) for (5) would enumerate all the users and mode selection options, which increases its computational load exponentially with the number of users. The structure of the optimization problem in (5) is very interesting. With known discrete variables, the objective function of (5) is a concave function in power, and all the constraints are either linear or convex. By exploiting this special structure, in the following, we will present a branch-and-bound-based OAA to solve (5).

IV. Proposed Approach to a Solution

As mentioned earlier, the coupling of the integer domain, with the continuous domain and nonlinearities in the problem, make the class of problem mentioned in (5) very challenging. As the integer variables (user admission and mode selection in our case) increase, the complexity analysis results tend toward NP-completeness. Despite all these challenges, the optimization problem in (5) has a very special structure. By exploiting this special structure, here, we will present an OAA method to solve (5). The OAA solves (5) in a finite sequence of alternately nonlinear programming subproblems (by fixing the discrete variables ϕ and $\boldsymbol{x}$) and relaxation of a mixed-integer linear-programming-based master problem (MILP-MP). The solution of the subproblem provides a point that will generate supporting hyperplanes of the objective and constraint functions. The OAA method adds one linearization for each constraint and the objective function for every subproblem. These linearizations of the problem are collected in a MILP-MP. The solution of the master program determines a new set of discrete variables that will be used for the succeeding iteration [39].

A. Algorithm Description

Let us denote $\mathcal{U}_\psi$ as the set of constraints C1 to C10 in (5), $\mathcal{P} = \{\boldsymbol{t},\boldsymbol{p^d},\boldsymbol{p}^{\mathbf{ul}},\boldsymbol{p}^{\mathbf{dl}}\}$, and $\Theta = \phi \cup \boldsymbol{x}$. We can easily prove that (5) satisfies the following propositions.

Proposition 1: $\mathcal{P}$ is a compact, nonempty, and convex set, and the objective function $\mathcal{U}_t$ and $\mathcal{U}_\psi$ are convex in $\mathcal{P}$ for fixed values of Θ.

Proposition 2: $\mathcal{U}_t$ and $\mathcal{U}_\psi$ are once continually differentiable.

Proposition 3: A constraint qualification holds at the solution of each nonlinear continuous subproblem obtained by fixing the values of Θ.

Proposition 4: The nonlinear programming problem obtained by fixing Θ can be solved exactly.

Algorithm 1 OAA

$j \leftarrow 1$
Initialize Θ^j
$\varepsilon \leftarrow 10^{-3}$
Convergence $\leftarrow$ FALSE
while Convergence == FALSE **do**
  $\mathcal{P}^j \leftarrow \begin{cases}\arg\min_{\mathcal{P}} & -\mathcal{U}_t(\Theta^j,\mathcal{P})\\ \text{subject to} & \mathcal{U}_\psi(\Theta^j,\mathcal{P}) \leq 0;\end{cases}$
  UpperBound $\leftarrow \mathcal{U}_t(\Theta^j,\mathcal{P}^*)$
  $(\Theta^*,\mathcal{P}^*,\eta^*) \leftarrow \begin{cases}\arg\min_{\Theta,\mathcal{P},\eta} \eta\\ \text{subject to}\\ \eta \geq -\mathcal{U}_t(\Theta^j,\mathcal{P}^j)\\ -\nabla\mathcal{U}_t(\Theta^j,\mathcal{P}^j)\binom{\mathcal{P}-\mathcal{P}^j}{0}\\ \mathcal{U}_\psi(\Theta^j,\mathcal{P}^j)\\ -\nabla\mathcal{U}_\psi(\Theta^j,\mathcal{P}^j)\binom{\mathcal{P}-\mathcal{P}^j}{0} \leq 0\end{cases}$
  LowerBound $\leftarrow \eta$
  if UpperBound − LowerBound $\leq \varepsilon$ **then**
    Convergence $\leftarrow$ TRUE
  else
    $j \leftarrow j+1$
    $\Theta^j \leftarrow \Theta^*$
  end if
end while

These propositions make the problem in (5) a special class of problems that can be solved using OAA method [37]. The convexity of (5) ensures that the linearization of constraint and objective function produces outer approximation. Although the algorithm proposed in the later section is also applicable to nonconvex objectives, it can give a local optimal solution instead of a global optimal solution. Proposition 3 is useful as many nonlinear programming solvers use Kuhn–Tucker conditions, which require a constraint qualification to hold. The OAA uses a sequence of nonincreasing upper and nondecreasing lower bounds for mixed-integer problems that satisfy the Propositions 1–4. The OAA converges in a finite number of iterations with ε-convergence capability [39]. The sequence of upper and lower bounds are obtained by solving the primal and master problems, respectively. The primal problem is obtained by fixing Θ variables. At the jth iteration of OAA, let the values of integer variable be Θ^j. We can write the primal problem as

$$\begin{aligned} \min_{\mathcal{P}} \quad & -\mathcal{U}_t(\Theta^j, \mathcal{P}) \\ \text{subject to} \quad & \mathcal{U}_\psi(\Theta^j, \mathcal{P}) \leq 0. \end{aligned} \tag{8}$$

