ORIGINAL RESEARCH PAPER

Quality of service optimisation of device-to-device communications underlaying cellular networks

Radwa Ahmed Osman1,2 | Xiao-Hong Peng1 | Mohamed A. Omar2 | Qiang Gao3

1 School of Engineering & Applied Science, Aston University, Birmingham, UK
2 College of Engineering & Technology Arab Academy for Science, Technology & Maritime Transport Alexandria, Egypt
3 School of Electronic and Information Engineering, Beihang University, Beijing, China

Correspondence
Radwa Ahmed Osman, School of Engineering & Applied Science, Aston University, Birmingham B4 7ET, UK.
Email: radwa.ahmed@aast.edu

Abstract
Device-to-device (D2D) communications play a significant role in increasing the capacity of cellular networks. D2D enables direct interaction between mobile users without traversing the base station (BS) and at the same time causes interference between D2D and cellular links which can affect the system performance. To ensure efficient and reliable D2D operations within a cellular network, the related quality of service (QoS) requirement needs to be met in the design of such a system involving both D2D and cellular users in a same network. In this study, we have investigated three different transmission schemes (cellular, D2D and cooperative D2D modes) by deriving the closed-form expressions of key QoS performance such as system reliability, achievable data rate, and energy efficiency for these three transmission schemes. Based on this establishment, we have also examined the effects of using different numbers of parallel relay branches and different number of relays within each branch on the network performance to reveal how effectively the cooperative D2D can enhance QoS in comparison with other transmission methods. The proposed approach can be optimised through adaptively selecting appropriate transmission schemes and, as a result, good trade-offs between system reliability and efficiency can also be achieved under various environmental conditions.

1 | INTRODUCTION

Device-to-device (D2D) communications have a great potential for improving user experience, network capacity, saving battery lifetime and enhancing the performance of cellular networks [1, 2]. Furthermore, it is considered as one of the most promising techniques for the future cellular networks, thanks to the benefits that it offers over traditional cellular communications [3], such as reducing latency, saving the limited resources for the whole network and reducing signalling overhead. Additionally, D2D is a recommended technique for improving the cellular network performance such as improving spectral efficiency and saving power within the network. Therefore, in order to design an efficient D2D communications underlay cellular networks, spectral and energy efficiency (EE) must be well considered [4, 5], and these are the two most important aspects that attract the focus of all the interested researchers in this area.

Like in any real-time content delivery and for efficient data transmissions, it is important to ensure quality of service (QoS) in D2D communications within cellular networks. However, to meet these requirements, there is a need to tackle challenges from physical and resource limitations, including multipath fading, Doppler spread and increment of data loss caused by changes in environment, interference and noise, as these factors will disperse the devices power involved in the network and also will affect network performance. We will show in this study how cooperative D2D (coop-D2D) can help to enhance QoS in the environment described above.

The coexistence of D2D links with the cellular network can be described using two operating modes, that is, the underlaying and the overlaying modes. In the underlaying mode, cellular users (CUs) and D2D users simultaneously transmit data over the same spectrum resources. As a consequence, interference exists between cellular user equipment (CUE) and D2D devices. In order to avoid the flooding interference, efficient resource sharing schemes and interference management mechanisms have been proposed [6] to fully exploit the benefits of...
using D2D transmissions. On the other hand, when the over-laying mode is used, an optimal power and rate control solution is given for D2D users, while satisfying the interference limits related to CUs; thus enhancing the system performance and achieving proportional fairness between D2D users and CUs [7].

Moreover, coop-D2D communication is considered as an effective way to help enhance the system performance and improve the quality of the communication link between the base station (BS) and the CUE in addition to D2D links. In coop-D2D communications devices can help each other in transmitting the data and these devices are known as relays. Decode-and-forward (DF) and amplify-and-forward (AF) relaying are the most common cooperative communications protocols [8, 9] and have extensively investigated communications among CUEs to share their limited resources. However, involving more relay nodes consumes more energy, although this can be mitigated to some degree through proper power allocation schemes [10].

