Telecommunication Systems (2020) 74:129–143
https://doi.org/10.1007/s11235-019-00643-y

Energy-efficient RRH-association and resource allocation in D2D enabled multi-tier 5G C-RAN

Sher Ali[1] · Ayaz Ahmad[1] · Yasir Faheem[2] · Muhammad Altaf[1] · Habib Ullah[3]

Published online: 20 December 2019

Abstract
The device-to-device (D2D) enabled cloud radio access network (C-RAN) is considered as a promising network model which provides high data rate and energy efficiency. In this paper, we formulate a joint mode selection, subchannel assignment (SA), power allocation (PA) and remote radio head (RRH)-association problem in D2D enabled single carrier frequency division multiple access based C-RAN in the uplink. This problem is mixed-integer non-linear problem which is extremely difficult to solve in its original form. To solve this problem, we propose an iterative technique which solves this problem in two stages; mode selection stage and joint SA, PA and RRH-association (SAPARA) stage. For mode selection, a link quality based technique is presented while, for joint SAPARA, we developed an iterative technique that solves this this problem in three steps such that SA and PA are carried out in the first and second step, respectively, while RRH-association is performed in the third step. Our results show the efficiency of the presented techniques.

1 Introduction

The evolving fifth-generation (5G) cellular networks are intended to overcome the basic challenges of current cellular networks, e.g., higher data-rates, lower latency, network capacity and energy-efficiency (EE). To meet these challenges, 5G networks need to adopt a multi-tier architecture containing different network tiers e.g., macrocells, different types of licensed small cells and device-to-device (D2D) communication to serve their intended users with different quality of service (QoS) demands in an energy-efficient and spectrum-efficient way. The coexistence of different network tiers can be more beneficial if they share the same resources. But, the coexistence of these tiers and sharing the same resources among them may result in severe interference which may degrade the performance of 5G networks. Therefore, a well capable centralized mechanism is required which can efficiently allocate resources to different network tiers in order to achieve the envisioned goals of 5G. To this end, cloud radio access networks (C-RANs) have been presented as an effective solution to provide EE, and to tackle the exponential rise in mobile data requirements caused by rate greedy applications in the fifth-generation (5G) wireless networks [1]. C-RANs have three main components: remote radio heads (RRHs) positioned at the remote locations, with main responsibility of transmitting radio signals to end users; base-band units (BBUs) pool in a cloud center equipped with efficient processors; and a high-bandwidth transport network [2]. The RRHs and BBU-pool are interconnected through the fronthaul links while the connection between cloud and core network is called Backhaul as shown in Fig. 1. The basic purpose of C-RAN is to isolate the RRHs from the BBUs and shift the latter to a cloud center. This makes the RRHs light-weight and allows them to be placed anywhere. C-RANs can provide high EE, improved network-capacity, high network sum-rate, high spectral efficiency and reduced

✉ Ayaz Ahmad
ayaz.uet@gmail.com

Sher Ali
malaksherkhan@yahoo.com

Yasir Faheem
fahim.yasir@gmail.com

Muhammad Altaf
mohammadaltaf@gmail.com

Habib Ullah
h.ullah@uoh.edu.sa

1 Department of Electrical and Computer Engineering, COMSATS University Islamabad, Wah Campus, Wah Cantt., Pakistan

2 Department of Computer Science, COMSATS University Islamabad, Islamabad Campus, Islamabad, Pakistan

3 College of Computer Science and Engineering, University of Ha'il, Hail, Saudi Arabia

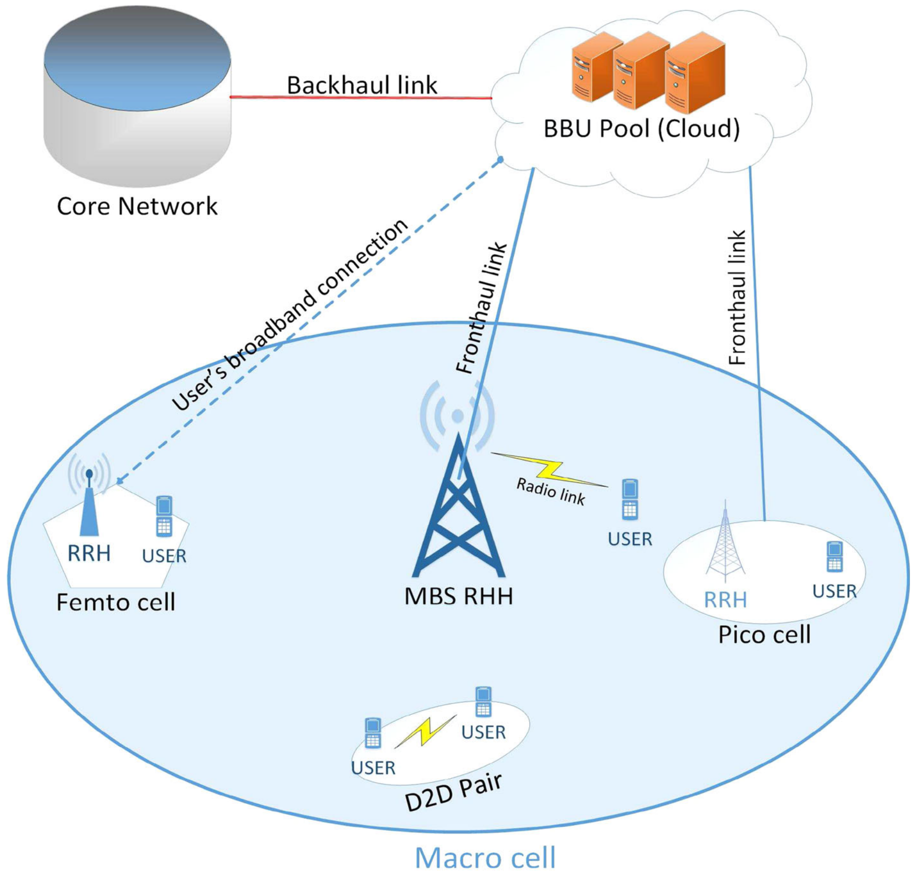

Fig. 1 Multi-tier C-RAN

operating expenditures. D2D communications can be integrated into C-RANs as D2D communications bring direct transmission between physically proximate users which can improve the system's EE, spectrum-efficiency and data rate [3]. However, integrating C-RAN and D2D communications poses many challenges in the designing of resource allocation (RA) techniques owing to the dense deployment of RRHs and sharing the same spectrum. Both the EE and QoS are challenged by the severe intra and inter-tier interferences. Without efficient RA schemes, the expected gains offered by such a multi-tier network may not be practically achievable.

Single Carrier Frequency Division Multiple Access (SC-FDMA) has been considered as a suitable multiple-access technique in the uplink (UL) by the Third Generation Partnership Project-Long Term Evolution - Advanced (3GPP-LTE-A) [4]. SC-FDMA has basically replaced the orthogonal frequency division multiple access (OFDMA) as an UL multiple access technique. OFDMA-based networks face high peak-to-average power ratio (PAPR), therefore, a substantial research is going on to reduce the effect of high PAPR [5]. Contrarily, SC-FDMA results in lower PAPR leading to the transmit-power efficiency of the mobile device. SC-FDMA uses frequency domain equalization and single-carrier modulation. Both of the multiple access techniques are similar in overall performance and structure but, unlike the OFDMA which transmits the orthogonal subchannels in parallel, SF-FDMA brings the sequential transmission of subchannels. This sequential transmission substantially decreases the envelope variations in transmitted waveform which results in lower PAPR [6]. SC-FDMA has two types: localized-FDMA and interleaved-FDMA. In localized-FDMA, subchannels assigned to a user are contiguous while in interleaved-FDMA, users are assigned with subchannels spread over the full frequency-band [6]. In 3GPP-LTE/LTA-A, the current working supposition is to utilize localized-FDMA and OFDMA for UL and downlink (DL), respectively [7].

2 Related work and contribution

Recently, considerable works have been carried out on the problems associated to RA in D2D communications enabled cellular systems. To this end, the authors in [8] and [9] developed a simple power control and SA algorithms, respectively, for D2D enabled cellular systems to mitigate the interference among D2D users reusing the same subchannels. The authors in [10] presented an efficient RA algorithm for EE maximization in D2D communications enabled cellular systems.

The RA techniques in [8–10] are developed under the supposition that all the D2D pairs are already in D2D mode.

However, to make the co-existence of D2D communication and cellular network more effective, mode selection plays a vital role in such systems because it can additionally enhance the system performance. Thus, mode selection has been taken into account by researchers while developing RA techniques for D2D communications enabled cellular systems [11–14] and joint mode selection and RA (JMSRA) techniques have been studied where mode selection describes that the users in a potential D2D pair can communicate directly or through a base-station. The authors in [11] formulated a JMSRA problem for the system throughput maximization subject to the minimum data rate guarantee, and solved this JMSRA problem using a algorithm based on particle swarm optimization. In [12], the JMSRA problem is decomposed into two sub-problems, and a tabu-Search meta-heuristic based algorithm is applied to find the most beneficial mode of communication. The authors in [13] studied a JMSRA problem which is then decoupled into joint SA and mode selection, and power allocation (PA) sub-problems. The former is solved using high complexity branch-and-bound (B&B) method. To avoid the complexity of B&B method, alternative techniques are modeled by taking the system load into consideration.