The solution of this problem will give the $\mathcal{P}^j$ that will be used for the master problem. The primal problem gives the upper bound, and the master problem will give the lower bound. The master problem is derived with the help of the primal solution, i.e., $\mathcal{P}^j$, and is based upon the linearization (outer approximation) of the nonlinear objective $\mathcal{U}_t$ and constraints $\mathcal{U}_\psi$ around the primal solution $\mathcal{P}^j$ [40], [41]. The solution of the master problem provides the information for the next set of integer variables Θ^{j+1}. As the iteration proceeds, these two bounds come close to each other. The algorithm will terminate when the difference between the two bounds is less than ε. The master problem is derived in two steps: In the first step, we need projection of (5) onto the integer space-Θ. We can rewrite the problem (5) as

$$\begin{aligned} \min_{\Theta} \min_{\mathcal{P}} \quad & -\mathcal{U}_t(\Theta^j, \mathcal{P}) \\ \text{subject to} \quad & \mathcal{U}_\psi(\Theta^j, \mathcal{P}) \leq 0. \end{aligned} \tag{9}$$

We can also write (9) as

$$\min_{\Theta} -\upsilon(\Theta) \tag{10}$$

where

$$\begin{aligned} \upsilon(\Theta) = \min_{\mathcal{P}} \quad & -\mathcal{U}_t(\Theta^j, \mathcal{P}) \\ \text{subject to} \quad & \mathcal{U}_\psi(\Theta^j, \mathcal{P}) \leq 0. \end{aligned} \tag{11}$$

Problem (10) is the projection of (5) on Θ space. Since a constraint qualification holds at the solution of every primal problem (8) for every Θ^j, the projection problem has the same solution as the problem in the following:

$$\begin{aligned} \min_{\Theta} \min_{\mathcal{P}} \quad & -\mathcal{U}_t(\Theta^j, \mathcal{P}^j) - \nabla\mathcal{U}_t(\Theta^j, \mathcal{P}^j) \begin{pmatrix} \mathcal{P} - \mathcal{P}^j \\ \Theta - \Theta^j \end{pmatrix} \\ \text{subject to} \quad & \mathcal{U}_\psi(\Theta^j, \mathcal{P}^j) - \nabla\mathcal{U}_\psi(\Theta^j, \mathcal{P}^j) \begin{pmatrix} \mathcal{P} - \mathcal{P}^j \\ \Theta - \Theta^j \end{pmatrix} \leq 0. \end{aligned} \tag{12}$$

By introducing a new variable η, we can rewrite an equivalent minimization problem as

$$\begin{aligned} \min_{\Theta, \mathcal{P}, \eta} \quad & \eta \\ \text{subject to} \quad & \eta \geq -\mathcal{U}_t(\Theta^j, \mathcal{P}^j) - \nabla\mathcal{U}_t(\Theta^j, \mathcal{P}^j) \begin{pmatrix} \mathcal{P} - \mathcal{P}^j \\ \Theta - \Theta^j \end{pmatrix} \\ & \mathcal{U}_\psi(\Theta^j, \mathcal{P}^j) - \nabla\mathcal{U}_\psi(\Theta^j, \mathcal{P}^j) \begin{pmatrix} \mathcal{P} - \mathcal{P}^j \\ \Theta - \Theta^j \end{pmatrix} \leq 0. \end{aligned} \tag{13}$$

This is the master problem used to generate lower bound. Under Propositions 1–3, (13) is equivalent to (5). Problem (13) is now a mixed-integer linear programming problem and can be solved using an iterative framework. A pseudocode for the OAA is given in Algorithm 1.

B Discussion on Algorithm Optimality and Convergence

If the problem holds all four propositions and the discrete variables (Θ) are finite, then the Algorithm 1 terminates in a finite number of steps at an ε-optimal solution [39]. As mention earlier, in a ε-optimal solution, for any $\varepsilon > 0$, ε-optimal algorithms guarantee the solution within the ε of optimal solution. Lower values of ε mean a high degree of accuracy. The main reason for the ε-optimal solution of OAA is its branch-and-bound-like architecture. In the branch-and-bound procedure, any combination of discrete variable (Θ in our case, which is the union of users and mode selection variable) will never be used twice. The optimality of $\mathcal{P}$ in (13) implies that η is greater than $\mathcal{U}_t(\Theta^j, \mathcal{P}^j)$ for any feasible point in (13). If the value of η is less than $\mathcal{U}_t(\Theta^j, \mathcal{P}^j)$, it means that the master problem has no feasible solution for the choice of discrete variables Θ^j. If there is no feasible solution for any particular Θ^j in (13), then the algorithm excludes that value of Θ^j from any subsequent master problems. It means that the algorithm is finitely converging. The optimality of the algorithm follows from the convexity of the objective and constraints for any fixed values of Θ. It is proven in the mixed-integer programming literature that the convergence rate of OAA is linear [41]. A detailed convergence proof of a general OAA algorithm is given in [37]. An ESA for (5) would enumerate all the user and mode selection options, which increases its computational load exponentially with the number of users. In this paper, we have compared the results of the proposed OAA with the ESA and GA. The simulation results show that the performance of the OAA is almost the same as the optimal solution obtained and the ESA and is better than the GA. One more advantage of the OAA is its guaranteed ε-optimal results. The problem with the GA is that it cannot guarantee any optimal or ε-optimal solution. The GA can give good results, but there is no proven convergence criterion for the GA, whereas the OAA has proven convergence to ε-optimal solution.

V. SIMULATION RESULTS

Here, we show simulation results to demonstrate the performance of the proposed OAA scheme. The results show the effect of the number of users on the total throughput and analyze the effectiveness of joint admission control and mode selection utility. The system parameters used in the simulation are shown in Table III. We use Basic Open-source Nonlinear Mixed INteger (BONMIN) Programming software for OAA. We compare the results of the OAA with the standard continuous GA [42].