In this study, based on the initial work presented in [11], we examine the overall system performance of three different transmission modes in a cellular network that includes D2D, coop-D2D and CUE-to-BS (or CUE-BS) communications. EE is a very important requirement for D2D communications as most D2D devices are powered by batteries. Therefore, we aim to maximise the EE and the achievable data rate (DR) with QoS enhancement for the three transmission modes presented in the study. In addition, we show how D2D communication influences other existing communication links (CUE-BS) which share the same spectral resource. We also investigate, under different conditions such as relaying method, channel conditions, transmission distance, and interference, the advantages and disadvantages of cooperative transmission schemes in comparison with non-cooperative schemes. Through this investigation, proper transmission schemes can be identified for optimising the performance of different network scenarios.

The remainder of this study is organised as follows. Section 2 discusses the relevance of this research to other work. EE and achievable DR models for three different transmission modes in a cellular network are presented in Section 3. Simulation results and discussions are provided in Section 4. Finally, the study is concluded in Section 5.

2 RELATED WORK

Addressing the co-channel interference issue by developing an appropriate interference management scheme is crucial for maintaining the QoS of D2D and cellular networks. Therefore, [12] studied cross-tier interference management for underlay D2D users in a heterogeneous macro-small cell network assuming imperfect channel state (ICS) information to maximise the coverage probability and the signal-to-interference-noise ratio (SINR) for both D2D link and CU. On the other hand, for improving the QoS at the BS, a D2D mode selection scheme was proposed to manage the intra-cell interfer-

ence inside a finite cellular network region [13]. In [14], a transmission cost minimisation problem was investigated for guaranteeing QoS in a D2D-based distributed storage system. In addition, an efficient resource allocation algorithm for D2D underlaying cellular systems was developed [15], which maximises the EE of D2D links while guaranteeing QoS for cellular links.

Additionally, other techniques are considered to reach the maximal possible EE for cellular networks, such as multi-user multiple-input multiple-output (MIMO) systems [16]. On the other hand, [17] studied the cellular multiple-input single-output (MISO) overheard by multiple eavesdroppers, in the presence of multiple pairs of single-antenna D2D nodes working as an underlay, with an aim to design the robust transmit covariance of confidential message and artificial noise, such that the worst-case sum secrecy rate is maximised. Recently, some researches have exploited the idea of the coop-D2D communications in order to maximise the total average achievable rate under the outage probability constraint for both CUs and D2D links [18]. In addition, the optimisation of cooperation level and uplink spectrum sharing are analysed by employing physical layer security concept in the D2D communications underlaying cellular networks [19]. This approach aims to maximise the secrecy rate under constraints of satisfying the QoSs for CUs and the receiving device.

On the EE aspect, an efficient power allocation algorithm based on Dinkelbach algorithm and Lagrange dual method was proposed in [20], to improve the EE for both D2D communications and CU. Additionally, robust power control problems in D2D communications were analysed in [21] with two types of channel uncertainty sets being considered. Furthermore, the downlink resource (subchannels and power) allocation problem for D2D communication with wireless power transfer technique in a cellular network was addressed in [22] to maximise EE for D2D and CUs.

The study in [23] proposed a new mobility management and vertical handover algorithm that handle the transmission mode transition during the D2D connection. Also, it showed the effect of the of the cellular UE movement on the quality of the communication between the D2D pair to maximise the overall system throughput. Furthermore, a multi-agent reinforcement learning-based autonomous channel selection scheme for D2D communication was proposed in [24], which allows a D2D pair to learn to select a channel from the available resources autonomously to improve the system performance in terms of average D2D user throughput, energy consumption and fairness value. To model effectively the power allocation problem and manage the spectrum between D2D users and CUs, two approaches have been considered in [25] to maximise the EE of the D2D users which is subject to limited battery capacity and QoS requirements.