The works in [11–14] are based on OFDMA based HetNets where the macro base-station becomes overloaded with the densification of small cells and D2D pairs. Therefore, due to the computational efficiency of C-RANs, the authors studied JMSRA in [15–18] for OFDMA based C-RANs. The authors in [15] presented a stochastic optimization based RA problem for D2D communication underlaying C-RAN. In [16], the authors considered a C-RAN with non-uniformly placed D2D users, where D2D mode is selected if the users are located outside a defined circle from any RRH. Based on the analytical model presented in this work, user's average ergodic rate and coverage are characterized. By specifying the exclusion area properly, the presented non-uniform D2D placement outperformed the uniform D2D placement. A game-theoretic algorithm is developed in [17,18] for JMSRA in a D2D enabled UL C-RAN to enhance the system spectral-efficiency.

In [19] and [20], a single-cell OFDMA based underlaying system is considered and a JMSRA technique is presented for sum-rate maximization. The single cell scenario in [19] and [20] is extended in [21] where a multi-cell RA technique based on Dynamic Interference Limitation-Region is presented to avoid the interference between cellular and D2D users. Initially, the dynamic interference limitation-area is found. Then, for the inter-area interference, a priority-based Fraction Frequency Reuse technique is used to find the reuse. Finally, the simulation outcomes illustrate that the presented technique can dynamically assign resources without limiting the number of reusable resources of D2D users, thus effectively increasing the system capacity. [22] considered the RA problem as a coalition formation game in the D2D communication underlaying cellular networks. The objective of this work is sum-rate maximization subject to ensure the minimum rate of each user. In [23], the authors studied cooperative D2D communication in an UL cellular network where D2D users act as relays for cellular users. The outage probability of a cellular user is derived followed by the achievable rate from a D2D receiver from D2D transmitter in analytic form. Finally, the SA and PA are obtained to maximize the sum-rate under the outage probability constraint. While, [24] studied dynamic RA in a DL to maximize EE of the cellular users served by either macrocells or small cells, while assuring a minimum QoS for the D2D users.

The authors in [25–27], and [28] studied distributed RA techniques , where in [25], a distributed multi-agent learning based SA technique is presented. The presented technique enables D2D users to attain spectrum efficiency and higher throughput, low outage ratio, and improved computational efficiency in comparison to distance based resource criterion. Another distributed JMSRA technique is presented in [26] for potential D2D pairs in C-RAN, in which users' pairs are capable of decision-making. The presented technique is sub-divided into three stages: transmission mode and SA, utility value determination, and strengthening the learning based approach update. The core idea is that D2D pairs self-optimize the mode selection and RA without global channel state information under several practical limitations. In [27], a distributed RA technique based on matching theory is presented to minimize the interferences between cellular and D2D users, and improve the QoS. It is verified through simulation that the presented technique achieves fast convergence. The authors in [28] considered the resource block allocation problem in the UL of a D2D enabled HetNets. Exploiting the framework of potential games, they studied combinatorial problem of sum-rate maximization in an interference-limited network. Precisely, they developed a distributed solution based on a max-sum message passing technique that promises the convergence to a local optimum.

2.1 Contributions

The above mentioned works in [8–28] on mode selection and RA utilized OFDMA as multiple access technique in UL or DL for different objectives. But, Energy-efficient RA in D2D enabled C-RANs using SC-FDMA in the UL is not yet studied. Therefore, we consider the D2D communications as an underlay to the C-RANs using SC-FDMA in the UL and present a mode selection and RA technique which performs joint mode selection, SA, PA and RRH-association. The objective of this work is EE maximization. The formulated JMSPR problem is intractable in its original form. Therefore, this problem is solved in two stages; mode selection stage and joint SA, PA and RRH-association (SAPARA) stage. For mode selection, a link quality based technique is developed while, for joint SAPARA, we develop a technique which iteratively solves this MINLP problem in three steps such that SA is executed in the first step, PA in the second step and RRH-association in the third step. In addition, we present two techniques for SA namely, individual subchannel assignment (ISA) and subchannels block assignment (SBA) techniques.

2.2 Organization of the paper

The remaining sections are managed as follows. Section 2 contains the system model and problem formulation. Sections 3 and 4 contain the presented three steps RA technique and simulation results, respectively. Section 5 contains the conclusion of this paper.

3 System model and problem formulation

System model and problem formulation are presented in the following two sub-sections, respectively.

3.1 System model

We consider a D2D enabled multi-tier C-RANs using SC-FDMA in the UL which has a single BBU pool, M RRHs including one macrocell RRH, $(M-1)/2$ picocell-RRHs and $(M-1)/2$ femtocell-RRHs, C C-RAN transmitters and D potential D2D pairs. There are total 4 communication tiers in the system including macrocell tier, picocell tier, femtocell tier and D2D communication tier as shown in Fig. 1. The set of potential D2D pairs is represented by $\mathcal{D} = \{1, 2, \ldots, D\}$ where each pair consists of a transmitter $T_x(d)$ and a receiver $R_x(d)$ which communicate either in D2D mode or in C-RAN mode while the set of C-RAN transmitters is represented by $\mathcal{C} = \{1, 2, 3, \ldots, C\}$ which use conventional cellular communication. Furthermore, $\mathcal{U}$ is the set of all the users including C-RAN users and potential D2D users. In addition, $\mathcal{N} = \{1, 2, \ldots, N\}$ is the available set of subchannels which is reused by all the RRHs and D2D transmitters in the system. B and W are the total bandwidth of the system and bandwidth of each subchannel, respectively. It is assumed that each C-RAN transmitter is associated to a single RRH and multiple adjacent subchannels can be allocated to a transmitter u if its transmit power lies below the transmitter's maximum transmit-power represented by p_u^{max}.

Let $p_{d,n}$ be the transmit-power of D2D transmitter d on subchannel n, $h_{d,d}$ be the channel gain between D2D transmitter and receiver, $h_{u,d}^n$ be the channel gain from user u to receiver d on subchannel n and σ^2 be the noise at D2D receiver d. Then, SINR of D2D transmitter d on subchannel n in D2D mode is modeled as follows

$$\gamma_d^{n,D2D} = \frac{p_{d,n}|h_{d,d}|^2}{\sigma^2 + \sum_{u\epsilon\mathcal{U},u\neq d} p_{u,n}|h_{u,d}^n|^2} \tag{1}$$

The total SINR of transmitter d is formulated as follows [29]

$$\Gamma_d^{D2D} = \frac{1}{|N_d|}\sum_{n\epsilon N_d}(\gamma_d^{n,D2D}) \tag{2}$$

where $|N_d|$ is the cardinality of the set of subchannels assigned to the D2D transmitter d.

The achievable data rate of D2D transmitter d in D2D mode is given as follows [29]

$$R_d^{D2D} = W|N_d|\log_2\left(1+\Gamma_d^{D2D}\right) \tag{3}$$

When transmitter d chooses C-RAN mode, it would transmit to RRHs and the SINR of transmitter d on subchannel n to RRH m in C-RAN mode is modeled as follows

$$\gamma_d^{n,C-RAN} = \frac{p_{d,n}|h_{d,m}^n|^2}{\sigma^2 + \sum_{u\epsilon\mathcal{U},u\neq d} p_{u,n}|h_{u,m}^n|^2} \tag{4}$$

where $p_{d,n}$ is the transmit-power of transmitter d on subchannel n while $h_{d,m}^n$ and $h_{u,m}^n$ are the channel-gains of transmitters d and u, respectively, to RRH m on nth subchannel.

The total SINR of transmitter d in C-RAN mode is given as follows

$$\Gamma_d^{C-RAN} = \frac{1}{|N_{d,m}|}\sum_{n\epsilon N_{d,m}}(\gamma_d^{n,C-RAN}) \tag{5}$$

The attainable data rate of transmitter d in bits/sec on n to m in C-RAN mode [34] is presented as follows

$$R_{d,m}^{C-RAN} = W|N_{d,m}|\log_2\left(1+\Gamma_d^{C-RAN}\right) \tag{6}$$

The SINR of C-RAN user c connected to m on n [34] is expressed as follows

$$\gamma_{c,m}^n = \frac{p_{c,n}|h_{c,m}^n|^2}{\sigma^2 + \sum_{u\epsilon\mathcal{U},u\neq c} p_{u,n}|h_{u,m}^n|^2} \tag{7}$$

while similar to the Γ_d^{D2D} and Γ_d^{C-RAN}, the total SINR of user c is expressed as follows

$$\Gamma_c = \frac{1}{|N_{c,m}|}\sum_{n\epsilon N_{c,m}}(\gamma_{c,m}^n) \tag{8}$$