TABLE III
SIMULATION PARAMETERS

Parameter	Value
P_{eNB}^{max}	{2,4}Watts
$P_{c,k}^{max}$	{0.5,0.75}Watts
$P_{d,k}^{min}$	100mW
C_k^{min}	{100,200}kbs
d_o	20
eNB coverage	1000m
d	Uniformly distributed distance
ξ_o	10dB
G_o	50
p_s	0.90
p_m	0.10
p_c	0.50

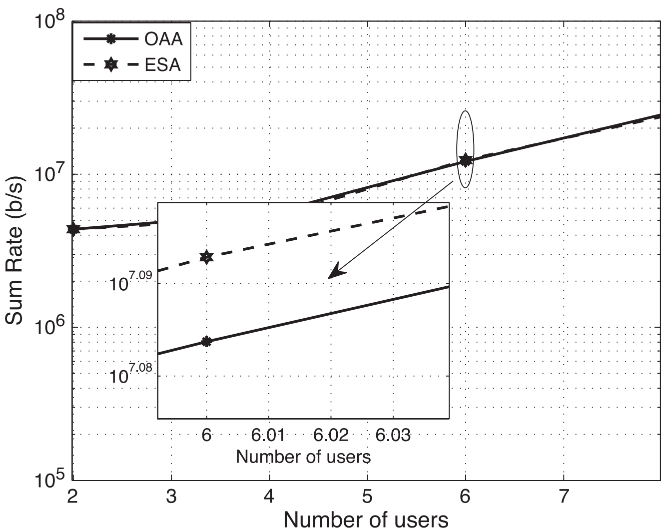

Fig. 2. Performance of OAA with an ESA for different numbers of users.

In the simulation, the eNB maximum coverage is set to 1000 m. The maximum eNB power $P_{\text{eNB}}^{\max}$ is set to {2,4} W. The coverage distance for D2D is 20 m. In cellular mode $P_{c,k}^{\max} = \{0.5, 0.75\}$ W. In all the simulation results, $d_o = 20$ m, $G_o = 50$, and $\xi_o = 10$ dB. We assume that distance d is greater than d_o. For convergence, ε is set to 0.00001. In all simulations, for GA, probability of crossover p_c, probability of mutation p_m, and probability of selection p_s are set to 0.9, 0.1, and 0.5, respectively. Elitist selection and uniform crossover rules with global best value adaptation are used to get high-quality GA solutions. We apply GA for discrete variables (user and mode selection), and for each realization of discrete variables, a conventional convex optimization algorithm is used to get the optimal power allocation. In the simulation results, $\mathcal{U}$ represents a utility function that jointly maximizes the throughput and users' admission considering mode selection, whereas $\mathcal{U}_T$ represents a utility function that only maximizes the throughput considering mode selection.

In Fig. 2, we compare the results of the optimal solution obtained by the ESA and OAA for different numbers of users. For the ESA approach, we need to 2^{2K} enumeration of discrete variables,[4] and for each realization of discrete variable, there is a need to solve one nonlinear convex optimization problem. The computational complexity of the ESA increases exponentially. This makes the ESA unsuitable for such kind of problems. The result in Fig. 2 shows that the performance of the OAA is almost similar to the optimal ESA. To get one result using the ESA required a lot of time; for brevity, we only present one result of ESA in this paper.

[4] K variables for admission control and K variables for mode selection.

Fig. 3(a)–(d) investigate the performance of the OAA and the GA for joint user and throughput maximization on the cellular network. Fig. 3(a) shows a plot of sum rate versus the number of users with the parameters $\{P_{\text{eNB}}^{\max}, P_{c,k}^{\max}\} = \{4, 0.5\}$ and {20, 2} W, respectively. The results present the comparison of different rate thresholds for a power-constraint cellular network with D2D capability using the OAA and GA. As there is an increase in the rate requirement, for same constraints, the sum-rate decreases. This is because a fewer number of users are admitted due to high rate requirement and stringent power constraint in D2D mode. In Fig. 3(c), we present the comparison results of the OAA and GA in terms of spectral efficiency, and in Fig. 3(d), we show the OAA and GA results for different data rates. All the results highlight the effectiveness of the OAA over the GA. This is because of ε-optimal nature of the OAA. Due to the stochastic nature of the GA, there is no guarantee that the GA will give an optimal solution.

Fig. 4(a)–(c) investigates the effect of joint user and throughput maximization (in log scale) on the cellular network. These figures compare the throughput obtained by users using $\mathcal{U}$ and $\mathcal{U}_T$ utilities. The straight horizontal line shows the rate requirement. In Fig. 4(a) with parameters $P_{\text{eNB}}^{\max} = 2$ W, $P_{c,k}^{\max} = 0.75$ W and $C_k^{\min} = 200$ kb/s, the performance of both utilities is almost same. The sum rate for $\mathcal{U}$ and $\mathcal{U}_T$ is the same. In the figure, the fifth user is not selected due to bad channel conditions.

In Fig. 4(b) and (c), we set the parameters as $P_{\text{eNB}}^{\max} = 2$ W, $P_{c,k}^{\max} = 0.5$ W, $C_k^{\min} = 100$ kb/s, and as $P_{\text{eNB}}^{\max} = 4$ W, $P_{c,k}^{\max} = 0.5$ W, $C_k^{\min} = 200$ kbps, respectively. In Fig. 4(b), we can see that six users are admitted with $\mathcal{U}$ utility, whereas only two users are selected for $\mathcal{U}_T$ utility. The sum- ate for $\mathcal{U} = 1.68$ Mb/s and $\mathcal{U}_T = 4.33$ Mb/s. Similarly for Fig. 4(c), four users are admitted with $\mathcal{U}$ utility, whereas three users are selected for $\mathcal{U}_T$ utility. The sum rate for $\mathcal{U} = 2.574$ Mb/s and $\mathcal{U}_T = 3.2$ Mb/s. We can see that although the sum rate for $\mathcal{U}_T$ is high, it is at the cost of a low number of admitted users.