The EE and the spectral efficiency over non-cooperative or cooperative communication links have been investigated by most of the recent studies, but they only studied and reported the effect of using only one relay branch in the system. There is a need of data concerning how to choose the suitable transmission mode and decide the particular number of parallel branches...
and the required number of the relays in each branch under various environmental conditions. For instance, we will show that the transmission distance of a CUE-BS or D2D link plays a role in finding a solution that can ensure the best QoS of a network in concern.

In this study, our investigation will recognise the conditions for building up suitable transmission strategies among diverse commonly used transmission schemes in the context of a cellular network that accommodates both D2D and CUE-BS links with cooperative relaying branches. Our approach is based on the development of analytical and simulation models for EE, achievable DR and outage probability and the performance of these transmission schemes will be demonstrated, including the trade-offs between coop- and direct D2D transmission schemes.

3 | SYSTEM MODEL AND PROBLEM FORMULATION

In this section, the analytical models are established for both cooperative and non-cooperative transmission schemes for enhancing the QoS of a cellular network with D2D communication links. The proposed models can be exploited to develop an adaptive transmission strategy for system performance optimisation.

As shown in Figure 1, a cellular network consists of BS, number of CUEs, and D2D pairs equipped with a transmitter (DTx) and a receiver (DRx) for each D2D device. There are three different transmission modes: (a) cellular mode (CM): refers to the traditional communications between CUEs and BS; (b) direct D2D mode (DM): refers to communications between DTx and DRx directly; and (c) coop-D2D mode. We aim to optimise the system design in order to maximise the overall EE and the achievable DR of the system which is set by:

\[
\begin{align*}
\text{Max} & \sum_i EE_{bi} & E_{Ebi} := f_1(P_C, P_D) \\
\text{s.t.} & P_C \leq P_{C_{max}} \\
\text{s.t.} & P_D \leq P_{D_{max}}
\end{align*}
\]

and

\[
\begin{align*}
\text{Max} & \sum_i DR_{bi} & DR_{bi} := f_2(P_C, P_D) \\
\text{s.t.} & P_C \leq P_{C_{max}} \\
\text{s.t.} & P_D \leq P_{D_{max}}
\end{align*}
\]

where \(EE_{bi}\) and \(DR_{bi}\) are the EE in bits/Joule and achievable DR in bits/s, respectively, of the \(i\)th transmission link either between CUE and BS or between D2D devices. \(P_C\) and \(P_{C_{max}}\) are the transmitting power and the maximum transmitted power between CUE-BS, respectively. \(P_D\) and \(P_{D_{max}}\) are the transmitting power and the maximum transmitted power between D2D links, respectively. Both \(f_1(\cdot)\) and \(f_2(\cdot)\) are function of \(P_C\) and \(P_D\).

Figure 1 shows the investigated different transmission schemes involving D2D and CUE-to-BS links, including traditional cellular mobile, non-coop and coop-D2D communications. Relaying scenarios in the cooperative communications (Figure 1(c)), which will be based on varied numbers of branches and relays in each branch, will be considered in analytical modelling in connection with CUE-BS transmission in Sections 3.1–3.3.

In the proposed models, we consider that the transmission links are subject to narrowband Rayleigh fading with Additive White Gaussian Noise (AWGN) and propagation path-loss. Additionally, we assume that the channel fades for different links are statistically mutually independent.

3.1 | CM

Figure 1(a) shows the proposed CM where DTx sends the data to DRx through the BS acting as a DF relay node, in addition to communications between CU (CUE) and BS. In CM mode, the resource allocation should be divided between the CU and the D2D link. Considering that the portion of the exclusive resources exploited by the CUE-BS link is \(\beta\), and
the remaining (1-\(\beta\)) are exploited by the D2D link, assuming that \(\beta\) is 0.5. This mode is identical to the one operated in a traditional cellular network.