The attainable data rate of C-RAN user c associated to m [34] is expressed as follows

$$R_{c,m} = W|N_{c,m}|\log_2\left(1+\Gamma_c\right) \tag{9}$$

EE is the number of bits sent per unit energy on transmitter end. In our case, the network sum EE comprises of the EE of potential D2D transmitters functioning in D2D mode denoted by η_d^{D2D}, the EE of potential D2D transmitters functioning in C-RAN mode denoted by $\eta_{d,m}^{C-RAN}$ and the EE of C-RAN transmitters denoted by $\eta_{c,m}$. The EE of potential D2D transmitters in D2D mode can be mathematically expressed as follows

$$\eta_d^{D2D} = \frac{R_d^{D2D}}{P_d^T} \tag{10}$$

where P_d^T represents the energy consumption of user transmitter d in D2D mode, which is the total transmit-powers on all the subchannels assigned to it denoted by $\sum_{n\epsilon N_d} p_{d,n}$ and the circuit energy consumptions denoted by p_d^{ckt} [30]. p_d^{ckt} is experienced by various active circuit-blocks and signal processing at the transmitter and consists of two types of powers, static power consumption denoted by p_d^s and dynamic power of transmitter d in D2D mode denoted by εR_d^{D2D} [30]. The circuit energy consumptions can be modeled as below

$$p_d^{ckt} = p_d^s + \varepsilon R_d^{D2D} \tag{11}$$

where ε shows the dynamic power consumed per unit rate. The EE of D2D transmitter in D2D mode can be formulated as below

$$\eta_d^{D2D} = \frac{R_d^{D2D}}{\xi\sum_{n\epsilon N_d} p_{d,n} + p_d^s + \varepsilon R_d^{D2D}} \tag{12}$$

where ξ represents the drain efficiency of the power amplifier. Similarly, $\eta_{d,m}^{C-RAN}$ and $\eta_{c,m}$ [30,35] can be formulated as in the following two equations, respectively.

$$\eta_{d,m}^{C-RAN} = \frac{R_{d,m}^{C-RAN}}{\xi\sum_{n\epsilon N_{d,m}} p_{d,n} + p_{d,m}^s + \varepsilon R_{d,m}^{C-RAN}} \tag{13}$$

$$\eta_{c,m} = \frac{R_{c,m}}{\xi\sum_{n\epsilon N_{c,m}} p_{c,n} + p_{c,m}^s + \varepsilon R_{c,m}} \tag{14}$$

We introduce mode selection and RRH-association matrices in the following two equations, respectively.

$$x_d = \begin{cases} 1, & \text{if transmitter } d \text{ selects D2D mode} \\ 0, & \text{if transmitter } d \text{ selects C-RAN mode} \end{cases} \tag{15}$$

$$\alpha_{c,m} = \begin{cases} 1, & \text{if transmitter } c \text{ is connected to RRH } m \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

Based on the above assumptions, the JMSPR problem is formulated in the following sub-section.

3.2 Joint mode selection, subchannel assignment, power allocation and RRH-association (JMSPR) problem

In this section, we formulate the JMSPR problem for EE maximization in the UL of a multi-tier C-RAN system. This work considers RA in UL because RA in DL has been widely studied in the literature, while RA in UL has not yet attracted the significant number of researchers. In addition, this work considers SC-FDMA based C-RAN, while SC-FDMA has been used by 3GPP-LTE-A as a suitable multiple access technique for the UL, and OFDMA for the DL. This is because; OFDMA suffers from high envelope variations hence leading to higher PAPR than SC-FDMA. The lower PAPR characteristics of SC-FDMA is likely to benefit the user equipment in terms of transmit power efficiency. Therefore, SC-FDMA is currently appealing consideration as a multiple access technique in the uplink. The JMSPR problem is formulated as follows:

$$\max_{N_c^m, x_d, \alpha_{c,m}, p_{u,n}, \alpha_{d,m}} \sum_{m=1}^{M}\Bigg[\sum_{c=1}^{C}\alpha_{c,m}\eta_{c,m} + \sum_{d=1}^{D}\Big\{x_d\eta_d^{D2D}$$
$$+(1-x_d)\alpha_{d,m}\eta_{d,m}^{C-RAN}\Big\}\Bigg] \tag{17}$$

$$s.t.\ \sum_{n\epsilon N_{u,m}} p_{u,n} \le p_u^{max}, \forall u,\ p_{u,n} \ge 0, \forall u, n \tag{18}$$

$$\sum_{m=1}^{M}\alpha_{c,m} = 1,\ \forall c, \alpha_{c,m}\epsilon\{0,1\}, \forall c, m \tag{19}$$

$$\sum_{m=1}^{M}\alpha_{d,m} = 1, \forall d, \alpha_{d,m}\epsilon\{0,1\}, \forall d, m \tag{20}$$

$$N_{c,m}\bigcap N_{j,m} = \emptyset,\ \forall c \ne j, \forall m \tag{21}$$

$$\Bigg\{n \cap \Bigg(\bigcup_{j=1, j\ne c}^{c} N_{j,m}\Bigg) = \emptyset|$$
$$n\epsilon\{n_1, n_1+1, \ldots, n_2-1, n_2\}\Bigg\}, \forall c, m \tag{22}$$

$$R_{c,m} \ge R_c^{min}\forall c \tag{23}$$

$$x_d R_d^{D2D} + (1-x_d)R_{d,m}^{C-RAN} \ge R_d^{min}, \forall d \tag{24}$$

where $n_1 = min(N_c^m)$, $n_2 = max(N_c^m)$. R_c^{min} and R_d^{min} are the minimum rate requirements of users c and d, respectively.

Equation 17 represents the EE maximization of the system as objective function. Equation 18 reflects the constraint on maximum transmit-power of transmitter c. The constraint in Eq. 19 tells that a transmitter c can get association with single RRH at a time. Equation 20 reflects that a potential

D2D user can select either D2D or C-RAN mode at a time. Equations. 21 and 22 represent the SA constraints i.e., exclusivity and adjacency, respectively. Finally, the Eqs. 23 and 24 show the minimum data rate requirements of C-RAN user c and D2D user d, respectively.

4 Solution approach

The joint optimization problem in Eqs. (17)–(24), which perform JMSPR is MINLP. Therefore, we solve this problem in two stages such that mode selection problem is solved in the first stage, while, joint SAPARA problem is solved in the second stage. The following sub-sections contain the detail discussions of these stages.

4.1 D2D mode selection

To solve the mode selection, the problem in Eqs. (17)–(24) can be rewritten as below.

$$\max_{x_d,\alpha_{d,m}} \sum_{m=1}^{M} \Bigg[\sum_{c=1}^{C} \alpha_{c,m}\eta_{c,m} + \sum_{d=1}^{D} \Big\{ x_d \eta_d^{D2D} + (1-x_d)\alpha_{d,m}\eta_{d,m}^{C-RAN} \Big\} \Bigg] \tag{25}$$

$$s.t. Equations\ 18,\ 20\ and\ 24 \tag{26}$$

To solve the problem in Eqs. (25, 26), we present a novel two-step iterative mode selection technique which first identifies the potential D2D communication pairs by defining the proximity of the transmitters and then enables D2D communication between the proximate users based on link quality. The two steps of the mode selection technique are explained in the following. Step. 1: In D2D communication mode, two users can communicate directly, i.e., without passing through the RRH. A transmitter can bypass the RRH and transmit directly to its intended receiver if the intended receiver is positioned within the D2D proximity of that transmitter. Therefore, the D2D proximity of the transmitters denoted by L_u is determined first. The L_u is calculated using maximum transmit-power of a transmitter u and minimum sensitivity of the receiver ρ_{min} [31]. That is, $L_u = (p_u^{max}/\rho_{min})^{1/\delta_{D2D}}$, where δ_{D2D} shows the path-loss exponent of the D2D links. A transmitter which has its intended receiver positioned within its proximity is known as potential D2D transmitter.

Step. 2: A potential D2D transmitter selects D2D communication mode if the link quality of D2D communication is at least as good as the link quality of C-RAN. That is, a potential D2D transmitter selects the D2D communication mode if $(r_{d,d})^{-\rho^{D2D}} \geq (r_{d,\bar{m}})^{-\rho^{C-RAN}}$ where $r_{d,d}$ is the D2D link distance, $r_{d,\bar{m}}$ is the distance between the transmitter d and its closest RRH, ρ^{D2D} is the sensitivity of the D2D receiver and ρ^{C-RAN} is the sensitivity of the C-RAN receiver. On the other hand, if $(r_{d,d})^{-\rho^{D2D}} < (r_{d,\bar{m}})^{-\rho^{C-RAN}}$, the potential D2D transmitter selects C-RAN mode for communication. It is clear from the above two steps that for a transmitter to select D2D communication mode, the requirements in both the steps (i.e., D2D proximity and link quality requirements) should be satisfied.

We define $\{x_d\}$ as the set of mode selections which is updated with mode selection in each iteration. Initially, The technique selects a potential D2D transmitter and performs mode selection. In the next iteration, another potential D2D transmitter is selected from the remaining D2D transmitters for which, mode selection is performed. This way, mode selections are carried out for all the potential D2D transmitters. Algorithm 1 contains the mode selection technique.

