TRANSACTIONS ON EMERGING TELECOMMUNICATIONS TECHNOLOGIES
Trans. Emerging Tel. Tech. 2017; 28: e3000
Published online 11 November 2015 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ett.3000

SPECIAL ISSUE PAPER

Joint mode selection and resource allocation for machine-type D2D links

Jingjing Zhao[1]*, Kok Keong Chai[1], Yue Chen[1], John Schormans[1] and Jesus Alonso-Zarate[2]

[1] School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK
[2] Centre Technològic de Telecommunications de Catalunya (CTTC), Barcelona, Spain

ABSTRACT

Low-power machine-type communications devices in machine-to-machine networks are expected to operate autonomously for years, or even decades. Meanwhile, device-to-device (D2D) communications make large benefits on users' data rate and power consumption because of the proximity between potential D2D transmitters and receivers. In this paper, we facilitate machine-type D2D links where the machine-type communications devices are connected to a nearby device, such as a number of sensors connected to a gateway that acts as the relay towards the evolved NodeB. A challenging problem is the co-channel interference caused by spectrum sharing between underlaying machine-type D2D links and traditional cellular user equipments (CUEs). Therefore, we consider joint mode selection, radio resource allocation and power control to improve overall system data rate and reduce average traffic delay. We first formulate a problem to maximise the sum of users' utilities with signal-to-interference-plus-noise and power constraints for both D2D links and CUEs. Furthermore, we adopt the coalition formation game with transferable utility to solve the formulated problem. In the game model, the D2D links and CUEs that share the same resource block pair form a coalition, and the coalition formation decisions are determined by the best-reply rule. In addition, 'experimentation' is introduced in the coalition formation process to improve the effectiveness of the final coalition structure. Simulation results show that the proposed scheme outperforms the scheme with heuristic greedy algorithm in terms of overall system throughput, average traffic delay and users' fairness.

***Correspondence**
J. Zhao, School of Electronic Engineering and Computer Science, Queen Mary University of London, London, UK.
E-mail: j.zhao@qmul.ac.uk

Received 29 June 2015; Revised 30 September 2015; Accepted 19 October 2015

1. INTRODUCTION

The 3rd Generation Partnership Project has defined two important technologies for the future network. The first one is device-to-device (D2D) communications, where devices may be enabled to communicate directly bypassing the evolved NodeBs (eNBs). There are three types of promising gains for D2D communications: (1) the proximity gain; (2) the reuse gain; and (3) the hop gain [1, 2]. Further, D2D communications may bring benefits such as cellular coverage extension, local data sharing and offloading traffic from the eNB [3]. Another important technology is the machine-to-machine (M2M) communications, or machine-type communications (MTC), which refer to information exchange between autonomous devices without any human interaction. A common feature of MTC is simultaneous transmission attempts to the cellular network from a large number of MTC devices (MTDs) in the use cases such as public safety, healthcare and metering. In addition, it requires low-power consumption because the battery-limited MTDs may have no access to power sources and human interaction over long periods of time [4].

The motivation for introducing D2D communications to MTC lies in the possibility to offload traffic from the eNB whenever a large number of MTDs require transmissions and also in the possibility to save power consumption thanks to the reduced transmission distance. In addition, if we want to run mission-critical applications, such as safety messages in car-to-car applications, it is needed to reduce the latency below 1 ms. The end-to-end delay can be dramatically reduced if use D2D in MTC because of avoidance of the need to route traffic via the eNB.

Device-to-device communications can be either under the control of the eNB or without it. In any case, the co-channel interference becomes a challenge when D2D users are allowed to operate in underlay mode, that is, using the same frequency allocated to the regular cellular links.

Recently, many works have dealt with this problem through proper mode selection and smart radio resource allocation.

The user equipments (UEs) in network-assisted D2D links still keep cellular operation and can switch between direct (D2D mode) and traditional cellular communications (cellular mode) with each other. If the co-channel interference caused by spectrum sharing deteriorates the system performance, D2D users may engage in cellular mode. In [5], an optimal mode selection scheme for D2D users in a multi-cell scenario was proposed. The eNB estimates the expected throughput based on the Signal to Interference plus Noise Ratio (SINR) and selects the communication mode with the highest throughput. Simulation results showed that there was a 50 per cent cell throughput gain. In [6], the work focused on the optimised cell rate by mode selection for D2D communications. The numerical results showed substantial gains from D2D communications handling local traffic.

Because the system performance can be improved by choosing proper resource sharers for D2D users, radio resource allocation is also a very important issue [7–11]. In [8], a greedy heuristic Resource Block (RB) allocation algorithm was proposed where any cellular user equipment with higher channel quality could share RBs with the D2D user that had lower channel quality. The performance of this algorithm can be further improved by considering more factors as it only used the interference channel gain as the factor to choose spectrum-reusing partners for D2D users. In [9], the authors proposed two algorithms to allocate radio resources to D2D users. The two algorithms were based on interference mitigation between cellular and D2D users using interference tracing and tolerable interference broadcasting mechanisms, respectively. The simulation results showed that the overall throughput performance could be improved by 41%. In [10], the authors proposed a resource allocation scheme consisting of three steps, that is, access admission, optimal power control and resource allocation, to find the optimal solution of the formulated problem. Numerical results showed that the overall network throughput could be significantly improved. The authors in [11] proposed a two-level combinational auction game to jointly allocate channels to D2D users and power to both D2D users and Cellular UEs (CUEs) to improve energy efficiency. Simulation results showed that the proposed algorithm improved the system performance in terms of expected data, lifetime and data rate.

From the aforementioned, mode selection and resource allocation, when applied alone, are efficient approaches to improve system data rates. Furthermore, it is worthwhile to consider these two issues jointly because they have influences on each other. For example, if a D2D pair fails to find a proper resource sharer, it will be encouraged to transmit in traditional cellular mode. The joint mode selection and resource allocation scheme can be developed in either centralised [12–20] or distributed approach [21, 22]. In [12], a joint mode selection and resource allocation scheme for D2D communications underlaying cellular networks was proposed, where interference suppression and Quality of Service (QoS) requirements were taken into consideration. Numerical results showed that the proposed scheme achieved higher system capacity than the benchmark algorithm. The authors in [13] proposed an algorithm with reduced complexity to solve the formulated joint mode selection and resource allocation problem. Evaluation results showed that the potential of D2D communications could be further exploited for achieving significant spatial reuse gain. In [18], the authors jointly investigated the problems of optimal system resource allocation and mode selection for large-scale networks. The optimal system performance was obtained by formulating a max-flow optimization problem that maximises the system throughput through any possible of transmission modes and resource allocations. In [12–20], the mode selection and resource allocation for D2D links are performed at the eNB based on available channel state information, which will lead to a high load on the eNB and much control signalling overhead if the number of D2D links are large. Therefore, the distributed approach is required.