According to this transmission mode, the EE (\(EE_{CM}\)) and achievable DR (\(DR_{CM}\)) are given by [26]:

\[
EE_{CM} = \beta \frac{R_{CBCM}}{P_c} + \frac{1}{2} (1-\beta) \min \left\{ \frac{R_{DTxB}}{P_d} + \frac{R_{BDRx}}{P_s} \right\} + \frac{\gamma_{CB}}{N}
\]  
(2)

\[
DR_{CM} = \beta R_{CBCM} + \frac{1}{2} (1-\beta) \min \{R_{DTxB}, R_{BDRx}\}
\]  
(3)

where \(R_{CBCM}\) is the achievable rate, \(P_d, R_{DTxB}\) and \(R_{BDRx}\) are transmission power of BS, achievable DR at the uplink and downlink of the D2D link, respectively. \(P_s\) is internal circuitry power consumption. Assuming that \(R_{DTxB} = R_{BDRx}\) for avoiding data loss at BS and \(\beta\) is the system bandwidth. The achievable rates \(R_{CB}, R_{DTxB}\) and \(R_{BDRx}\) in bits/s for CM are expressed as:

\[
R_{CBCM} = B log_2 (1 + SINR_{CBCM})
\]  
(4)

\[
R_{DTxB} = B log_2 (1 + SINR_{DTxB})
\]  
(5)

\[
R_{BDRx} = B log_2 (1 + SINR_{BDRx})
\]  
(6)

The (SINRs) of the CUE-BS link, SINR\(_{CBCM}\) and the DTx-BS, BS-DRx links, SINR\(_{DTxB}, SINR_{BDRx}\) are given by:

\[
SINR_{CBCM} = \frac{P_c|h_{CB}|^2\gamma_{CB}}{N}
\]  
(7)

\[
SINR_{DTxB} = \frac{P_d|h_{DBRx}|^2\gamma_{DTxB}}{N}
\]  
(8)

\[
SINR_{BDRx} = \frac{P_s|h_{BDRx}|^2\gamma_{BDRx}}{N}
\]  
(9)

where \(N\) is the thermal noise power at any receiver, \(|h_{ij}|^2\) is the channel fading coefficient between transmitter \(i\) and receiver \(j\) of complex normal distribution \(CN(0, 1)\), and \(\gamma_{ij}\) is path loss between transmitter \(i\) and receiver \(j\) with the same index sets used for \(|h_{ij}|^2\), which is given by [27]:

\[
\gamma_{ij} = \gamma_{a}d_{ij}^{-\alpha}
\]  
(10)

where \(d_{ij}, \gamma_{a}\) and \(\alpha\) are the distance between transmitter \(i\) and receiver \(j\) with the same index sets for \(i\) and \(j\) as described above, the path loss constant and the path loss exponent, respectively.

An outage occurs when SINR at the receiver falls below a threshold \(\xi\) in the CUE-BS link (\(p_{outCBCM}\)) or \(\eta\) in the D2D link (\(p_{outD2DCM}\)), which allows error free decoding. The outage probability of this mode is given by [28]:

\[
p_{outCBCM} = p(SINR_{CBCM} \leq \xi) = 1 - \exp\left(\frac{-\xi N}{P_c|h_{CB}|^2\gamma_{CB}}\right)
\]  
(11)

\[
p_{outD2DCM} = p(SINR_{DTxB} \leq \xi) + p(SINR_{BDRx} \leq \xi) = 1 - \exp\left(\frac{-\xi N}{P_d|h_{DBRx}|^2\gamma_{DTxB} + P_s|h_{BDRx}|^2\gamma_{BDRx}}\right)
\]  
(12)

The optimisation problem of CM mode can be formulated as shown in Equations (13) and (14).

\[
\delta_{CM}, \Omega_{CM}, \delta_{DCM} \text{ and } \Omega_{DCM} \text{ denote the Lagrangian factors for CUE-BS and D2D power constraints for CM, respectively.}
\]