Algorithm 1 Mode selection technique

1: **Initialization** M; K; U; $\widetilde{M} = \{1,\ldots,M\}$; $\widetilde{K} = \{1,\ldots,K\}$; $\widetilde{U} = \{1,\ldots,U\}$;
2: ρ_{min}; δ_{D2D}; $\{x_d\} = \phi$
3: **for** $u = 1 : U$
4: **Step 1:** Determine L_u such that $L_u = p_u^{max}/\rho_{min}$
5: Update the set of potential D2D transmitters.
6: Repeat Line 4 and 5, respectively.
7: **end**
8: **for** $d = 1 : D$
9: **Step 2:** Select D2D mode if $(r_{d,d})^{-\rho^{D2D}} \geq (r_{d,\bar{m}})^{-\rho^{C-RAN}}$. Otherwise, select C-RAN mode.
10: Update $\{x_d\}$
11: Repeat Line 9 and 10, respectively.
12: **end**
13: Return $\{x_d\}$

4.2 Joint subchannel assignment, power allocation and RRH-association (SAPARA)

After obtaining $\{x_d\}$ in the first stage (i.e., mode selection), to perform joint SAPARA, the problem in (17–24) can be reduced as below.

$$\max_{N_c^m,\alpha_{c,m},\alpha_{d,m},p_{u,n}} \sum_{m=1}^{M} \Bigg[\sum_{c=1}^{C} \alpha_{c,m}\eta_{c,m} + \sum_{d=1}^{D} x_d \eta_d^{D2D} + (1-x_d)\alpha_{d,m}\eta_{d,m}^{C-RAN} \Bigg] \tag{27}$$

$$s.t. Equations\ 18,\ 19,\ 21,\ 22\ and\ 23 \tag{28}$$

The joint SAPARA alone is also MINLP problem, therefore, we divide this problem into three sub-problem i.e., SA, PA and RRH-association and present an iterative technique to solve these problems. The following sub-sections contain the detail discussions of this iterative technique.

4.2.1 Subchannel assignment (SA)

For SA, we consider the initial RRH-association $\boldsymbol{\alpha}^0 = \{\alpha_1^0, \alpha_2^0, ..., \alpha_C^0, \}$ and initial PA $\boldsymbol{p}^0 = p_{c,n}^0, \quad \forall c, \forall n$. We utilized Uniform-Power-Allocation and Path-Loss Based Association (UPA-PLBA) for initializing the presented iterative technique where $p_{c,n}^0 = (p_c^{max}/N_{c,m}) : \forall c, m, n$, and $\forall c : \alpha_{c,\bar{m}}^0 = 1$ for $\bar{m} = \arg max \gamma_{c,m}$ where $\gamma_{c,m}$ is the SINR of user c to m ; $\alpha_{c,m}^0 = 0, \forall m \neq \bar{m}$. For SA, the problem (17-24) can be rewritten as

$$\max_{N_c^m} \sum_{m=1}^{M} \Big[\sum_{c=1}^{C} \alpha_{c,m}\eta_{c,m} + \sum_{d=1}^{D} x_d \eta_d^{D2D} + (1 - x_d)\alpha_{d,m}\eta_{d,m}^{C-RAN} \Big] \tag{29}$$

$$N_{c,m} \bigcap N_{j,m} = \emptyset, \ \forall c \neq j, \forall m \tag{30}$$

$$\Big\{ n \cap \Big(\bigcup_{j=1, j\neq c}^{c} N_{j,m} \Big) = \emptyset | \quad n \epsilon \{ n_1, n_1 + 1, ..., n_2 - 1, n_2 \} \Big\}, \forall c, m \tag{31}$$

$$R_{c,m} \geq R_c^{min} \forall c \tag{32}$$

At the beginning of iteration i such that $i \geq 1$, by solving Eqs. (29)-(32) for $\boldsymbol{\alpha} = \boldsymbol{\alpha^i}$ and $\boldsymbol{p} = \boldsymbol{p^i}$, subchannels are assigned to each user c which provides $N_c^m, \ \forall c, m$. We develop two techniques for SA which are ISA and SBA techniques. Both the developed techniques are discussed in the following.

(i) Individual Subchannel Allocation (ISA) technique: The ISA technique carries out SA to the users associated to RRH m. In each iteration, the ISA technique identifies the best user and subchannel pair (c^*, n^*) by selecting one RRH and computing the EE of its users on every subchannel and allocates the subchannel to that user who achieves the maximum EE on that subchannel. That is, the subchannels are assigned on the basis of maximum increase in the EE while assuring the adjacency and exclusivity constraints. In addition, the technique checks that whether the minimum data rate requirements of c^* in (c^*, n^*) is met. If not, an additional subchannel is allocated iteratively until the minimum data rate requirements of c^* is achieved or the set of feasible subchannels goes empty. Algorithm 2 contain the pseudocode of the ISA algorithm.

Algorithm 2 ISA algorithm

1: **Initialization** $M; C; N; \mathcal{M}; \mathcal{C}; \mathcal{N};$
2: $N_{c,m} = \phi, \forall c \epsilon \mathcal{C}, \forall m \epsilon \mathcal{M}; N_{c,m}^f = \mathcal{N}, \forall c \epsilon \mathcal{C}, \forall m \epsilon \mathcal{M};$
3: $R_c^{min}, \forall c \epsilon \mathcal{C}; R_{c,m} = 0, \forall c \epsilon \mathcal{C}, \forall m \epsilon \mathcal{M}$
4: **while** $\mathcal{M} \neq \phi$ **do**
5:   **while** $\mathcal{N}^m \neq \phi$ **do**
6:     $\forall c \epsilon \mathcal{C}^m$
7:     $\forall n \epsilon N_{c,m}^f \cup \mathcal{N}$
8:     $\eta_{c,m} = f(\eta_c), N_{c,m} \cup n$
9:     $c^*, n^* = \arg\max_{c,n} \eta_{c,m}$
10:     $N_{c^*,m} = N_{c^*,m} \cup n^*$
11:     $\mathcal{N}^m \backslash n^*$
12:     $N_{c,m}^f = \{\min(N_{c^*,m}) - 1, \max(N_{c^*,m}) + 1\} \cap \mathcal{N}^m$
13:     $R_{c^*,m} = W|N_{c,m}| \log_2 \left(1 + \frac{1}{|N_{c^*,m}|} \sum_{n \epsilon N_{c^*,m}} (\frac{p_{c^*,n}|h_{c^*,m}^n|^2}{\sigma^2 + I_{c^*,m}^n}) \right)$
14:     **while** $(R_{c^*,m} < R_{c^*}^{min} and N_{c^*,m}^f \neq \phi)$ **do**
15:       $\triangle\eta_{c^*,m} = f(\eta_{c^*}, N_{c^*,m} \cup n) - f(\eta_{c^*}, N_{c^*,m}), \forall n \epsilon N_{c^*,m}^f$
16:       $n^* = \arg\max_{n \epsilon N_{c^*,m}^f} \triangle\eta_{c^*,m}$
17:       Repeat steps 10 to 13
18:     **end while**
19:     $\mathcal{C} \backslash c^*$
20:   **end while**
21:   $\mathcal{M} \backslash m$
22: **end while**

Lines 1–3 shows the initialization of the ISA technique where $N_{c,m}$ and $N_{c,m}^f$ represent the currently allocated and the feasible subchannels sets, respectively, for user c associated to RRH m. At the beginning of the technique, $N_{c,m} = \phi$ and $N_{c,m}^f = N$. After initializing, the ISA technique identifies the (c^*, n^*) and then assigns the n^* to c^* (Lines 8-9). After allocating the subchannel n^* to user c^*, the set of subchannels which is currently allocated to user c^* associated to RRH m i.e., $N_{c^*,m}$ and the set of feasible subchannels for user c^* associated with RRH m i.e., $N_{c^*,m}^f$ are updated (Lines 10–12). In Line 13, the data rate achieved by user c^* on $N_{c^*,m}$ is calculated. After this, an additional subchannel is assigned to that user from the set of its feasible subchannels till the minimum data rate requirements of this user is fulfilled (Lines 14–18). Initially in Line 15, the rise in EE denoted by $\triangle\eta_{c^*,m}$ is computed after every additional subchannel $n \epsilon N_{c,m}$, which provides the difference of user c^*'s EEs with and without the additional subchannel $(i.e., f(\eta_{c^*}, N_{c^*,m} \cup n))$ and n $(i.e., f(\eta_{c^*}, N_{c^*,m}))$, respectively. Line 16 selects the subchannel resulting in hightes EE. The routines listed in Lines 10–13 are re-executed for updating $N_{c,m}$, $N_{c,m}^f$ and $R_{c^*,m}$ (Line 17). In Line 19, the users without subchannels are updated. The technique is re-executed until $\mathcal{M}$ goes empty (Lines 5–21).

(ii) Subchannels Block Allocation technique: The SBA technique divides the available set of subchannels denoted by $\mathcal{N}$ into C_m blocks having equal number of adjacent subchannels where C_m represents the users set connected with to RRH m. After this, for every RRH m, the SBA technique iteratively computes the EE of its all users on each block of subchannel, and then allocates the block to the user that attains the maximum EE on that subchannel block. This pair of user and subchannel block will not be considered in the next iteration for subchannel block assignment. In the next iteration, the attainable EE of every user except the one who has been assigned a subchannel block in the previous iteration, is calculated on the next block and its assignment is carried out on the basis of same criteria as in the previous iteration, i.e., the subchannel block is allocated to the user who attains the maximum EE on that subchannel block. This process continues until all the subchannel blocks are assigned.