Fig. 5(a)–(c) compare the throughput obtained by users using $\mathcal{U}$ and $\mathcal{U}_T$ utilities for 30 users with parameters as $P_{\text{eNB}}^{\max} = 4$ W, $P_{c,k}^{\max} = 0.75$ W, $C_k^{\min} = 100$ kb/s, $P_{\text{eNB}}^{\max} = 4$ W, $P_{c,k}^{\max} = 0.5$ W, $C_=200$ kb/s, and as $P_{\text{eNB}}^{\max} = 20$ W, $P_{c,k}^{\max} = 2$ W, $C_k^{\min} = 1$ Mb/s, respectively. Fig. 6 shows the effect of eNB coverage area to the throughput. In Fig. 5(a), 21 users are admitted with $\mathcal{U}$ utility, whereas only 18 users are admitted with $\mathcal{U}_T$ utility. With the increase in rate requirement for Fig. 5(b), 17 users are admitted with $\mathcal{U}$ utility, whereas only 13 users are admitted with $\mathcal{U}_T$ utility. We can conclude from the results that for the cellular system with D2D capability, joint admission control and mode selection add more fairness, as compared with the sum-rate maximization.

VI. CONCLUSION

In this paper, we have presented a computationally viable solution for solving the JACMSPA in D2D communications. We made use of the special structure of this problem to propose a

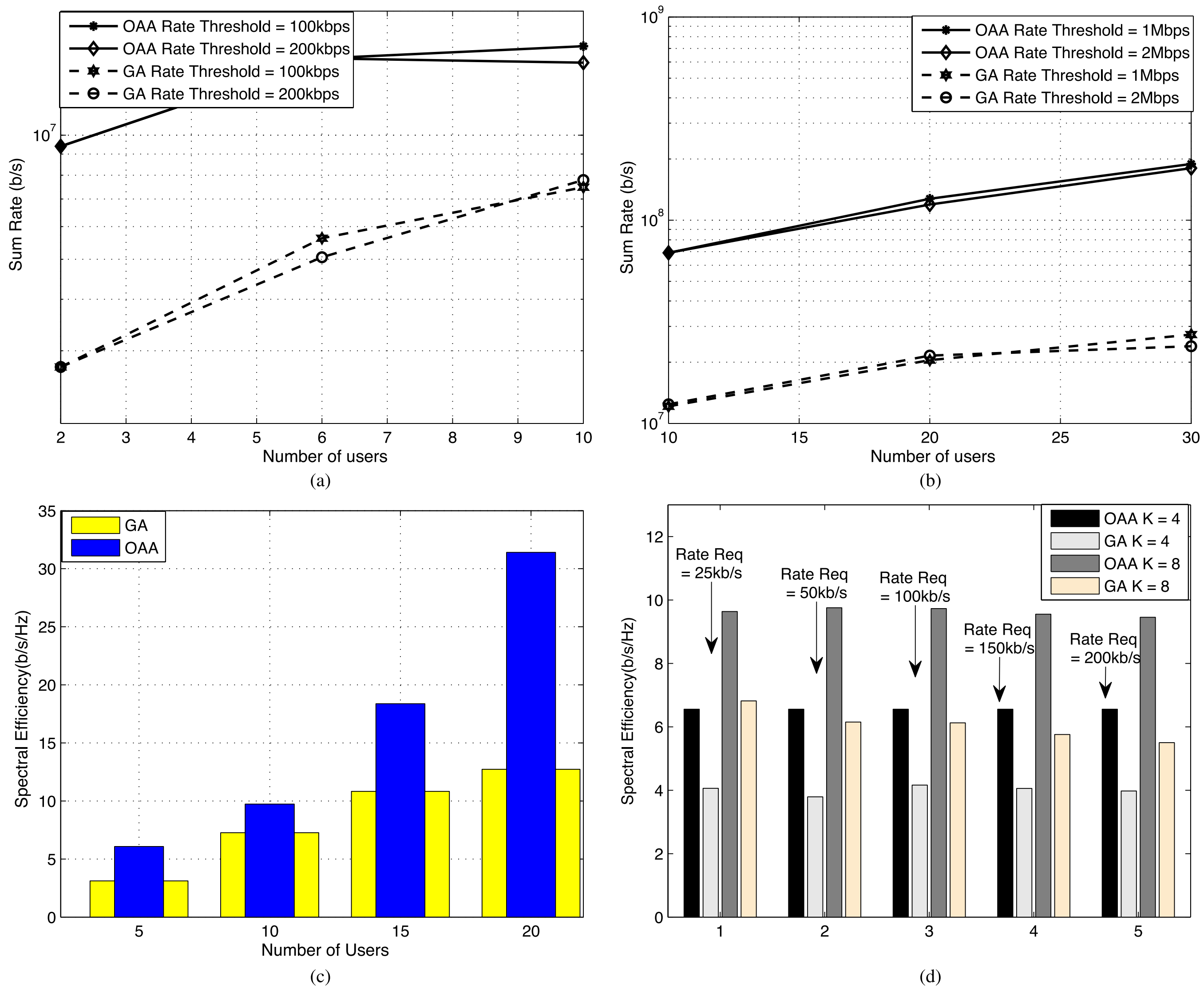

Fig. 3. Comparison of the OAA and GA. (a) Performance of OAA for different number of users with $P_{eND}^{\max} = 4$ W, $P_{c,k}^{\max} = 0.5$ W. (b) Performance of OAA for different number of users with $P_{eND}^{\max} = 20$ W, $P_{c,k}^{\max} = 2$ W. (c) Performance of OAA and GA for different number of users. (d) Performance of OAA and GA for different data rates.

solution based on branch-and-bound OAA. The proposed OAA method gives guaranteed ε-optimal results and has reasonable computational complexity. We verify the effectiveness of the proposed approach method by simulations that demonstrated the effect of number of users on the total throughput and also analyzed the effectiveness of joint admission control and mode selection utility.