The optimisation problem with two constraint variables and their Lagrangians is given by:

\[
\begin{align*}
\frac{\partial EE_{CM}}{\partial p_c} + \delta_{CM} \frac{\partial (P_{max} - P_c)}{\partial P_c} + \delta_{DCM} \frac{\partial (P_{max} - P_d)}{\partial P_d} & = 0 \\
\frac{\partial EE_{CM}}{\partial p_d} + \delta_{CM} \frac{\partial (P_{max} - P_c)}{\partial P_c} + \delta_{DCM} \frac{\partial (P_{max} - P_d)}{\partial P_d} & = 0 \\
\frac{\partial DR_{CM}}{\partial p_c} + \Omega_{CM} \frac{\partial (P_{max} - P_c)}{\partial P_c} + \Omega_{DCM} \frac{\partial (P_{max} - P_d)}{\partial P_d} & = 0 \\
\frac{\partial DR_{CM}}{\partial p_d} + \Omega_{CM} \frac{\partial (P_{max} - P_c)}{\partial P_c} + \Omega_{DCM} \frac{\partial (P_{max} - P_d)}{\partial P_d} & = 0
\end{align*}
\]  
(13) \quad (14) \quad (15) \quad (16)

The optimum \(EE_{CM}\) and \(DR_{CM}\) can be obtained, respectively, by solving Equations (13), (15) and (16) and by solving Equations (14), (17) and (18), respectively, with respect to the transmit power \(P_c\) and \(P_d\).

### 3.2 DM

Figure (1b) describes the direct D2D transmission mode. In this transmission mode, we consider that CUE sends the data to the BS, which forms CUE-BS links and at the same time any two CUEs can directly communicate together which is known as the D2D communications. In DM, when any D2D communicates, they share the same uplink (UL) resource of an active CUE that is transmitted data to the BS which causes interference at BS due DTx and at DRx due to the active CUE.

In DM, the EE\(_{DM}\) and DR\(_{DM}\) are the EE and achievable rate, respectively, which are expressed as:

\[
EE_{DM} = EE_{CB} + EE_{D2D} = \frac{R_{CB}}{P_c + P_s} + \frac{R_{D2D}}{P_d + 2P_s}
\]  
(19)
where $EE_{CB}$, $R_{DD}$ and $DR_{CB}$ are the EE, the data rate and the achievable DR of the CUE-BS link, respectively. $EE_{DD}$, $R_{DD}$ and $DR_{DD}$ are the EE and data rate and the achievable DR of the D2D link, respectively. Let $B$ be the system bandwidth. In DM, the achievable rates $R_{CBDM}$ and $R_{D2DDM}$ are expressed as:

$$R_{CBDM} = B \log_2 (1 + SINR_{CBDM})$$

$$R_{D2DDM} = B \log_2 (1 + SINR_{D2DDM})$$

and the SINRs of the CUE-BS link, $SINR_{CBDM}$, and the D2D links, $SINR_{D2DDM}$, are given by:

$$SINR_{CBDM} = \frac{P_C |b_C|^2 \gamma_{CB}}{P_D |b_{DB}|^2 \gamma_{DB} + N}$$

$$SINR_{D2DDM} = \frac{P_D |b_{DD}|^2 \gamma_{DD}}{P_C |b_{CD}|^2 \gamma_{CD} + N}$$

The outage probabilities of the CUE-BS link ($p_{outCBDM}$) and the D2D link ($p_{outD2DDM}$) in this transmission mode are given by [29]:

$$p_{outCBDM} = P\left( SINR_{CBDM} \leq \xi \right)$$

$$= 1 - \frac{P_C |b_C|^2 \gamma_{CB}}{\xi P_D |b_{DB}|^2 \gamma_{DB} + P_C |b_C|^2 \gamma_{CB}} \exp \left( -\frac{-\xi N}{P_C |b_C|^2 \gamma_{CB}} \right)$$