In [21], the authors considered the problem of mode selection for D2D communications and proposed a solution based on a coalitional game among D2D links to select their communication modes, which aimed at minimising the total power while guaranteeing the users' rate requirements. However, only D2D pairs in the same transmission modes formed coalitions, while the traditional CUEs were not taken into consideration. In [22], a distributed coalition formation algorithm was proposed to improve the overall data rate of the D2D communication system. The merge-and-split rule was used as the basic principle for the coalition formation process. However, different communication features of UEs were not taken into account in [22]. In this paper, we investigate how to leverage machine-type D2D links to improve overall system data rate and reduce average traffic delay via joint mode selection, radio resource allocation and power control. We consider different features of human-type communications and MTC, including differences in terms of power consumption, data rate and packet size. The coalition formation game is adopted because users can choose their transmission modes and resource sharers autonomously, which relieves the eNB from heavy signalling overhead and high computational complexity. In the game model, the Machine-type D2D links and CUEs that share the same RB pairs form a coalition, and the coalition formation decisions are determined by the best-reply rule. We also adopt the concept 'experimentation', which gives users the capability to destabilise the prevailing structure, hence improve the effectiveness of the final coalition structure. Simulation results demonstrate the throughput and QoS enhancements that can be achieved by employing the proposed scheme.

This paper is organised as follows. Section 2 introduces the system model. The problem formulation is discussed in Section 3. The joint power control, mode selection and

Trans. Emerging Tel. Tech. 2017; 28:e3000 © 2015 John Wiley & Sons, Ltd.
DOI: 10.1002/ett

radio resource allocation scheme is presented in Section 4. Section 5 illustrates the numerical results and gives some analysis. Section 6 concludes the paper.

2. SYSTEM MODEL

Because the uplink resources are under-utilised as compared with the downlink resources, we consider uplink resource sharing between machine-type D2D links and traditional CUEs in a single cell scenario. There are multiple human-type communications devices (HTDs) and MTDs in our scenario, as illustrated in Figure 1. All HTDs constitute the set $\mathcal{H} = \{H_1, \ldots, H_i, \ldots\}$ and $|\mathcal{H}| = P$. We assume that all the HTDs communicate in traditional cellular mode. All MTDs constitute the set $\mathcal{M} = \{M_1, \ldots, M_j, \ldots\}$ with $|\mathcal{M}| = Q$. We take the communication between sensors and the gateway as an example for M2M communications. The sensors can choose to transmit information to the wired gateway as a relay via D2D links, or transmit to the eNB directly via cellular links. The gateway is represented by R.

We consider the LTE-A uplink employing Single Carrier Frequency Division Multiple Access (SC-FDMA) where the radio resources are allocated in units of RB pairs and each user has been granted one RB pair for transmission in a random manner in advance. The total system bandwidth is B and is divided into $2K$ orthogonal RBs. Sensors can choose to communicate with the eNB in traditional cellular mode or transmit information to the gateway via D2D links. If D2D operations are enabled, a sensor chooses a HTD to share its RB pair. Intuitively, sensors can achieve higher data rates by transmitting via the gateway because of the reduced transmission distance. However, spectrum reusing between MTDs and HTDs may cause additional co-channel interference, which restricts the improvement of overall system data rates. To control the intra-cell interference in a reasonable range, we assume that one Machine-type D2D link can only share one existing HTDs RB pair, while the RB pair of an existing HTD can only be reused by one D2D link.

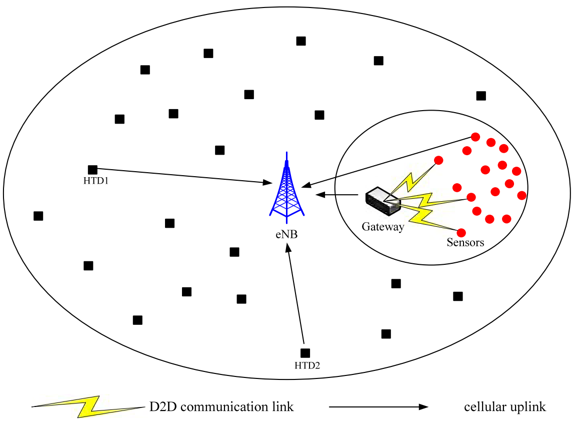


Figure 1. System model of human-to-human/machine-to-machine co-existence network.

We consider a frequency-flat fading channel, which includes pathloss, shadowing and other factors, if any. The channel gain can be expressed as

$$G = \beta L^{-\alpha} |h|^2 \tag{1}$$

where β is the system constant, L is the distance between signal transmitter and receiver, and h is the complex Gaussian random variables with zero mean.

3. PROBLEM FORMULATION

We formulate the joint mode selection and resource allocation problem to improve overall system data rate, as well as enhance network QoS by reducing the average traffic delay of all the UEs. Because of the reduced transmission distance via the D2D link, MTDs can benefit from the D2D communications. However, because spectrum sharing causes co-channel interference, it may also deteriorate UEs' data rates on the contrary. In addition, because traffic load has high impacts on users' queueing delay, it will relieve the eNB from high traffic load and reduce the average delay of UEs when sensors transmit data to the gateway via D2D links. Nevertheless, large traffic on the gateway may also cause high delay for the D2D links. Therefore, how much traffic should be transferred from the eNB to the gateway, that is, how many sensors should transmit via the gateway, needs to be considered.

Our problem is to allocate proper transmission modes and resources to UEs to enhance their utilities, which is given by

$$\max_{RB, p_{H_i}, p_{M_j}} \left(\sum_{i=1}^{P} U_{H_i} + \sum_{j=1}^{Q} U_{M_j} \right) \tag{2}$$

$$s.t. \begin{cases} 0 < p_{H_i} \leqslant p_{H_i}^{\max}, & \forall H_i \in \mathcal{H}, \\ 0 < p_{M_j} \leqslant p_{M_j}^{\max}, & \forall M_j \in \mathcal{M}, \\ R_{H_i} \geqslant R_{H_i}^{thr}, & \forall H_i \in \mathcal{H}, \\ R_{M_j} \geqslant R_{M_j}^{thr}, & \forall M_j \in \mathcal{M}, \end{cases} \tag{3}$$

where

$$U_{H_i} = \omega \times R_{H_i} - (1-\omega) \times d_{H_i} \tag{4}$$

$$U_{M_j} = \omega \times R_{M_j} - (1-\omega) \times d_{M_j} \tag{5}$$

The transmission power of each HTD and MTD is denoted by p_{H_i} and p_{M_j}, and $p_{H_i}^{\max}$ and $p_{M_j}^{\max}$ represent the maximum power consumption for HTDs and MTDs, respectively. The first two constraints in Equation (3) restrict the transmission power to be a positive value and smaller than users' maximum allowed transmission power. Specifically, the transmission power of MTDs needs to be restricted within a smaller range because of the low-capacity battery. The last two constraints in Equation (3) show the minimum data rate requirements imposed by different data volumes. For MTDs, the data packages are transmitted regularly in small size, which puts forward the requirement for low-rate D2D links. However, the packet size for HTDs is relatively large, hence they demand high data-rate links. In Equations (4) and (5), ω and $(1-\omega)$ indicate the degree of sensitivity of UEs to data rates and delay, respectively.