4.2.2 Power allocation (PA)

To allocate powers to the subchannels allocated to the users in the SA step, the optimization problem in (17–24) reduces as below

$$\max_{p_{u,n}} \sum_{m=1}^{M} \Big[\sum_{c=1}^{C} \alpha_{c,m}\eta_{c,m} + \sum_{d=1}^{D} x_d \eta_d^{D2D} + (1-x_d)\alpha_{d,m}\eta_{d,m}^{C-RAN} \Big] \tag{33}$$

$$s.t. \sum_{n \epsilon N_{c,m}} p_{c,n} \leq p_c^{max}, \forall c,\ p_{c,n} \geq 0, \forall c, n \tag{34}$$

After achieving $N_{c,m}$ by performing SA in the first step and for given $\boldsymbol{\alpha} = \boldsymbol{\alpha}^{\boldsymbol{i}}$, PA across all the assigned subchannels of each user is performed using (a) interior point algorithm (IPA) and (b) equal power distribution (EPD). IPA is an efficient solver of linear and non-linear problems. The IPA achieves optimality conditions in four phases. Firstly, transformation from inequality to equality constraints is performed. Secondly, non-negativity situations are indirectly tackled by their addition to the objective function as logarithmic barrier terms. Third, transformation from optimization problem with equality constraints to unconstrained one is performed. Finally, using Newton method, the Karush–Kuhn Tucker optimality conditions are solved. For more details, [32] can be referred. Whereas EPD uniformly divides the user's maximum transmit-power among the subchannels allocated to it. If, p_u^{max} and $N_{u,m}$ are the user's u maximum transmit-power and its set of assigned subchannels by RHH m, respectively, then EPD can be expressed mathematically as follows

$$p_{u,n} = p_u^{max}/|N_{u,m}|, \forall u, n, m \tag{35}$$

The solution achieved is considered as $\boldsymbol{p}^{\boldsymbol{i+1}}$.

4.2.3 RRH-association

To find the RRH-association ($\boldsymbol{\alpha}$) with obtained D2D mode selection, SA and PA, the optimization problem in (17-24) can be reduced as follows.

$$\max_{\alpha_{c,m},\alpha_{d,m}} \sum_{m=1}^{M} \Big[\sum_{c=1}^{C} \alpha_{c,m}\eta_{c,m} + \sum_{d=1}^{D} x_d \eta_d^{D2D} + (1-x_d)\alpha_{d,m}\eta_{d,m}^{C-RAN} \Big] \tag{36}$$

$$\sum_{m=1}^{M} \alpha_{c,m} = 1,\ \forall c,\ \alpha_{c,m} \epsilon \{0, 1\}, \forall c, m \tag{37}$$

This problem is solved by putting all $\alpha_{c,m}$ as zeros, except that $\alpha_{c,\bar{\bar{m}}=1}$ where $\bar{\bar{m}}$ can be mathematically written as below

$$\bar{\bar{m}} = \arg\max(\eta_{c,m}) \tag{38}$$

where $\eta_{c,m}$ shows the EE of user c associated with RRH m.

We used integer relaxation method [33] to solve the problem in Eqs. 36 and 37. The proposed method connects user c to the RRH which results in highest EE. We express this solution by $\boldsymbol{\alpha}^{\boldsymbol{i+1}}$ and then the next iteration begins. The iterative technique is re-executed until convergence.

In the integer relaxation method, first the integer variable is relaxed (i.e., $\alpha_{c,m} \in [0, 1]$) and then, the resulted linear problem is solved for the non-integer values of the variable. Then the obtained non-integer values are rounded to integer on the basis of highest energy efficiency results such that the constraints in Eq. 36 are not violated. The overall complexity of the integer relaxation method lies in the solution of linear problem and the worst case complexity of the solution of linear problem with $C + M$ variables is approximately $\mathcal{O}((C + M)^3)$ [37].

The flow chart of JMSPR technique is given in Fig. 2.

To analyze the overall complexity of our proposed algorithm, the complete iterations of the middle while loop and inner most while loop in Algorithm 1 are considered. In Algorithm 1, the section containing middle while loop and inner most while loop will run for M number of times. The complexity of the algorithm mainely depends upon steps 8 and 15 in which η_c^m and $\triangle\eta_{c*}^m$ are computed, respectively. The first complete iteration of the middle while loop will need $\mathcal{O}(NC)$ operations for the computation of η_c^m. This complexity decreases for the subsequent iterations because the number of users and sub-channels will be less than C and N, respectively. While, the first complete iteration of the inner most while loop will need $\mathcal{O}(|N_c^f|)$ operations for the computation of $\triangle\eta_{c*}^m$. Its worst case complexity will be $\mathcal{O}((N-1)|N_c^f|)$. This complexity decreases for the subsequent iterations of the inner most while loop because in the subsequent iterations, the number of the sub-channels will be less than $(N - 1)$. Because there are N middle iterations which will run for M number of times, the worst case complexity of the algorithm cannot exceed $\mathcal{O}(M(N(NC + (N-1)|N_c^f|)))$.

5 Simulations results

We consider the D2D enabled multi-tier C-RANs using SC-FDMA in the UL. There are total four communication tiers in the system including macrocell tier having a coverage

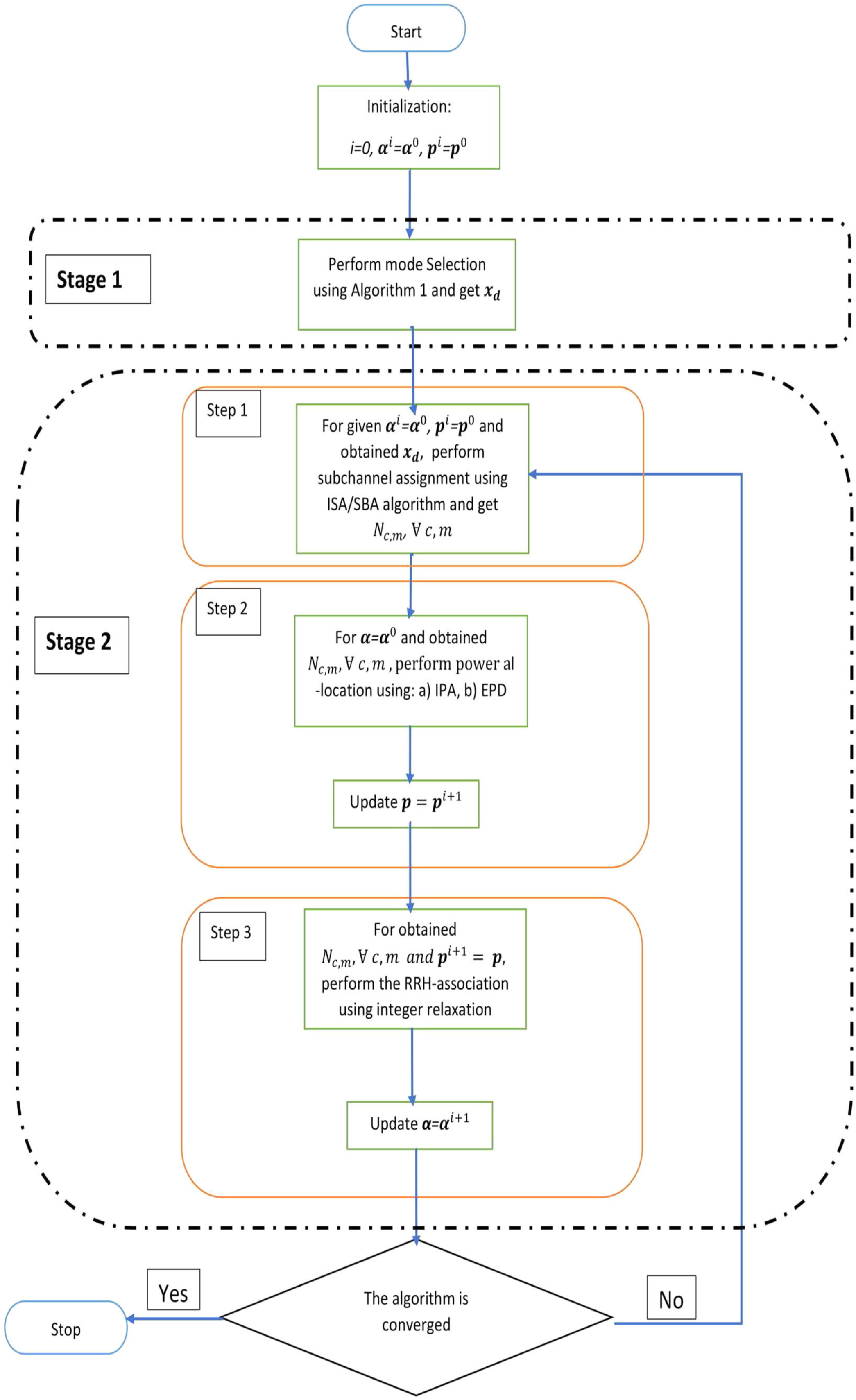

Fig. 2 Flow chart of the presented technique

Table 1 Simulations parameters

Parameter	Values/types
Total number of RRHs	5 (one MBS RRH, two femtoocell RRH and two picocell RRH)
System bandwidth	9 MHz
Bandwidth per subchanel	200 KHz
Path-loss model	Cost HATA model
Power spectral density of noise	− 174 dBm/Hz
Channel type	Frequency selective rayleigh fading channel
Standard deviation of shadow fading	8 dB
Simulator	Matlab

circle of radius r meters, picocell tier, femtocell tier and D2D communication tier such that all the four tiers co-exist in the coverage circle of macrocell tier. Moreover, the system bandwidth B is equally divided into N sub-channels each with bandwidth W and the available set of subchannels N is reuse at all the 4 communication tiers. Furthermore, there are U total users which are randomly deployed in the cell. The sensitivity of each receivers (RRHs and $R_x(d)$) is $\rho_{min} = -90dBm$ and the path-loss exponents $\delta_{D2D} = \delta_{C-RAN} = 4$ [31]. The spectral density of noise is taken as $-174\ dBm/Hz$. The channel gain contains two parts: a path-loss part computed by Cost-Hata model [36] and Rayleigh fast-fading part. Different parameters and their values/types used in simulations are listed in the Table 1.