Appendix
Proof of Theorem 1

We prove that, even with known uplink and downlink power, the joint admission control, network mode selection, and power allocation is an NP-complete problem. One example of known power is equal power distribution among selected users. We first show that the JACMSPA is equivalent to the 0-1 MCMDKP. We will start by describing the input and output formal description of the decision problem associated with MCMDKP and JACMSPA.

Problem 1: The MCMDKP problem is to select the items $x_{j,q}$ in disjoint classes to maximize the total profit such that an item can only be selected by at most one class subject to satisfaction of W resource constraints.

Instance: We have J disjoint classes, Q items, and W resource constraints (capacity of knapsack with W dimensions). The qth item of class j has profit $f_{j,q}$ and weight $w_{j,q}$ [43].

Output: We have a selection of items $\boldsymbol{X}$.

Decision Problem Associated With MCMDKP: The MCMDKP decision problem is to determine, for a given profit F, whether it is possible to load the multidimensional knapsack to keep the total weight in each dimension no greater than W, while making the total profit at least equal to F.

Problem 2: The JACMSPA problem is to select the disjoint subsets of users that are either using D2D or eNB for communication such that 1) the total data rate (sum capacity) of the system is maximized, and 2) the data rate of each selected user must be more than or equal to a predefined threshold.

Instance: We have number of users K; rate threshold $R_k, k = 1, 2, \ldots, K$; channel gains h_k, f_k, g_k of the kth user; and arbitrary users' power.