3.1. Throughput

For different transmission modes of MTDs, the data rates can be calculated based on the following two cases:

(i) When an MTD chooses the D2D transmission mode, the received SINR on the gateway is given by

$$\xi_{M_j} = \frac{p_{M_j} G_{M_j,R}}{p_{H_i} G_{H_i,R} + N_0} \tag{6}$$

and the received SINR on the eNB is

$$\xi_{H_i} = \frac{p_{H_i} G_{H_i,B}}{p_{M_j} G_{M_j,B} + N_0} \tag{7}$$

where $G_{M_j,R}$ is the channel gain between M_j and the gateway. Similarly, the channel gain between H_i and the gateway, the channel gain between H_i and the eNB and the channel gain between M_j and the eNB are denoted by $G_{H_i,R}$, $G_{H_i,B}$ and $G_{M_j,B}$, respectively. Moreover, p_{M_j} is the transmission power of M_j, and p_{H_i} is the transmission power of H_i, $N_0 = 2B_{RB}\sigma^2$ is the additive white Gaussian noise power, where B_{RB} is the bandwidth of a RB that equals to 180 KHz and σ^2 is the power spectral density. The achievable throughput of M_j and H_i are given by

$$R_{M_j} = 2B_{RB} \log_2(1 + \xi_{M_j}) \tag{8}$$

and

$$R_{H_i} = 2B_{RB} \log_2(1 + \xi_{H_i}) \tag{9}$$

respectively.

(ii) If spectrum reusing between HTDs and MTDs causes severe co-channel interference, MTDs may need to transmit information directly to the eNB. In this scenario, the data rate of the link between MTD and the eNB is

$$R_{M_j} = 2B_{RB} \log_2\left(1 + \frac{p_{M_j} G_{M_j,B}}{N_0}\right) \tag{10}$$

For the HTDs that do not share their RB pairs with any MTD, the data rate is given by

$$R_{H_i} = 2B_{RB} \log_2\left(1 + \frac{p_{H_i} G_{H_i,B}}{N_0}\right) \tag{11}$$

3.2. Delay

In our work, we consider the M/GI/1 queueing model where traffic arrivals are modulated by a Poisson process. We assume the packet arrival rate at each HTD and MTD are $\lambda_{H_i}, \lambda_{M_j}$, and the traffic size at each HTD and MTD are μ_{H_i} and μ_{M_j}, respectively. Because one of the features of MTC is the small data packets and infrequent traffic (in most cases), we assume that $\lambda_{M_j} < \lambda_{H_i}, \mu_{M_j} < \mu_{H_i}$. The traffic load at each user is $\gamma_{H_i} = \lambda_{H_i} \times \mu_{H_i}$ and $\gamma_{M_j} = \lambda_{M_j} \times \mu_{M_j}$. The data rate of an HTD if it occupies the whole channel allocated to the eNB is

$$R'_{H_i} = W \log_2\left(1 + \frac{p_{H_i} G_{H_i,B}}{N_0}\right) \tag{12}$$

where W is the total bandwidth of the channel allocated the eNB. Then the system load at H_i is defined as

$$\rho_{H_i} = \frac{\lambda_{H_i} \mu_{H_i}}{R'_{H_i}} \tag{13}$$

which denotes the fraction of time required to deliver traffic load γ_{H_i} from H_i to the eNB. Similarly, for the MTDs transmitting in traditional cellular mode, we can get the data rate when it occupies the whole channel allocated to the eNB as

$$R'_{M_j} = W \log_2\left(1 + \frac{p_{M_j} G_{M_j,B}}{N_0}\right) \tag{14}$$

and the system load at M_j is

$$\rho_{M_j} = \frac{\lambda_{M_j} \mu_{M_j}}{R'_{M_j}} \tag{15}$$

Then the total system load at the eNB is given by

$$\rho_{eNB}^{total} = \sum_{i=1}^{P} \rho_{H_i} + \sum_{j=1}^{Q_1} \rho_{M_j} \tag{16}$$

where Q_1 is the number of MTDs transmitting in traditional cellular mode.

Similarly, for the MTDs transmitting in D2D mode, the system load is expressed as

$$\rho_{M_j} = \frac{\lambda_{M_j} \mu_{M_j}}{R'_{M_j}} \tag{17}$$

where

$$R'_{M_j} = W \log_2\left(1 + \frac{p_{M_j} G_{M_j,R}}{N_0}\right) \tag{18}$$

Then the total system load at the gateway is

$$\rho_{R}^{total} = \sum_{j=1}^{Q_2} \rho_{M_j} \tag{19}$$

where Q_2 is the number of MTDs transmitting via the gateway.

Trans. Emerging Tel. Tech. 2017; 28:e3000 © 2015 John Wiley & Sons, Ltd.
DOI: 10.1002/ett

As proved in [23], $\rho^{total}/(1-\rho^{total})$ is equal to the average number of flows served by the eNB. To guarantee that the eNB is not overloaded, ρ^{total} needs to be restricted with $0 < \rho^{total} < 1$. According to the Little's law, the long-term average number of users in a stable system is equal to the long-term average effective arrival rate multiplied by the average time a user spends in the system. Therefore, we can get the average traffic delay for UEs transmitting via the eNB and the gateway as

$$d_{eNB} = \frac{\rho_{eNB}^{total}/(1-\rho_{eNB}^{total})}{\lambda} \tag{20}$$

$$d_{R} = \frac{\rho_{R}^{total}/(1-\rho_{R}^{total})}{\lambda} \tag{21}$$

respectively.

4. POWER CONTROL, MODE SELECTION AND RADIO RESOURCE ALLOCATION

4.1. Power control

In this step, we assume that each MTD has been allocated with the proper transmission mode and RB pair in advance. When a MTD chooses the D2D mode, the sum of the throughput of the spectrum sharer (H_i, M_j) is

$$R(p_{M_j}, p_{H_i}) = R_{M_j} + R_{H_i} \tag{22}$$

where R_{M_j} and R_{H_i} are as expressed in Equations (8) and (9). The problem of maximising $R(p_{M_j}, p_{H_i})$ has been discussed in [24]. Because $R(p_{M_j}, p_{H_i}^{\max})$ is convex with p_{M_j} [24], M_j chooses the transmission power between the highest and lowest allowed transmission power that can achieve the higher $R(p_{M_j}, p_{H_i})$. Because of symmetry, this analysis also holds for H_i. If we denote the optimal power allocation as $(p_{M_j}^{*}, p_{H_i}^{*})$, we have $(p_{M_j}^{*}, p_{H_i}^{*}) \in \mathcal{P}$ where $\mathcal{P} = \{(p_{M_j}^{\max}, p_{H_i}^{\max}), (p_{M_j}^{\min}, p_{H_i}^{\max}), (p_{M_j}^{\max}, p_{H_i}^{\min})\}$.

For the MTDs that transmit in traditional cellular modes, no interference needs to be taken into account. Therefore, they are allowed to transmit with the maximum power, that is, $p_{M_j}^{\max}$. Similarly, for the HTDs that do not share their RB pairs with any MTD, the allocated power is $p_{H_i}^{\max}$ to maximise their data rates.