The performance of the presented ISA based JMSPR (ISA-JMSPR) and SBA based JMSPR (SBA-JMSPR) techniques are compared with that of the low complexity equal power and equal subchannel allocation; and distance based RRH-association (EPESDR) technique and a high complexity base-line technique. In EPESDR technique, the subchannels of a RRH are uniformly divided among the users connected to it, the user's maximum transmit-power is uniformly divided among the subchannels allocated to it and a distance dependent RRH-association is carried out. In base-line technique, RRH-association and SA are performed using branch and bound (B&B) method, while PA is performed using IPA. Our formulated ISA-JMSPR and SBA-JMSPR problems are MINLP problems which are generally NP-hard. Therefore, regardless of the high complexity of B&B method and IPA, they are utilized as comparison base line, because they result in near-optimal outcomes.

To show the effectiveness of D2D communication, Figures 3 and 4 present the EE performance comparison of the ISA-JMSPR, SBA-JMSPR, EPESDR and base-line techniques for different cell radii in multi-tier C-RAN without D2D communication and with D2D communication enabled, respectively. The comparison of both the figures shows that when D2D communication is enabled as shown in Fig. 4, the EE performances of all the four algorithms are better than the scenario when D2D communication is not enabled as shown in Fig. 3. This is due to the fact that by enabling D2D communication, the distance between transmitter and receiver decreases which results in lower transmit power between proximate users. This lower transmit power increases the overall EE. In addition, both the figures show that the EE

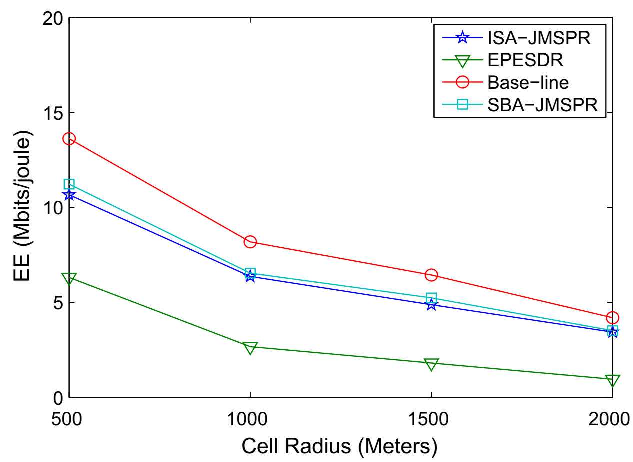

Fig. 3 EE comparison of the presented techniques with EPESDR and base-line techniques for different cell radii without D2D communication

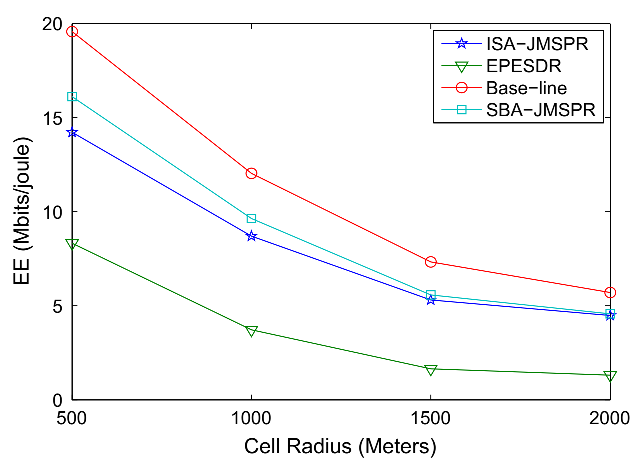

Fig. 4 EE comparison of the presented techniques with EPESDR and base-line techniques for different cell radii with D2D communication

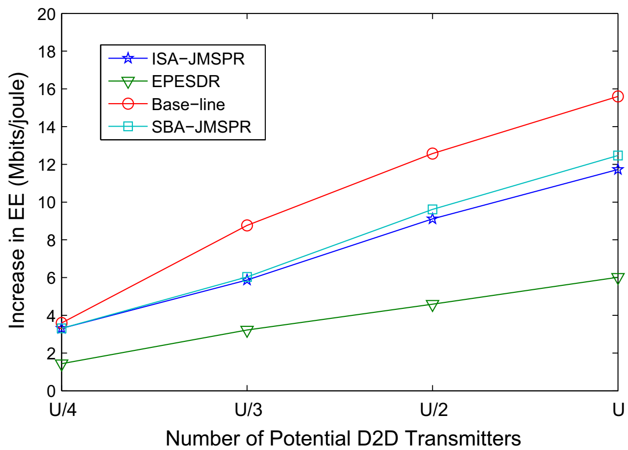

Fig. 5 Improvement/increase in EE versus the number of potential D2D transmitters

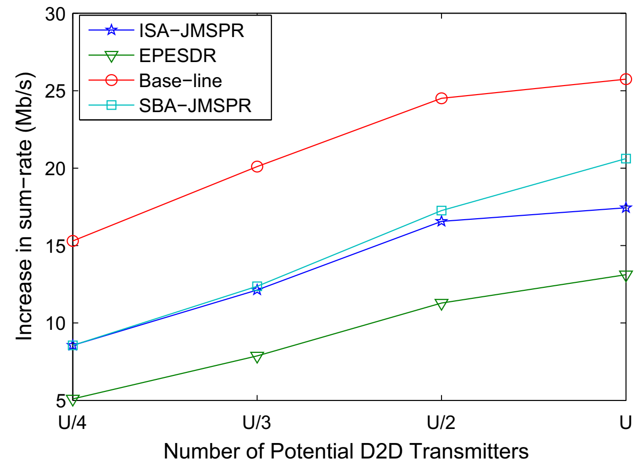

Fig. 6 Improvement/increase in sum-rate versus the number of potential D2D transmitters

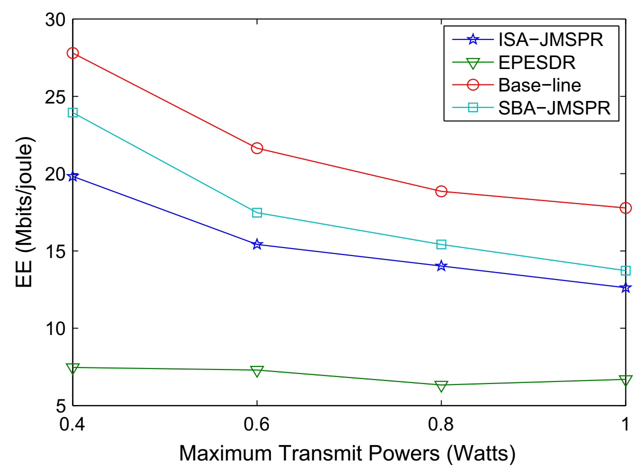

Fig. 7 EE against transmit-power for K=5, N=10

decreases with increase in cell radius for all four techniques. However, it can be seen in Fig. 3 that for cell radius equal to 500 m, the EPESDR, ISA-JMSPR, SBA-JMSPR and base-line techniques result in EE equal to 6 Mb/joul, 10.5 Mb/joul, 11 Mb/joul and 14 Mb/joul, respectively, Which decrease to 3.5 Mb/joul, 6.3 Mb/joul, 6.7 Mb/joul and 8.7 Mb/joul, respectively, for cell radius equal to 1000 m. While in Fig. 4, the EPESDR, ISA-JMSPR, SBA-JMSPR and base-line techniques result in EE equal to 8.5 Mb/joule, 14 Mb/joule, 16 Mb/joule and 20 Mb/joule, respectively, Which decrease to 4 Mb/joule, 9.5 Mb/joule, 10.3 Mb/joule and 13.5 Mb/joule, respectively, for cell radius equal to 1000 m. In Figs. 3 and 4, the performance comparison of all the above mentioned techniques in terms of EE shows that enabling D2D communication in multi-tier C-RAN can remarkably enhance the network EE. Furthermore, both the figures also show the effectiveness of our presented techniques.