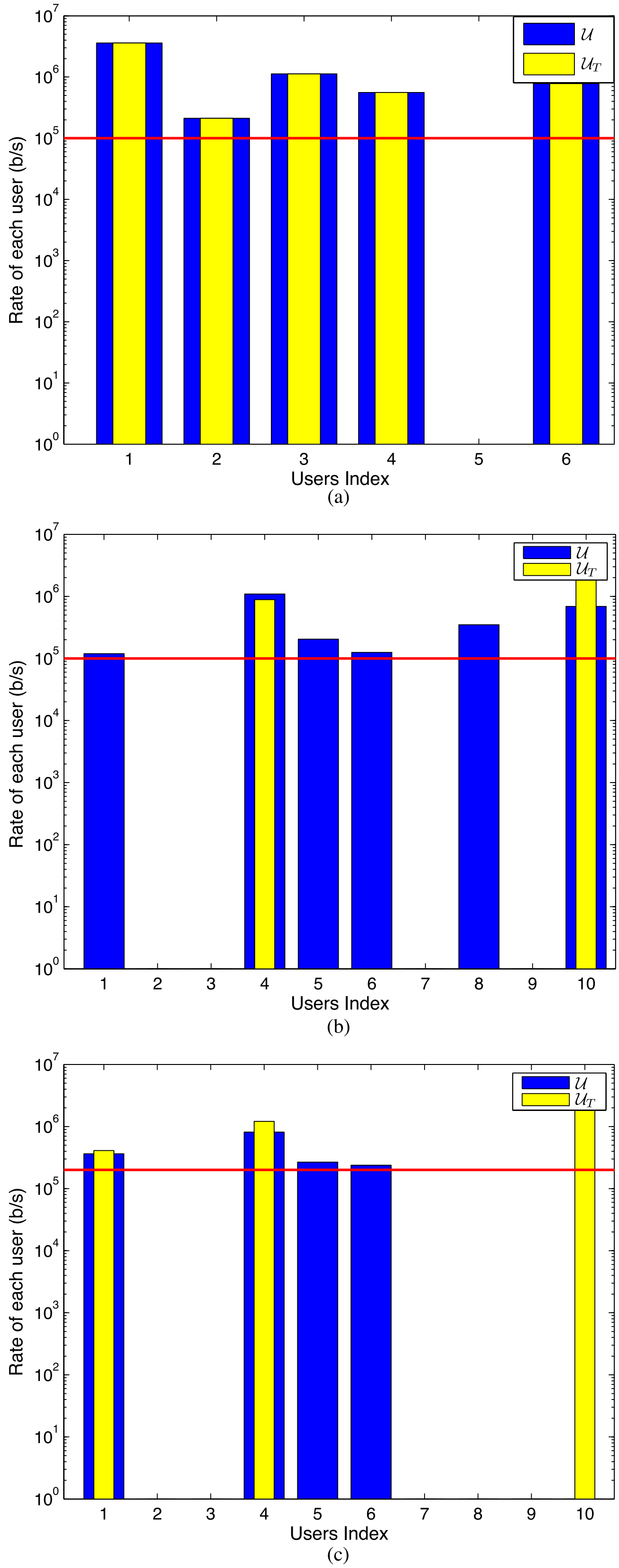

Fig. 4. Comparison of $\mathcal{U}$ and $\mathcal{U}_T$. (a) Comparison of $\mathcal{U}$ and $\mathcal{U}_T$ with $P_{eNB}^{\max} =$ 4 W, $P_{c,k}^{\max} = 0.5$ W, and $C_k^{\min} = 100$ kb/s. Sum-rate for $\mathcal{U}$ and $\mathcal{U}_T$ is the same. (b) Comparison of $\mathcal{U}$ and $\mathcal{U}_T$ with $P_{eNB}^{\max} = 2$ W, $P_{c,k}^{\max} = 0.5$ W, and $C_k^{\min} = 200$ kb/s. Sum-rate for $\mathcal{U} = 1.68$ Mb/s and $\mathcal{U}_T = 4.33$ Mb/s. (c) Comparison of $\mathcal{U}$ and $\mathcal{U}_T$ with $P_{eNB}^{\max} = 4$ W, $P_{c,k}^{\max} = 0.5$ W, and $C_k^{\min} = 200$ kb/s. Sum-rate for $\mathcal{U} = 2.574$ Mb/s and $\mathcal{U}_T = 3.2$ Mb/s.

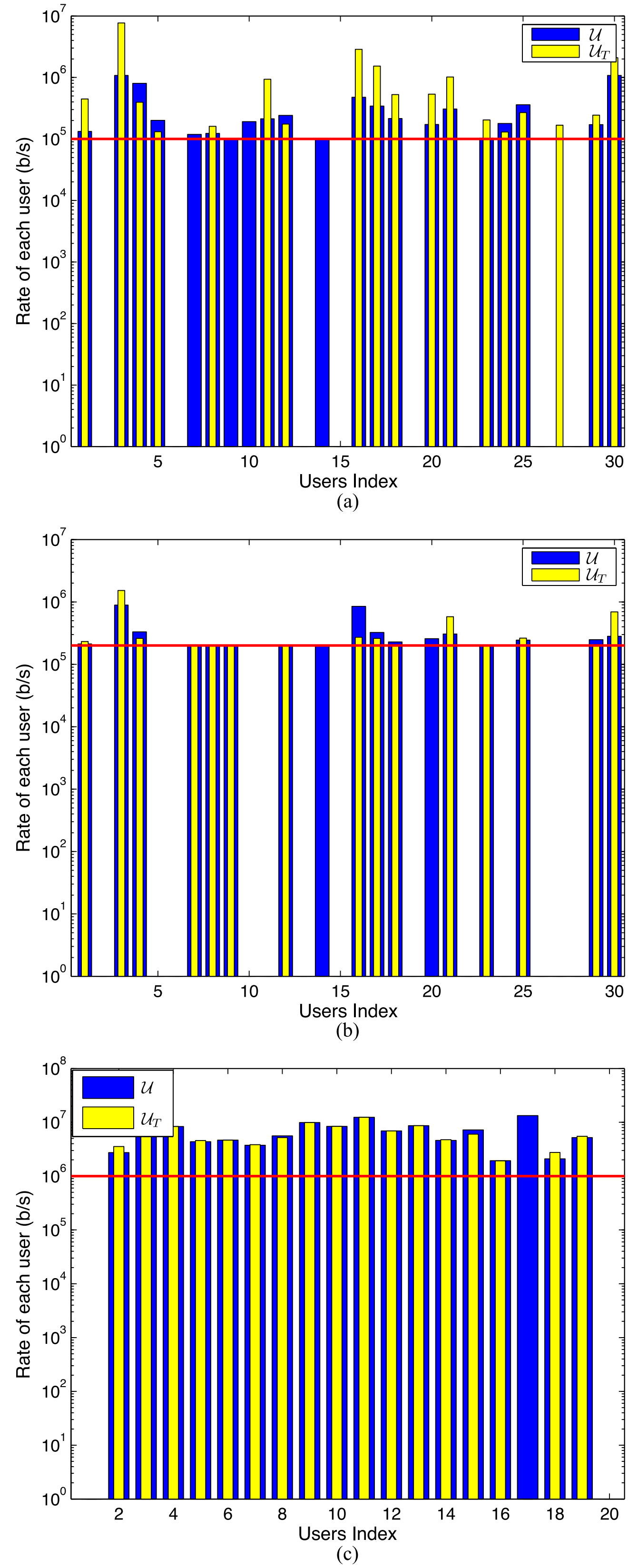

Fig. 5. Comparison of $\mathcal{U}$ and $\mathcal{U}_T$. (a) Comparison of $\mathcal{U}$ and $\mathcal{U}_T$ with $P_{eNB}^{\max} =$ 4 W, $P_{c,k}^{\max} = 0.75$ W, and $C_k^{\min} = 100$ kb/s. Sum-rate for $\mathcal{U} = 7.46$ Mb/s and $\mathcal{U}_T = 19.6$ Mb/s. (b) Comparison of $\mathcal{U}$ and $\mathcal{U}_T$ with $P_{eNB}^{\max} = 4$ W, $P_{c,k}^{\max} = 0.5$ W, and $C_k^{\min} = 200$ kb/s. Sum-rate for $\mathcal{U} = 6.18$ Mb/s and $\mathcal{U}_T = 6.38$ Mb/s. (c) Comparison of $\mathcal{U}$ and $\mathcal{U}_T$ with $P_{eNB}^{\max} = 20$ W, $P_{c,k}^{\max} =$ 2 W, and $C_k^{\min} = 1$ Mb/s. Sum-rate for $\mathcal{U} = 123$ Mb/s and $\mathcal{U}_T = 110.41$ Mb/s.