4.2. Mode selection and radio resource allocation based on coalition formation game

In this step, proper transmission modes and spectrum resources are allocated to MTDs to improve system throughput and reduce average traffic delay. To relieve the eNB from high computational complexity, we use the distributed coalition formation game to solve this problem.

4.2.1. Coalition formation game model.

In the game model, a set of players seek to form cooperative groups, that is, coalitions, to strengthen their positions in the game [25]. In our work, the player set is $\mathcal{N} = \mathcal{H} \cup \mathcal{M}$. The coalition structure representing the partition of players is denoted by $\mathcal{S} = \{S_1, \ldots, S_p, \ldots S_P\}$, where S_p is a coalition. For $\forall p' \neq p, S_{p'} \cap S_p = \emptyset$, we have $\cup_{p=1}^{P} S_p = \mathcal{N}$.

According to the mode that each MTD chooses, we can categorise the coalitions in our work into the following three cases:

(1) Case 1: A coalition contains one HTD and one MTD, that is, $S_p = \{H_i, M_j\}$. In this case, M_j chooses the D2D mode and reuses the RB pair of H_i.

(2) Case 2: An MTD forms a singleton set, that is, $S_p = \{M_j\}$. In this case, M_j chooses the traditional cellular mode and uses an exclusive RB pair.

(3) Case 3: An HTD forms a singleton set, that is, $S_p = \{H_i\}$. In this case, H_i does not share its RB pair with any MTD.

Definition 1. *If the coalition value that quantifies the worth of a coalition depends solely on the members of that coalition, with no dependence on how the players in other coalitions are structured, this coalitional game is in the characteristic form.*

In our work, UEs sharing the same RB pair are in the same coalitions, that is, players in different coalitions are allocated with orthogonal RBs. Therefore, players in different coalitions do not cause interference to each other. In other words, the utility of each player only depends on the other player in the same coalition, with no relevance to the players in other coalitions. Hence, the proposed game model is in the characteristic form.

For a coalition formation game in the characteristic form, the payoff allocation vector of players is denoted by $\Phi = \{\varphi_1, \ldots, \varphi_x, \ldots\}$, which represents the utility gains of each player.

Definition 2. *In a coalitional game, the transferable utility (TU) property implies that the coalition value is a real number, and the payoff that each player receives is a random division from the coalition value. The non-transferable utility property implies that the coalition value is a set of payoff vectors. The payoff that each player receives is no longer a random value, but depends on the selected strategies.*

In the proposed game model, the value of a coalition $v(S_p)$ is defined as the sum of utilities of all the players in the coalition,

$$v(S_p) = \sum_{x \in S_p} U_x \tag{23}$$

where x can be either an MTD or an HTD in the coalition S_p, and U_x is the corresponding utility achieved by the user as defined in Equations (4) and (5).

The payoff that each player receives is defined as the individual contribution that the player provides to the coalition value, which is expressed as

$$\varphi_x = v(S_p) - v(S_p \mid x) \tag{24}$$

When we consider maximising the system sum rate, each player can consider any joint resource allocation and mode selection strategy that achieves the maximum total sum rate; thus, the proposed game model is in TU form.

4.2.2. Best-reply process.

The initial state of the game is the set of singleton coalitions, where all MTDs and HTDs are assumed to communicate in traditional cellular mode. Thus, each player's payoff is the coalition value at this state. In the following steps, MTDs will be chosen randomly to select their proper modes and spectrum sharers. If an MTD finds that communicating in cellular mode can achieve higher payoff, it will choose to stay in the singleton coalition.

In our work, we assume that all the users are myopic and self-serving, which means that they will join in a coalition if and only if it can make them the best benefits. Thus, the coalition formation process is based on the best-reply rule: a player will join in a coalition only if this coalition promises her the highest payoff in the next step [26].

Definition 3. *Coalition collection is defined as a set of disjoint coalitions. In this game model, the coalitions, which contain MTDs, form the MTD collection $\mathcal{A}_M$, while the singleton coalitions, each of which contains only one HTD, form the HTD collection $\mathcal{A}_H$.*

The coalition structure changes when an MTD chooses to leave the current coalition to form a singleton coalition or join in a coalition of the HTD collection. In this game model, an MTD's opportunity being selected to change her strategy arises at random. We assume that M_j is selected to revise her strategy, then all the other players keep their strategies, that is,

$$\forall x \neq M_j \Longrightarrow S^{t+1}(x) = S^t(x), u_x^{t+1} = u_x^t \tag{25}$$

where $S^t(x)$ represents the coalition in which the player x exists at time t, and u_x^t is the payoff of x at time t. Because the best-reply rule guarantees that players can select the coalition that promises her the highest payoff, the payoff and selected coalition of M_j at time $t+1$ can be calculated as in Equations (26) and (27),

$$u_{M_j}^{t+1} = \max\left\{\max_{S_m \in \mathcal{A}_H \cup \emptyset}\left(v\left(S_m \cup \{M_j\}\right) - u_{H_i}^t\right), u_{M_j}^t\right\} \tag{26}$$

$$S^{t+1}(M_j) = \begin{cases} \left\{\arg\max_{S_m \in \mathcal{A}_H \cup \emptyset}\left(v\left(S_m \cup \{M_j\}\right) - u_{H_i}^t\right)\right\} \cup \{M_j\}, & u_{M_j}^{t+1} \neq u_{M_j}^t, \\ S^t(M_j), & u_{M_j}^{t+1} = u_{M_j}^t \end{cases} \tag{27}$$

where S_m is an empty set or a coalition of the HTD collection. If S_m is an empty set, we have $u_{H_i}^t = 0$; otherwise, $u_{H_i}^t$ is the payoff of the HTD in coalition S_m at time t. It should be noted that Equations (26) and (27) exist only when the constraints in Equation (3) are satisfied.

One characteristic of a coalition formation game is that forming a coalition can bring gains to the players, while the gains are restricted by the cost for forming a coalition [25]. In our game model, if M_j chooses to join in a coalition of the HTD collection where H_i exists, it means that M_j chooses the D2D mode and shares the RB pair with H_i. In this way, the gain for M_j is the higher data rate because of the reduced transmission distance, while the gain for H_i is the lower delay because of the smaller traffic load at the eNB. However, for both H_i and M_j, the cost of forming the coalition (H_i, M_j) is the co-channel interference caused by RB reusing.

4.2.3. Experimentation.

For a TU game, the payoff allocation vector $\Phi = \{\varphi_1, \ldots, \varphi_x, \ldots\}$ is said to be blocked by a coalition S_b if

$$\sum_{x \in S_b} \varphi_x < v(S_b) \tag{28}$$

Based on the current best-reply rule, the players can only switch between existing coalitions, therefore, it is possible that there exists a blocking coalition that cannot be formed directly based on the current coalition structure. This is the reason why 'experimentation' was introduced in [26], where it provided players with the capability to destabilise the prevailing structure. Players are allowed to take random actions (with a small probability) whenever they are members of a potentially blocking coalition even though the new coalition is a suboptimal one. This is consistent with the psychological phenomenon, where a player will tend to get 'fed up' with the current situation and might do something irrational if she realises that she is performing poorly, just in order to induce some changes. Thus, 'experimentation' does not require any higher degree of rationality, or farsightedness for players.