$$\text{Max} \sum EE_{DM}$$

$$\text{Max} \left\{ \beta R_{CBDM} + \frac{1}{2} (1 - \beta) R_{D2DDM} + \delta_{CCM} (P_{C_{max}} - P_C) + \delta_{DCM} (P_{D_{max}} - P_D) \right\}$$

$$\text{s.t.} \{ P_C \leq P_{C_{max}}, P_D \leq P_{D_{max}} \}$$

and

$$\text{Max} \sum DR_{DM}$$

$$\text{Max} \left\{ \beta R_{CBDM} + \frac{1}{2} (1 - \beta) R_{D2DDM} + \delta_{CCM} (P_{C_{max}} - P_C) + \Omega_{DCM} (P_{D_{max}} - P_D) \right\}$$

$$\text{s.t.} \{ P_C \leq P_{C_{max}}, P_D \leq P_{D_{max}} \}$$

$$P_{outD2DDM} = P\left( SINR_{D2DDM} \leq \eta \right)$$

$$= 1 - \frac{P_D |b_{DD}|^2 \gamma_{DD}}{\eta P_C |b_{DD}|^2 \gamma_{DD} + \Omega P_D |b_{DD}|^2 \gamma_{DD}} \exp \left( -\frac{-\eta N}{P_D |b_{DD}|^2 \gamma_{DD}} \right)$$

Assume $\xi N < \xi P_C |b_C|^2 \gamma_{CB}$ and $\eta N < \Omega P_D |b_{DD}|^2 \gamma_{DD}$, so Equations (25) and (26) can be rewritten as:

$$p_{outCBDM} = 1 - \frac{P_C |b_C|^2 \gamma_{CB}}{\xi P_D |b_{DB}|^2 \gamma_{DB} + P_C |b_C|^2 \gamma_{CB}}$$

$$p_{outD2DDM} = 1 - \frac{P_D |b_{DD}|^2 \gamma_{DD}}{\eta P_C |b_{CD}|^2 \gamma_{CD} + P_D |b_{DD}|^2 \gamma_{DD}}$$

In the same way as shown through Equations (13) and (14), we can formulate the optimisation problem of DM as follows:

$$\text{Max} \sum EE_{DM}$$

$$\text{Max} \left\{ EE_{CB} + EE_{DD} + \delta_{CCM} (P_{C_{max}} - P_C) + \delta_{DCM} (P_{D_{max}} - P_D) \right\}$$

$$\text{s.t.} \{ P_C \leq P_{C_{max}}, P_D \leq P_{D_{max}} \}$$

where $\delta_{CDM}$ and $\Omega_{CDM}$ denote the Lagrangian factors for the power constraints of CUE-BS in DM, respectively. $\delta_{DDM}$ and $\Omega_{DDM}$ denote the Lagrangian factors for the power constraints of D2D links in DM, respectively.

The optimisation problem with two constraint variables and their Lagrangians is given by:

$$\frac{\partial EE_{DM}}{\partial P_C} + \delta_{CDM} \frac{\partial (P_{C_{max}} - P_C)}{\partial P_C} + \delta_{DDM} \frac{\partial (P_{D_{max}} - P_D)}{\partial P_C} = 0$$

$$\frac{\partial EE_{DM}}{\partial P_D} + \delta_{CDM} \frac{\partial (P_{C_{max}} - P_C)}{\partial P_D} + \delta_{DDM} \frac{\partial (P_{D_{max}} - P_D)}{\partial P_D} = 0$$

$$\frac{\partial DR_{DM}}{\partial P_C} + \Omega_{CDM} \frac{\partial (P_{C_{max}} - P_C)}{\partial P_C} + \Omega_{DDM} \frac{\partial (P_{D_{max}} - P_D)}{\partial P_C} = 0$$

$$\frac{\partial DR_{DM}}{\partial P_D} + \Omega_{CDM} \frac{\partial (P_{C_{max}} - P_C)}{\partial P_D} + \Omega_{DDM} \frac{\partial (P_{D_{max}} - P_D)}{\partial P_D} = 0$$
3.3 | Coop-D2D mode

In this mode, there are three transmission methods being considered, namely, communications between CUE-BS links, direct D2D communications and D2D communications through relay devices, as shown in Figure 1(c). A noisy version of the transmitted symbol from the source is received by the relay device, and then after some processing the relay transmits the received symbol to the next relay or the DRx. In this case the interference occurs at DRx and the receiving relays due to the active CUE and at the same time BS will be subjected to interference from the DTx and the transmitting relays.