Figures 5 and 6 show the improvement/increase in EE and network sum-rate for a different proportions of D2D transmitters in total users, respectively. The figures show that an increase in the proportion of the D2D transmitters in total users significantly increase the EE and network sum-rate which verify the effectiveness of D2D communication. This is because in D2D communication, potential D2D transmitter directly transmits to its intended receiver using lower transmit power and facing lower path-loss. The lesser distance between transmitter and receiver results in lesser transmit power which leads to increase in EE. Therefore, as the proportion of D2D users increases, the number of D2D links also increases which leads to increase in the EE as shown in Fig. 5. Similarly, D2D communication results in lower path-loss between users, and this lower path-loss results in increased data rate. Therefore, as the proportion of D2D users increases, the overall path-loss decreases which leads to increase the sum-rate as shown in Fig. 6. As for as the performances of our presented techniques are concerned, both of our presented ISA-JMSPR and SBA-JMSPR techniques outperform the EPESDR technique while their performances are closed to the base-line technique.

In Figs. 7 and 8, we show the EE and system sum-rate performance of the presented techniques, respectively, for various values of p_u^{max} and compare them with the EPESDR and base-line techniques. For both figures, U and N are kept constant while R_u^{min} is set as 200 Kbps. It can be seen in Fig. 7 that an increase in p_u^{max} leads to decrease in the EE while Fig. 8 shows that the increase in p_u^{max} results in increased network sum-rate. In addition, both the figures reveal that ISA-JMSPR and SBA-JMSPR techniques provide better results than the EPESDR technique while they are near in performance to the base-line technique.

We next assess the EE and system sum-rate performances of our presented techniques for different values of R_u^{min}. For easiness, we assume that the minimum data rate requirements

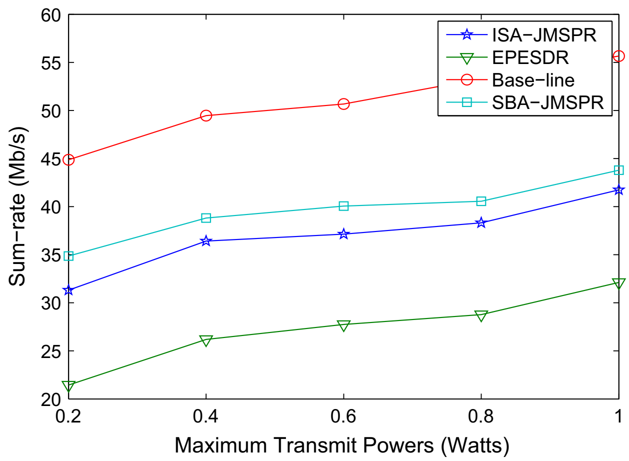

Fig. 8 Network sum-rate against transmit-power for K=5, N=10

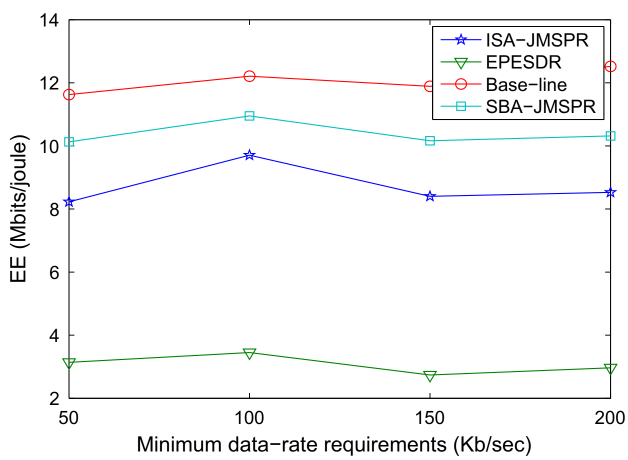

Fig. 9 EE evaluation and comparison for different minimum data rate requirements of the users

of all the users are same. Moreover, various minimum data rate requirements of the users taken are 50 kbps, 100 kbps, 150 kbps and 200 kbps. The graphs for EE and system sum-rate are plotted in Figs. 9 and 10, respectively, which illustrate that the EE and system sum-rate performances of the presented ISA-JMSPR and SBA-JMSPR techniques are substantially better than the EPESDR technique. The figures also show that the ISA-JMSPR and SBA-JMSPR techniques are near to the base-line technique in terms of EE and system sum-rate performances. Among our presented techniques, SBA-JMSPR technique outperforms the ISA-JMSPR technique.

6 Conclusion

D2D communications as an underlay to the single carrier frequency division multiple access (SC-FDMA) based C-RAN in the uplink is considered and an energy-efficient mode

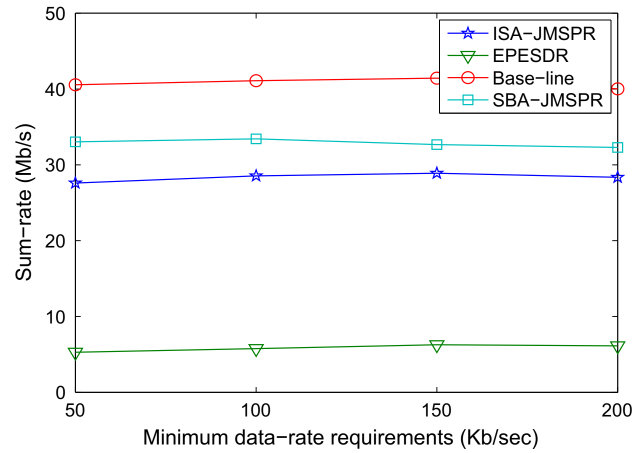

Fig. 10 Network sum-rate evaluation and comparison for different minimum data rate requirements of the users

selection and resource allocation (RA) technique is presented which jointly optimizes mode selection, subchannel assignment (SA), power allocation (PA) and remote radio head (RRH)-association (JMSPR). The objective of this work was EE maximization subject to transmit-power budget, minimum data rate requirements, sub-channel exclusivity and adjacency constraints. The JMSPR problem is mixed-integer non-linear problem (MINLP) which is extremely difficult to solve in its original form. Therefore, this problem is solved in two stages; mode selection stage and joint SA, PA and RRH-association (SAPARA) stage. For mode selection, a link quality based technique is presented while, for joint SAPARA, we developed an iterative technique that solves this MINLP problem in three steps such that SA and PA are carried out in the first and second step, respectively, while RRH-association is performed in the third step. The performance of our presented technique is compared with the EPESDR and base-line techniques and it is found that our proposed techniques outperform EPESDR and are closed to the performance of base-lain technique.

References

1. Peng, M., Li, Y., Zhao, Z., & Wang, C. (2015). System architecture and key technologies for 5G heterogeneous cloud radio access networks. *IEEE Network*, *29*(2), 6–14.
2. Peng, M., Sun, Y., Li, X., Mao, Z., & Wang, C. (2016). Recent advances in cloud radio access networks: System architectures, key techniques, and open issues. *IEEE Communications Surveys and Tutorials*, *18*(3), 2282–308.
3. Ali, S., & Ahmad, A. (2017). Resource allocation, interference management, and mode selection in device-to-device communication: A survey. *Transactions on Emerging Telecommunications Technologies*, *28*(7), e3148.
4. Rico-Alvarino, A., Vajapeyam, M., Xu, H., Wang, X., Blankenship, Y., Bergman, J., et al. (2016). An overview of 3GPP enhancements on machine to machine communications. *IEEE Communications Magazine*, *54*(6), 14–21.