The algorithm for joint mode selection and radio resource allocation based on the best-reply process with 'experimentation' is described in Algorithm 1.

Trans. Emerging Tel. Tech. 2017; 28:e3000 © 2015 John Wiley & Sons, Ltd.
DOI: 10.1002/ett

Algorithm 1 Distributed Joint Mode Selection and Resource Management Algorithm

Initialise $t = 0$;
The initial state is the set of singleton coalitions. All singleton sets of HTDs constitute the HTD collection $\mathcal{A}_H^0$, i.e., $\mathcal{A}_H^0 = \{\{H_0\}, \ldots, \{H_P\}\}$, while all singleton sets of MTDs constitute the MTD collection $\mathcal{A}_M^0$, i.e., $\mathcal{A}_M^0 = \{\{M_0\}, \ldots, \{M_Q\}\}$;
loop
  At time $t > 0$, randomly select a coalition $S^t(M_j) \in \mathcal{A}_M^t$ to revise M_j's strategy, where $S^t(M_j)$ is the coalition that the player M_j exists at time t. Other players keep their strategies, i.e., $S^{t+1}(x) = S^t(x)$, $u_x^{t+1} = u_x^t$, for all $x \neq M_j$;
  If there exists a coalition $S_b(M_j)$ blocking the current payoff allocation, then M_j will take the best-reply process with probability $1 - \varepsilon$ and "experiment" with probability ε. Otherwise, M_j takes the best-reply process with probability 1.
  - - - - - - ***Best-reply Process***
  Calculate the maximum expected payoff obtained by M_j based on the current coalition structure, i.e.,

$$u_{M_j}^e = \max_{S_m \in \mathcal{A}_H^t} \left(v(S_m \cup \{M_j\}) - u_{H_i}^t \right) \tag{29}$$

  where $u_{M_j}^e$ is the expected payoff.
  if $u_{M_j}^e > u_{M_j}^t$ and all the constraints in Equation (3) are satisfied **then**
    $S^{t+1}(M_j) = \{\arg \max_{S_m \in \mathcal{A}_H^t} (v(S_m \cup \{M_j\}) - u_{H_i}^t)\} \cup \{M_j\}$,
    $\mathcal{A}_M^{t+1} = \{\mathcal{A}_M^t \setminus \{S^t(M_j)\}\} \cup \{S^{t+1}(M_j)\}$,
    $\mathcal{A}_H^{t+1} = \{\mathcal{A}_H^t \setminus \{S^{t+1}(M_j) \setminus \{M_j\}\}\} \cup \{S^t(M_j) \setminus \{M_j\}\}$;
  else
    $S^{t+1}(M_j) = S^t(M_j)$, $\mathcal{A}_M^{t+1} = \mathcal{A}_M^t$, $\mathcal{A}_H^{t+1} = \mathcal{A}_H^t$;
  end if
  $t = t + 1$;
  - - - - - - ***Experimentation***
  M_j randomly chooses a coalition S_r from the HTD collection with equal probability to join in as long as constraints in Equation (3) are all satisfied;
  $S^{t+1}(M_j) = S_r \cup \{M_j\}$,
  $\mathcal{A}_M^{t+1} = \{\mathcal{A}_M^t \setminus \{S^t(M_j)\}\} \cup \{S^{t+1}(M_j)\}$,
  $\mathcal{A}_H^{t+1} = \{\mathcal{A}_H^t \setminus \{S_r\}\} \cup \{S^t(M_j) \setminus \{M_j\}\}$;
  $t = t + 1$;
end loop when a stable state is obtained.

Because players are selected randomly to change their strategies at each stage, the coalition structure $\mathcal{CS}_t$ at each step can be regarded as a random variable. As the transition probability at any present state $\mathcal{CS}_t$ does not depend on the prior ones, the Markovian property is supported. Therefore, we can model the coalition formation process as a Markov chain. The state space of the proposed Markov chain is the set of all the possible coalition structures, and its size is given as $\sum_{j=0}^{Q} \binom{P}{j} \times \binom{Q}{j} \times j!$.

Based on the best-reply rule with 'experimentation', the state transition probability of the proposed Markov Chain is given by

$$p(\mathcal{CS}_{t+1} \mid \mathcal{CS}_t) = \frac{1}{Q} \times \frac{1}{P'} \times \gamma(\mathcal{CS}_{t+1} \mid \mathcal{CS}_t) \tag{30}$$

where $\mathcal{CS}_{t+1}$ is a coalition structure that can be derived from $\mathcal{CS}_t$ in one step, that is, $\mathcal{CS}_{t+1} = ((\mathcal{CS}_t \setminus \{S_k\}) \setminus \{S_m\}) \cup (S_k \setminus \{M_j\}) \cup (S_m \cup \{M_j\})$. P' is the number of coalitions in the HTD collection at time t. $\gamma(\mathcal{CS}_{t+1} \mid \mathcal{CS}_t)$ is the probability that the player decides to change the current coalition structure from $\mathcal{CS}_t$ to $\mathcal{CS}_{t+1}$ based on the best-reply rule with 'experimentation', which is expressed as

$$\gamma(\mathcal{CS}_{t+1} \mid \mathcal{CS}_t) = \begin{cases} 1, & \chi(\mathcal{CS}_{t+1}) > \chi(\mathcal{CS}_t), \\ \varepsilon, & \text{otherwise,} \end{cases} \tag{31}$$

where $\chi(\mathcal{CS}_t)$ is the sum of values of all the coalitions in $\mathcal{CS}_t$.

Next, we will discuss the computational complexity of the proposed distributed algorithm. For each best-reply operation, the MTD needs to search for all the coalitions in the HTD collection to find the optimal one. Assuming the worst case, that is, all the MTDs were not able to find the optimal coalitions to join in during the previous iterations, the number of calculations for best-reply operations is $P \times Q$. Searching for blocking coalitions also contributes much to the computational complexity, which requires an exhaustive search to check $P \times Q$ different coalitions. Therefore, the computational complexity of the proposed algorithm can be expressed as $\mathcal{O}(Q * P^2)$. It can be easily seen that the complexity is much lower than an exhaustive search in the centralised approach.

5. SIMULATION RESULTS AND ANALYSIS

5.1. Performance metrics

In this section, we evaluate the performance of the joint mode selection and resource allocation algorithm for D2D communications. The benchmark is a modified joint mode selection and resource allocation scheme based on the greedy heuristic algorithm proposed in [8]. In the heuristic algorithm [8], the eNB selects the cellular uplink with the highest channel gain to share resource with the D2D pair with the lowest interference channel gain. Different from the algorithm in [8], we allow the D2D pairs that did not find a proper spectrum reusing partner to transmit in cellular mode rather than leave them idle in the benchmark.

The metrics that we use to evaluate the performance of the proposed algorithm include the following:

- Throughput gain: this metric indicates the percentage improvement of the system throughput compared

Table I. Simulation Parameters.