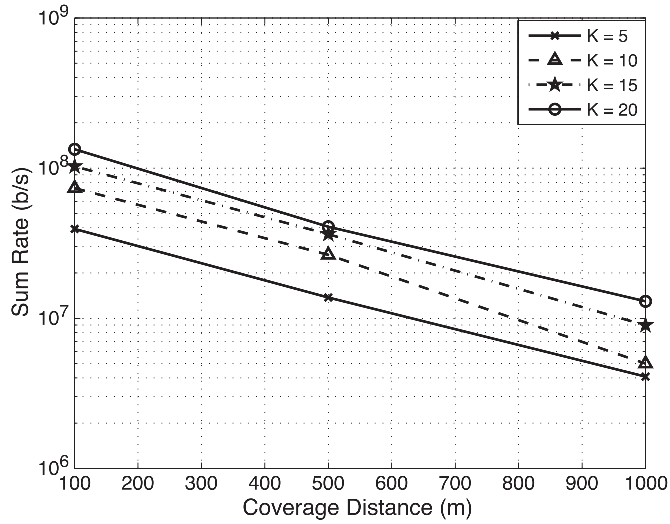

Fig. 6. Coverage distance versus sum throughput comparison for different numbers of users.

Output: We have a selection of users and their respective mode.

Decision Problem Associated With JACMSPA: The decision problem associated with the JACMSPA is to determine, for a given throughput C, whether it is possible to select multiple users with multiple modes (cellular or D2D) such that the rate of each selected users with any specific mode is more than R.

Lemma 1: The JACMSPA problem is polynomial-time verifiable.

Proof: We can easily observe that if we are given a set of selected users that represents the mapping between D2D and cellular modes, we can verify in polynomial time that the total throughput of the selected users is at least C and the rate of each selected user is more than R. Since the dimension of the matrix for users and mode selection is $2 \times K$, therefore, its length is polynomial in the size of the input. We can write an algorithm that can verify the result in $O(2K)$ iterations, which shows polynomial-time verification. ∎

Lemma 2: MCMDKP is polynomial-time reducible to JACMSPA.

Proof: We can do reduction by simple equivalence. We make the K users as disjoint classes and the items as mode. The R_k rate of selected users is the same as the capacity of knapsack with W dimensions. The channels h_k, f_k, and g_k are item profit. For any given instance $J, Q, W, f_{j,q}$ of MCMDKP, if there is a matrix X with entries of selected items $x_{j,q}$ that maximizes the total profit such that an item can only be selected by at most one class subject to satisfaction of W resource constraints, then there will be a user-mode selection matrix that maximizes the total data rate (sum capacity) of the system such that a user can only operate in one mode subject to rate constraint. This reduction by simple equivalence means every yes-instance of MCMDKP implies yes-instance of JACMSPA in polynomial time. ∎

Lemmas 1 and 2 imply the NP-completeness of JACMSPA.

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Mushtaq Ahmad received the B.Sc. degree in electrical engineering from the University of Engineering and Technology, Lahore, Pakistan, in 1990; the M.S. degree in electrical engineering from the University of Michigan, Ann Arbor, MI, USA, in 1994; and the Masters of Telecommunication Management degree from the Institut National Des Telecom France, Evry, France, in 1999. He is currently working toward the Ph.D. degree with COMSATS Institute of Information Technology, Wah Cantt, Pakistan.

He has served as an Incumbent Operator with Pakistan Telecommunication Company Limited; as a Regulator with the Pakistan Telecommunication Authority; as a Member (Telecom) with the Ministry of Information Technology and Communication, Pakistan; and as the Chief Executive Officer of reputable public and private institutions. He is currently a Principal Engineer with COMSATS Institute of Information Technology, Pakistan. His main research interests include resource allocation in next-generation networks.

Muhammad Naeem (S'09–M'12) received the B.S. and M.S. degrees in electrical engineering from the University of Engineering and Technology, Taxila, Pakistan, in 2000 and 2005, respectively, and the Ph.D. degree from Simon Fraser University, Burnaby, BC, Canada, in 2011.

From 2012 to 2013, he was a Postdoctoral Research Associate with WINCORE Laboratory, Ryerson University, Toronto, ON, Canada. Since August 2013, he has been an Assistant Professor with the Department of Electrical Engineering, COMSATS Institute of Information Technology, Wah Campus, Wah Cantt, Pakistan, and a Research Associate with WINCORE Laboratory, Ryerson University. From 2000 to 2005, he was a Senior Design Engineer with Comcept Pvt. Ltd. With the design department of Comcept Pvt. Ltd., he participated in the design and development of smart-card-based Global System for Mobile Communications and code-division multiple-access payphones. He is also a Microsoft Certified Solution Developer. His research interests include the optimization of wireless communication systems, nonconvex optimization, and resource allocation in cognitive radio networks and approximation algorithms for mixed-integer programming in communication systems.

Dr. Naeem received a Canada Graduate Scholarship from the Natural Sciences and Engineering Research Council of Canada.

Muhammad Iqbal was born on October 15, 1976 in Multan, Pakistan. He received the B.Sc. degree in electrical engineering from the University of Engineering and Technology, Lahore, Pakistan, in 1999; the M.S. degree in telecommunication engineering from the University of Engineering and Technology, Peshawar, Pakistan, in 2007; and the Ph.D. degree from Beijing University of Posts and Telecommunications, Beijing, China, in 2011.

After his undergraduate studies, he was with a state-owned telecommunication company for more than seven years. He is currently an Assistant Professor with the Department of Electrical Engineering, COMSATS Institute of Information Technology, Wah Campus, Wah Cantt, Pakistan. His research interests include signal and information processing, wireless communications, smart grid, and applied optimization.