5. Varahram, P., & Ali, B. M. (2012). Peak-to-average power ratio reduction and digital predistortion effects in power amplifiers in OFDM system. *International Journal of Communication Systems*, *25*(4), 543–52.
6. Ahmad, A., & Shah, N. (2015). A joint resource optimization and adaptive modulation framework for uplink single-carrier frequency-division multiple access systems. *International Journal of Communication Systems*, *28*(3), 437–56.
7. Ghavimi, F., & Chen, H. H. (2015). M2M communications in 3GPP LTE/LTE-A networks: Architectures, service requirements, challenges, and applications. *IEEE Communications Surveys and Tutorials*, *17*(2), 525–49.
8. Yu, C. H., Tirkkonen, O., Doppler, K., Ribeiro, C. (2009). On the performance of device-to-device underlay communication with simple power control, In Proc. IEEE Vehicular Technology Conference (pp. 1–5). Springer, Spain.
9. Zhao, W., & Wang, S. (2015). Resource sharing scheme for device-to-device communication underlaying cellular networks. *IEEE Transactions on Communications*, *63*(12), 4838–4848.
10. Jiang, Y., Liu, Q., Zheng, F., Gao, X., & You, X. (2016). Energy-efficient joint resource allocation and power control for D2D communications. *IEEE Transactions on Vehicular Technology*, *65*(8), 6119–6127.
11. Peng, M., Li, Y., Quek, T., & Wang, C. (2014). Device-to-device underlaid cellular networks under Rician fading channels. *IEEE Transactions on Wireless Communications*, *13*(8), 4247–4259.
12. Zhou, H., Ji, Y., Li, J., & Zhao, B. (2014). Joint mode selection, MCS assignment, resource allocation and power control for D2D communication underlaying cellular networks. In Proceedings of WCNC (pp. 1667–1672). Istanbul.
13. Yu, G., et al. (2014). Joint mode selection and resource allocation for deviceto- device communications. *IEEE Transactions on Communications*, *62*(11), 3814–3824.
14. Azam, M., et al. (2015). Joint admission control, mode selection and power allocation in D2D communication systems. *IEEE Transactions on Vehicular Technology*, *65*(9), 7322–7333.
15. Mo, Y., Peng, M., Xiang, H., Sun, Y., & Ji, X. (2017). Resource allocation in cloud radio access networks with device-to-device communications. *IEEE Access*, *5*, 1250–62.
16. Abana, M. A., Peng, M., Zhao, Z., & Olawoyin, L. A. (2016). Coverage and rate analysis in heterogeneous cloud radio access networks with device-to-device communication. *IEEE Access*, *4*, 2357–70.
17. Sun, Y., Peng, M., & Wang, C. (2016). A. distributed approach in uplink device-to-device enabled cloud radio access networks. In *Global communications conference (GLOBECOM)* (pp. 1–6). IEEE.
18. Wang, Z., & Sun, Y. (2017). Mode selection and resource allocation in uplink device-to-device enabled cloud radio access networks. In *International conference on communications workshops (ICC workshops)* (pp. 1341–1345). IEEE.
19. Zhao, J., Li, S., Ma, D., & Mu, X. (2018). Research on Joint Mode Selection and Resource Allocation Scheme in D2D Networks. In *International Conference on Cyber-Enabled Distributed Computing and Knowledge Discovery (CyberC)* (pp. 429–4293). IEEE.
20. Zeng, T., Semiari, O., Saad, W. (2017). Exploring spatial motifs for device-to-device network analysis (DNA) in 5G networks. In *51st Asilomar conference on signals, systems, and computers* (pp. 1432–1436). IEEE.
21. Wang, J., Wang, S. (2018). A resource allocation algorithm based on DILA for D2D communication in LTE-A multi-cell network. In *2018 IEEE 3rd advanced information technology, electronic and automation control conference (IAEAC)* (pp. 114–117). IEEE.
22. Sun, Y., Wang, F., & Liu, Z. (2019). Coalition formation game for resource allocation in D2D uplink underlaying cellular networks. *IEEE Communications Letters*, *23*(5), 888–91.
23. Lee, J., & Lee, J. H. (2019). Performance analysis and resource allocation for cooperative D2D communication in cellular networks with multiple D2D pairs. *IEEE Communications Letters*, *23*(5), 909–12.
24. Naqvi, S. A., Pervaiz, H., Hassan, S. A., Musavian, L., Ni, Q., Imran, M. A., et al. (2018). Energy-aware radio resource management in D2D-enabled multi-tier HetNets. *IEEE Access*, *19*(6), 16610–22.
25. Zia, K., Javed, N., Sial, M. N., Ahmed, S., Pirzada, A. A., & Pervez, F. (2019). A Distributed multi-agent RL-based autonomous spectrum allocation scheme in D2D enabled multi-tier HetNets. *IEEE Access*, *1*(7), 6733–45.
26. Sun, Y., Peng, M., & Poor, H. V. (2018). A distributed approach to improving spectral efficiency in uplink device-to-device-enabled cloud radio access networks. *IEEE Transactions on Communications*, *66*(12), 6511–26.
27. Shamaei, S., Bayat, S., & Hemmatyar, A.M. (2018). Interference management in D2D-enabled heterogeneous cellular networks using matching theory. In *IEEE Transactions on mobile computing*.
28. Della Penda, D., Abrardo, A., Moretti, M., & Johansson, M. (2019). Distributed channel allocation for D2D-enabled 5G networks using potential games. *IEEE Access*, *9*(7), 11195–208.
29. Aijaz, A., Tshangini, M., Nakhai, M. R., Chu, X., & Aghvami, A. H. (2014). Energy-efficient uplink resource allocation in LTE networks with M2M/H2H co-existence under statistical QoS guarantees. *IEEE Transactions on Communications*, *62*(7), 2353–65.
30. Orakzai, F. A., Ahmad, A., Khan, M. T., & Iqbal, M. (2017). Optimal energy-efficient resource allocation in uplink SC-FDMA networks. *Transactions on Emerging Telecommunications Technologies.*, *28*(8), e3153.
31. ElSawy, H., Hossain, E., & Alouini, M. S. (2014). Analytical modeling of mode selection and power control for underlay D2D communication in cellular networks. *IEEE Transactions on Communications*, *62*(11), 4147–61.
32. Wu, Y. C., Debs, A. S., & Marsten, R. E. (1994). A direct nonlinear predictor-corrector primal-dual interior point algorithm for optimal power flows. *IEEE Transactions on Power Systems*, *9*(2), 876–83.
33. Matousek, J., & Gartner, B. (2007). Integer programming and LP relaxation. *Understanding and using linear programming* (pp. 29–40). Berlin: Springer.
34. Ali, S., Ahmad, A., Iqbal, R., Saleem, S., & Umer, T. (2018). Joint RRH-Association, Sub-channel assignment and power allocation in multi-tier 5G C-RANs. *IEEE Access*, *6*, 34393–34402.
35. Ali, S., Ahmad, A., & Khan, A. (2019). Energy-efficient resource allocation and RRH association in multitier 5G H-CRANs. *Transactions on Emerging Telecommunications Technologies.*, *30*(1), e3521.
36. Nisirat, M.A., Ismail, M., Nissirat, L., & AlKhawaldeh, S. (2012). Is Hata Path loss model a macro-cell model only? A question of debate. In *International conference on computer and communication engineering (ICCCE)* (pp. 274–277). IEEE.
37. Cohen, M. B., Lee, Y. T., & Song, Z (2019). Solving linear programs in the current matrix multiplication time. In *Proceedings of the 51st annual ACM SIGACT symposium on theory of computing* (pp. 938–942). ACM.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Sher Ali received his B.S. degree in Telecommunication Engineering from the University of Engineering and Technology, Peshawar, Pakistan, in 2009. In 2011, he received his M.S. degree in Electrical engineering from CECOS University, Peshawar, Pakistan. He obtained his Ph.D. in Electrical Engineering from COMSATS University Islamabad, Wah Campus, Pakistan in 2019. From 2012 to 2017, he served as a faculty member at the Department of Electrical Engineering, City University of Science and IT, Peshawar, Pakistan. His research interests include resource allocation in wireless networks.

Ayaz Ahmad is currently serving as Assistant Professor in the Department of Electrical and Computer Engineering, COMSATS University Islamabad, Wah Campus, Wah Cantt., Pakistan. He obtained his M.S. and Ph.D. degrees both in Telecommunication from Ecole Superieure d'Electricite (Supelec), Gif-sur-Yvette, France, in 2008 and 2011, respectively. He obtained his B.Sc. in Electrical Engineering from University of Engineering and Technology, Peshawar, Pakistan in 2006. From 2006 to 2007, he was a faculty member at the Department of Electrical Engineering, FAST-NUCES, Peshawar, Pakistan. Ayaz has several years of research experience and has authored/co-authored several scientific publications in various refereed international journals and conferences. He has also published several book chapters and is the leading co-editor of the book entitled, "Smart Grid as a Solution for Renewable and Efficient Energy" published by IGI Global, USA in 2016. He is currently an Associate Editor with IEEE Access, and Springer Human-centric Computing and Information Sciences. He has also served as the lead guest editor of a special issue on optimization for emerging wireless networks and co-guest editor of a special issue on energy harvesting both for IEEE Access. He is regularly serving as TPC member for several international conferences including IEEE GLOBECOM, IEEE ICC, and IEEE PIMRC, and as reviewer for several renowned international journals. He is Senior Member of IEEE. His research interests include resource allocation in wireless communication systems, energy management in smart grid, and application of optimization methods to engineering problems.

Yasir Faheem received the Ph.D. degree in Computer Science from the Universite' Paris Nord, France, in 2012, the M.S. degree in Networks and Distributed Systems from the Universite' de Nice-Sophia Antipolis, France, in 2008, and the B.S. degree in Computer Science from NUCES-FAST, Pakistan, in 2006. He is an Assistant Professor at the Department of Computer Science, COMSATS University Islamabad, Islamabad campus, Pakistan. His current research interests are in the internet of things, cloud computing, and wireless ad hoc networks (sensor networks, cognitive radio networks, opportunistic networks). Moreover, he is interested in the applications of the algorithmic game theory to various domains. He has served on the technical program committee of the IEEE ICC, IEEE GLOBECOM and various other conferences. Moreover, he regularly serves as a reviewer for the IEEE Communications Magazine and the Elsevier Journal of Network and Computer Applications. He is also an editorial board member for the IEEE Internet Policy and the IEEE Future Directions newsletters.

Muhammad Altaf completed his Ph.D. in the field of Multimedia and Networking from university of Essex United Kingdom. His research interests include video and image compression, video streaming over wireless and wired line networks, secure communication. He has published numerous technical papers and two book chapters on topics related to multimedia and networking. He has worked in London South University as visiting research fellow from Jan 2015 till June 2016 and worked on projects related to signal and image processing. Currently he is working as associate professor in the Department of Electrical Engineering COMSATS institute of information Technology Wah, Pakistan.

Habib Ullah did Ph.D. in 2015 from the University of Trento, Italy and the M.Sc. degree in Computer Engineering in 2009 from Hanyang University, Seoul, South Korea. He is currently working as Assistant Professor in the College of Computer Science and Engineering at the University of Ha'il, Ha'il, Saudi Arabia. His research interests include pedestrian motion analysis, video surveillance, and machine learning.