Cell radius	500 m, 1 km
Maximum transmission power of HTDs (p_{HTD}^{max})	250 mW
Maximum transmission power of MTDs (p_{MTD}^{max})	100 mW, 150 mW, 200 mW
Minimum data rate requirement for human-type links (R_{HTD}^{thr})	300 Kbps
Minimum data rate requirement for machine-type links (R_{MTD}^{thr})	50 Kbps
Maximum distance between sensors and the gateway (r)	20 m, 40 m, 60 m, 80 m, 100 m
Number of HTDs (P)	20, 50, 80
Number of MTDs (Q)	10%, 20%, ..., 100% of HTDs (P)
Bandwidth of each RB	180 kHz
ε	0.01
β	0.01
N_0	−98 dBm

Human-type communications devices, HTDs; machine-type communications devices, MTDs; Resource Block, RB.

to the scenario where all users transmit in traditional cellular mode;

- Ratio of the number of MTDs transmitting in D2D mode and the total number of MTDs: this metric reflects the percentage of MTDs that can transmit in D2D mode;
- Average traffic delay: this metric is calculated based on the Little's law as explained in Section 3;
- Fairness: Jain's fairness index is used to evaluate the users' fairness. The larger the index value, the better the fairness.

5.2. Scenario

In our scenario, for the sake of simplicity, we assume that the packet arrival rate λ at each HTD and MTD is 1 and 0.5, and the mean packet size μ at each HTD and MTD is 100 Kbits and 20 Kbits, respectively. The base station is centred in the cell, and the HTDs and the gateway locate randomly with the radial and angular coordinates following the uniform distribution. MTDs locate randomly within the circle, which is centred with the gateway. Other simulation parameters are listed in Table I. We give two values for cellular cell radius: 500 m and 1 km, to evaluate the performance of the algorithms under different cellular radii. We also give different maximum transmission power values of MTDs: 100 mW, 150 mW and 200 mW, to see how the proposed algorithm will perform under different scenarios.

5.3. Results and discussions

Figure 2 shows the effect of different cellular cell radii. From the figure, the throughput gain increases as the cellular cell radius increases, which is pretty intuitive because the MTDs benefit from the reduced distance by D2D communications.

Figure 3 compares the performance of the proposed and heuristic algorithms for different maximum transmission power and maximum distance between the gateway and the sensors. It is seen that the performance of the proposed and heuristic algorithms declines with the increment of

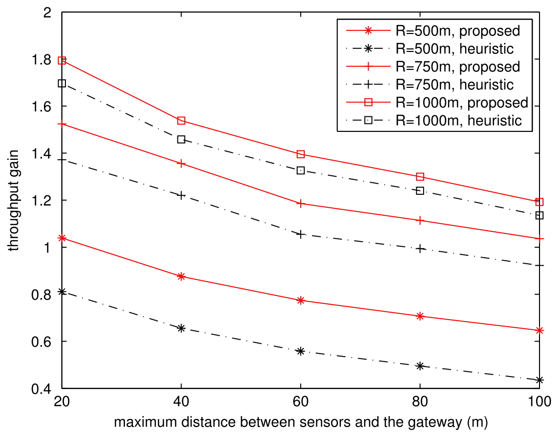
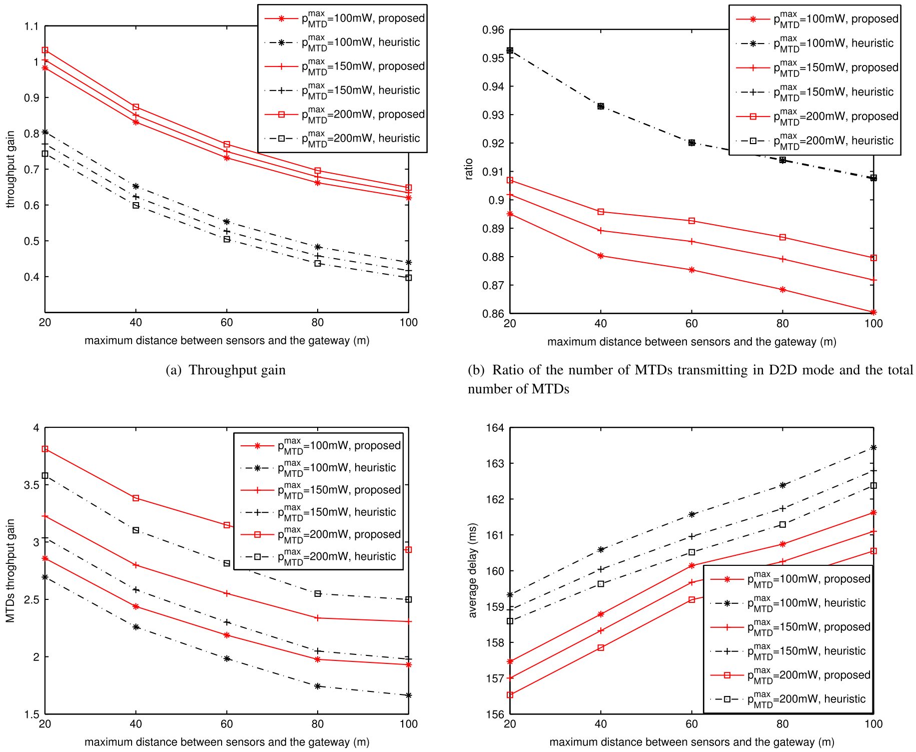


Figure 2. Performance for different cell radii, where p_{MTD}^{max}=100 mW, r=30 m, P=50, Q=20.

distance between sensors and the gateway. This can be easily understood because of the decreased channel gain when the distance gets larger. In Figure 3(a), the proposed algorithm improves the throughput gain for around 45% compared with the heuristic one. Further, the overall throughput gain increases as the maximum transmission power of MTDs increases for the proposed algorithm. This is because more sensors can get access to communicating with the gateway when the transmission power constraint is looser. In contrast, for the heuristic algorithm, the throughput gain decreases with the increment of maximum transmission power. This is because the heuristic algorithm does not give performance comparison when a device selects between D2D and cellular modes. Therefore, increasing the maximum transmission power of MTDs increases the interference caused to the HTDs. As a result, the overall throughput gain of the heuristic algorithm decreases.

We observe from Figure 3(b) that the percentage of MTDs transmitting in D2D mode for the heuristic algorithm is larger than that for the proposed algorithm, however, the MTDs throughput gain of the proposed algorithm is larger than that of the heuristic algorithm as shown in

Trans. Emerging Tel. Tech. 2017; 28:e3000 © 2015 John Wiley & Sons, Ltd.
DOI: 10.1002/ett



(a) Throughput gain

(b) Ratio of the number of MTDs transmitting in D2D mode and the total number of MTDs

(c) Throughput gain of MTDs

(d) Average system delay

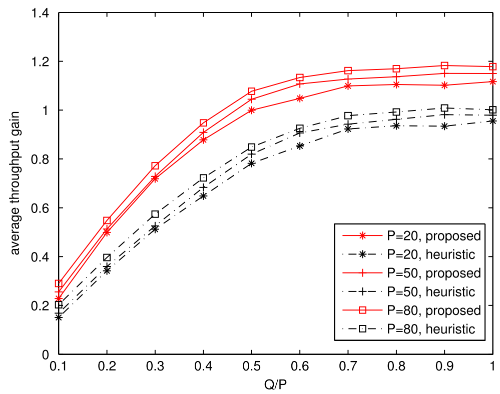
Figure 3. Performance for different maximum distances between sensors and the gateway where cellular cell radius = 500 m, $P = 50$, $Q = 20$. (a) Throughput gain, (b) Ratio of the number of machine-type communications devices (MTDs) transmitting in device-to-device (D2D) mode and the total number of MTDs, (c) Throughput gain of MTDs, (d) Average system delay.