Muhammad Azam received the B.Sc. degree in electronics engineering from the University of Engineering and Technology, Taxila, Pakistan, in 2012 and the M.Sc. degree in electrical engineering from COMSATS Institute of Information Technology, Islamabad, Pakistan, in 2015.

He is currently a Laboratory Engineer with the Department of Electrical Engineering, Foundation University Rawalpindi, Rawalpindi, Pakistan. His research interests include wireless communications, resource allocation in fifth-generation networks, optimization in energy-communication systems, smart grid, and related topics.

Ahmed Shaharyar Khwaja (M'13) received the B.Sc. degree in electronic engineering from Ghulam Ishaq Khan Institute of Engineering Science and Technology, Swabi Khabar Pakhtoon Khwa, Pakistan, and the M.Sc. and Ph.D. degrees in signal processing and telecommunications from the University of Rennes 1, Rennes, France.

He is currently a Postdoctoral Research Fellow with WINCORE Laboratory, Ryerson University, Toronto, ON, Canada. His research interests include compressed sensing, remote sensing, and optimization problems in wireless communication systems.

Alagan Anpalagan (SM'04) received the B.A.Sc., M.A.Sc., and Ph.D. degrees from the University of Toronto, Toronto, ON, Canada, all in electrical engineering.

Since 2001, he has been with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, where he was promoted to Full Professor in 2010. From 2004 to 2009, he served the department as a Graduate Program Director and, from 2009 to 2010, as an Interim Electrical Engineering Program Director. During his sabbatical (2010–2011), he was a Visiting Professor with the Asian Institute of Technology, Pathumthani, Thailand; and a Visiting Researcher with Kyoto University, Kyoto, Japan. His industrial experience includes working with Bell Mobility, Nortel Networks, and IBM Canada. He directs a research group working on radio resource management and radio access and networking areas within the WINCORE Laboratory, Ryerson University. He is the author or coauthor of three edited books: *Design and Deployment of Small Cell Networks* (Cambridge University Press, 2014), *Routing in Opportunistic Networks* (Springer, 2013), and *Handbook on Green Information and Communication Systems* (Academic Press, 2012). He also completed a course on Project Management for Scientists and Engineers with the Continuing Professional Development Center, University of Oxford, Oxford, U.K. His current research interests include cognitive radio resource allocation and management, wireless cross-layer design and optimization, cooperative communication, machine-to-machine communications, small-cell networks, and green communication technologies.

Dr. Anpalagan served as the IEEE Communication Society Toronto Chapter Chair from 2004 to 2005, the IEEE Toronto Section Chair from 2006 to 2007, and the IEEE Canada Professional Activities Committee Chair from 2009 to 2011, and the IEEE Canada Central Area Chair from 2013 to 2014. He served as the Technical Program Committee (TPC) Cochair for the 2005 International Conference on Wireless Networks, Communications, and Mobile Computing Symposium on Radio Resource Management; the 2004 and 2008 IEEE Canadian Conference on Electrical and Computer Engineering; the 2011 IEEE International Wireless Communications and Mobile Computing Conference Workshop on Cooperative and Cognitive Networks; the Cognitive Radio and Spectrum Management TPC of the 2011 IEEE International Symposium on Personal, Indoor, and Mobile Radio Communication; and the Wireless Networks TPC of the 2012 IEEE International Symposium on Wireless Personal Multimedia Communications. He served as an Editor for *EURASIP Journal of Wireless Communications and Networking* from 2004 to 2009 and as an Associate Editor for IEEE COMMUNICATIONS LETTERS from 2010 to 2013 and has been serving as an Associate Editor for *Springer Wireless Personal Communications* since 2009 and for IEEE COMMUNICATIONS SURVEYS & TUTORIALS since 2012. He also served as a Guest Editor for two *EURASIP Special Issues on Radio Resource Management in 3G+ Systems* (2006) and *Fairness in Radio Resource Management for Wireless Networks* (2008) and *MONET Special Issue on Green Cognitive and Cooperative Communication and Networking* (2012). He received the Faculty Scholastic, Research, and Creativity Award and the Faculty Service Award in 2010, as well as the Dean's Teaching Award in 2011, from Ryerson University. He is a registered Professional Engineer in the province of Ontario, Canada.

Saad Qaisar (SM'14) received the Master's and Ph.D. degrees in electrical engineering from Michigan State University, East Lansing, MI, USA, in 2005 and 2009, respectively, under the supervision of Dr. H. Radha.

He is currently serving as an Assistant Professor with the School of Electrical Engineering Computer Science, National University of Sciences and Technology (NUST), Karachi, Pakistan. He is the Lead Researcher and Founding Director of the Research Laboratory of Communications, Networks and Multimedia (CoNNekT Lab), NUST. As of September 2011, he has been the Principal Investigator or Joint Principal Investigator of multiple research projects spanning cyber–physical systems, applications of wireless sensor networks, network virtualization, communication and network protocol design, wireless and video communications, Internet measurements analysis, and multimedia coding and communications. He is the author of over 50 papers presented at reputed international venues. He is the Lead Researcher on a joint Internet performance measurement study in Pakistan with the Georgia Institute of Technology, the current Head of a core working group for the establishment of Pakistan IXP, the Technical Consultant to the United Nations Food and Agriculture Organization, and the Lead Architect for a Pakistan Laboratory Information Management System project. He is actively engaged with projects funded by King Abdullah City of Science Technology.

Dr. Qaisar serves as the Chair for the Mobile Computing, Sensing, and Actuation for Cyber Physical Systems (MSA4CPS) Workshop, in conjunction with the International Conference on Computational Science and Its Applications.