Figure 3(c). This is somewhat strange, but makes sense. As mentioned at the start of this part, the eNB allocates the spectrum resource of the cellular user with the highest uplink channel gain to the D2D candidate with the lowest interference channel gain as long as the SINR constraints are satisfied. In the proposed algorithm, an MTD can share the RB pair of a HTD with both the SINR constraints and the best-reply constraints, which is more strict than the constraints in the heuristic algorithm. Therefore, the percentage of MTDs transmitting in D2D mode of the proposed algorithm is lower than that of the heuristic one. For the heuristic algorithm, there is no constraint guaranteeing that the achievable throughput of the selected mode is higher than the current one; thus, the MTDs throughput gain is lower than that of the proposed algorithm.

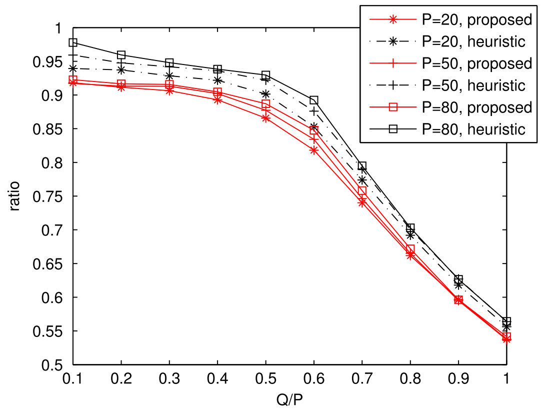
Figure 3(d) depicts the average system delay with different maximum distances between the gateway and the sensors and different maximum transmission power of MTDs. It can be seen that the proposed algorithm provides better performance than the heuristic one. When r increases, the average system delay increases, because the traffic load of MTDs increases with larger transmission distance. Figure 3(d) also shows that larger maximum transmission power of MTDs leads to lower system delay for the proposed algorithm, ascribed to the higher ratio of MTDs transmitting in D2D mode and the more traffic offloading by D2D communications.

Figure 4 demonstrates the effect of different numbers of HTDs and MTDs. From Figure 4(a), we observe that when Q/P reaches 0.6, the system throughput gain does not increase any more, which indicates the saturation of the network. This is because of more interference inflicted by the larger number of devices, and some MTDs will find a proper HTD to share spectrum with. Meanwhile, for the same value of Q/P, the performance improves with larger P. Increasing number of HTDs helps MTDs to choose a more proper spectrum-reusing partner. According to the ratio of MTDs transmitting in D2D mode with different values of P and Q shown in Figure 4(b), the degradation of the ratio becomes fast when the value of Q/P is larger than 0.6. Therefore, we can conclude that the number of devices transmitting in D2D mode in a network has better no larger than 60% of the number of cellular users.

Figure 5 shows the fairness performance of the proposed and the heuristic algorithms. We adopt the Jain's fairness index to do the evaluation [27], and the index is calculated by: $\mathcal{J} = \left(\sum_{x=1}^{n} r_x\right)^2 / \left(n \times \sum_{x=1}^{n} r_x{}^2\right)$. The results range from $\frac{1}{n}$ (worst case) to 1 (best case), and it is maximum when all users get the same value. From this figure, we can find that the proposed algorithm achieves better fairness compared to the heuristic one. In the heuristic



(a) Throughput gain



(b) Ratio of number of MTDs transmitting in D2D mode and the total number of MTDs

Figure 4. Performance for different numbers of human-type communications devices (HTDs) and machine-type communications devices (MTDs), where cellular cell radius = 500 m, p_{MTD}^{max} = 100 mW, r = 30 m. (a) Throughput gain, (b) Ratio of number of MTDs transmitting in device-to-device (D2D) mode and the total number of MTDs.

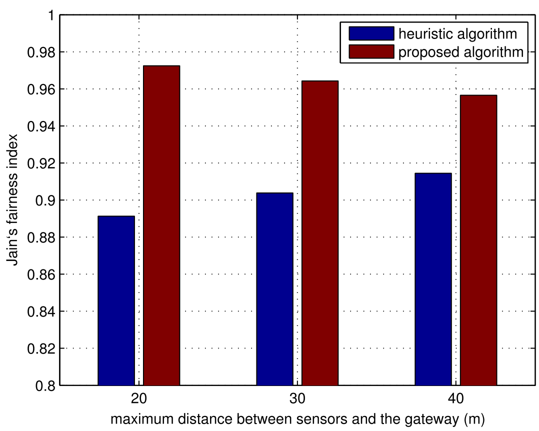


Figure 5. Jain's fairness index for different maximum distances between sensors and the gateway, where p_{MTD}^{max} = 100 mW, cellular cell radius = 500 m, P = 50, Q = 20.

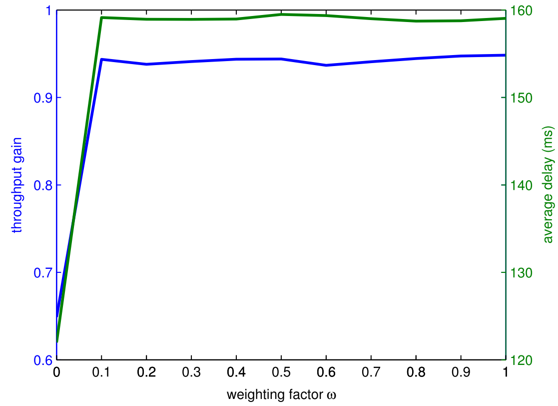


Figure 6. Throughput gain and delay with different values of ω, where p_{MTD}^{max} = 100 mW, cellular cell radius = 500 m, P = 50, Q = 20.

algorithm, the eNB selects the CU with highest channel gain of the CU-eNB link to share resource with the D2D pair with the lowest interference channel gain of the D2D-eNB link, which restricts the fairness performance. For the proposed algorithm, D2D pairs are selected randomly to find a proper transmission mode, which benefits the fairness.

Figure 6 shows the impact of the weighting factor ω in the overall performance. On one hand, it is shown that the average traffic delay is reduced by about 25% when explicit terms of delay are taken into consideration in the utility function compared to the scenario where the utility function is only a function of data rate. On the other hand, the network throughput gain is improved with larger value of ω, this is because of the higher degree of sensitivity that is put on the data rate.

6. CONCLUSIONS

In this paper, we have proposed a joint mode selection, radio resource allocation and power control algorithm to leverage machine-type D2D links to improve overall system data rate and reduce average traffic delay. We consider different features of HTC and MTC, including differences in terms of power consumption, data rate and packet size. The coalition formation game is adopted, where the UEs choose their transmission modes and radio resources autonomously. The coalition formation process is determined by the best-reply rule with 'experimentation'. Simulation results demonstrate that the proposed algorithm improves the system data rate and fairness. In addition, the average traffic delay is reduced because the delay term is added in the utility function.

REFERENCES

1. Fodor G, Dahlman E, Mildh G, Parkvall S, Reider N, Mikls G, Turnyi Z. Design aspects of network assisted device-to-device communications. *IEEE Communications Magazine* 2012; **50**(3): 170–177.

Trans. Emerging Tel. Tech. 2017; 28: e3000 © 2015 John Wiley & Sons, Ltd.
DOI: 10.1002/ett

2. Laya A, Wang K, Widaa AA, Alonso-Zarate J, Markendahl J, Alonso L. Device-to-device communications and small cells: enabling spectrum reuse for dense networks. *IEEE Wireless Communications* 2014; **21**(4): 98–105.
3. Militano L, Orsino A, Araniti G, Molinaro A, Iera A. Overlapping coalitions for D2D-supported data uploading in LTE-A systems. In *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Hong Kong, 2015; 1716–1720.
4. Condoluci M, Militano L, Orsino A, Alonso-Zarate J, Araniti G. LTE-direct vs. WiFi-direct for machine-type communications over LTE-A systems. In *IEEE PIMRC: Workshop on M2M Communications: Challenges, Solutions and Applications*, Hong Kong, 2015; 1145–1149.
5. Doppler K, Chia-Hao Y, Ribeiro CB, Janis P. Mode selection for device-to-device communication underlaying an LTE-advanced network. In *2010 IEEE Wireless Communications and Networking Conference (WCNC)*, Sydney, 2010; 1–6.
6. Chia-Hao Y, Doppler K, Ribeiro CB, Tirkkonen O. Resource sharing optimization for device-to-device communication underlaying cellular networks. *IEEE Transactions on Wireless Communications* 2011; **10**(8): 2752–2763.
7. Chunmei X, Shaoyi X, Sup KK. Overlapping coalition formation games-based resource allocation for device-to-device communication in LTE-A network. *Transactions on Emerging Telecommunications Technologies* 2015; **26**: 1–11.
8. Zulhasnine M, Huang C, Srinivasan A. Efficient resource allocation for device-to-device communication underlaying LTE network. In *2010 IEEE 6th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob)*, Niagara Falls, 2010; 368–375.
9. Peng T, Qianxi L, Wang H, Shaoyi X, Wang W. Interference avoidance mechanisms in the hybrid cellular and device-to-device systems. In *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, Tokyo, 2009; 617–621.
10. Feng D, Lu L, Yuan-Wu Y, Li GY, Feng G, Li S. Device-to-device communications underlaying cellular networks. *IEEE Transactions on Communications* 2013; **61**(8): 3541–3551.
11. Wang F, Chen X, Song L, Han Z. Energy-efficient resource allocation for device-to-device underlay communication. *IEEE Transactions on Wireless Communications* 2015; **14**(4): 2082–2092.
12. Si W, Zhu X, Zhang X, Yang D. QoS-aware mode selection and resource allocation scheme for Device-to-Device (D2D) communication in cellular networks. In *2013 IEEE International Conference on Communications Workshops (ICC)*, Budapest, 2013; 101–105.
13. Chien CP, Chen YC, Hsieh HY. Exploiting spatial reuse gain through joint mode selection and resource allocation for underlay device-to-device communications. In *2012 15th International Symposium on Wireless Personal Multimedia Communications (WPMC)*, Taipei, 2012; 80–84.
14. Lei L, Kuang Y, Cheng N, Shen X, Zhong D, Lin C. Delay-optimal dynamic mode selection and resource allocation in device-to-device communications - Part I: optimal policy. *IEEE Transactions on Vehicular Technology* 2015. DOI: 10.1109/TVT.2015.2444795.
15. Lei L, Kuang Y, Cheng N, Shen X, Zhong D, Lin C. Delay-optimal dynamic mode selection and resource allocation in device-to-device communications - Part II: practical algorithm. *IEEE Transactions on Vehicular Technology* 2015. DOI: 10.1109/TVT.2015.2444791.
16. Chen H, Ren P, Sun L, Du Q. A joint optimization of transmission mode selection and resource allocation for cognitive relay networks. In *2013 IEEE International Conference on Communications (ICC)*, Budapest, 2013; 2852–2856.
17. Marcin R. Location-based mode selection and resource allocation in cellular networks with D2D underlay. In *Proceedings of the 21th European Wireless Conference*, Budapest, 2015; 1–6.
18. Li Y, Jin D, Gao F, Zeng L. Joint optimization for resource allocation and mode selection in device-to-device communication underlaying cellular networks. In *2014 IEEE International Conference on Communications (ICC)*, Sydney, 2014; 2245–2250.
19. Guanding Y, Lukai X, Feng D, Yin R, Li GY, Jiang Y. Joint mode selection and resource allocation for device-to-device communications. *IEEE Transactions on Communications* 2014; **62**(11): 3814–3824.
20. Zhou H, Ji Y, Li J, Zhao B. Joint mode selection, MCS assignment, resource allocation and power control for D2D communication underlaying cellular networks. In *2014 IEEE Wireless Communications and Networking Conference (WCNC)*, Istanbul, 2014; 1667–1672.
21. Akkarajitsakul K, Phunchongharn P, Hossain E, Bhargava VK. Mode selection for energy-efficient D2D communications in LTE-advanced networks: a coalitional game approach. In *IEEE International Conference on Communication Systems (ICCS)*, Singapore, 2012; 488–492.
22. Cai Y, Chen H, Wu D, Yang W, Zhou L. A distributed resource management scheme for D2D communications based on coalition formation game. In *2014 IEEE International Conference on Communications Workshops (ICC)*, Sydney, 2014; 355–359.

23. Kim H, de Veciana G, Yang X, Venkatachalam M. Distributed α-optimal user association and cell load balancing in wireless networks. *IEEE/ACM Transactions on Networking* 2012; **20**(1): 177–190.
24. Gjendemsjo A, Gesbert D, Oien GE, Kiani SG. Optimal power allocation and scheduling for two-cell capacity maximization. In *2006 4th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, Boston, 2006; 1–6.
25. Saad W, Han Z, Debbah M, Hjorungnes A, Basar T. Coalitional game theory for communication networks. *IEEE Signal Processing Magazine* 2009; **26**(5): 77–97.
26. Arnold T, Schwalbe U. Dynamic coalition formation and the core. *Journal of Economic Behavior and Organization* 2002; **49**: 363–380.
27. Liu D, Chen Y, Chai KK, Zhang T, Elkashlan M. Opportunistic user association for multi-service hetnets using nash bargaining solution. *IEEE Communications Letters* 2014; **18**(3): 463–466.

Trans. Emerging Tel. Tech. 2017; 28 : e3000 © 2015 John Wiley & Sons, Ltd.
DOI: 10.1002/ett