The $EE_{CoopD2D}$ and $DR_{CoopD2D}$ which are the EE and achievable rate, respectively, in coop-D2D mode can be expressed as:

$$EE_{CoopD2D} = EE_{CB} + EE_{Coop}$$

$$DR_{CoopD2D} = DR_{CB} + DR_{Coop}$$

where $K$ and $n$ are the number of branches and the number of relay nodes of the coop-D2D link, respectively. The achievable rate $R_{CoopD2D}$ in bits/s is expressed as:

$$R_{Coop} = B \log_2 \left(1 + SINR_{D2D} + \sum_{j=1}^{K} SINR_{RjDRx} \right)$$

and the SINR of the $j$-th relay BS (R-BS) link, $SINR_{Rj}$ is given by:

$$SINR_{RjDRx} = \frac{P_{Dj} |b_{RjDRx}|^2 \gamma_{RjDRx}}{P_{Cj} |b_{CDRx}|^2 \gamma_{CDRx} + N}$$

where $P_{Dj}$, $b_{RjDRx}$ are the transmit power of cooperative relays and the channel coefficient of the cooperative R-DRx link, respectively. In this study, our focus will be on the investigation of two types of cooperative transmission schemes: (1) using multiple relaying branches ($K$), each branch consists of only one relay; and (2) using $K$ relaying branches, each branch consists of multiple relays ($n$). For these two schemes, the selective decode and forward (SDF) relaying is considered as cooperative protocol. This protocol is used by relays to perform cooperation when the information from the DTx is correctly received by them. Additionally, the selection combining technique is assumed to be used at the destination on the received packets.

The outage probability of the CUE-BS link ($p_{outCBCoop}$) and the D2D link ($p_{outD2DCoop}$) in this transmission mode is given by:

$$p_{outCBCoop} = 1 - \frac{1}{\xi} \sum_{j=1}^{K} \sum_{l=1}^{n} P_{Dj} |b_{Dj}|^2 \gamma_{Dj} + P_{CB} |b_{CB}|^2 \gamma_{CB}$$

$$p_{outD2DCoop} = p_{outD2D} \left(1 - \left(1 - p_{outsDx} \right) \left(\prod_{j=2}^{n-1} \left(1 - p_{out rel_j+1} \right) \right)^K \right)$$

where $p_{outD2D}$ is the outage probability between DTx and DRx, $p_{outsDx}$ is the outage probability between DTx and the first relay, $p_{out rel_j+1}$ represents the outage probability between any two consecutive transmitting and receiving relays and $p_{outsDx}$ is the outage probability between the last relay node and DRx. Similarly to the method used in Equations (13) and (14), we can formulate the optimisation problem of coop-D2D as follows:

$$\text{Max} \sum EE_{CD}$$

$$\text{Max} \left\{ EE_{CB} + EE_{CoopD2D} + \delta_{CCD} (P_{Cmax} - P_C) \right\}$$

and

$$\text{Max} \sum DR_{CD}$$

$$\text{Max} \left\{ R_{CB} + R_{CoopD2D} + \Omega_{CCD} (P_{Cmax} - P_C) \right\}$$

where $\delta_{CCD}$ and $\Omega_{CCD}$ denote the Lagrangian factors for power constraints of CUE-BS, respectively. $\delta_{DCD}$ and $\Omega_{DCD}$ denote the Lagrangian factors for power constraints D2D links in coop-D2D, respectively.

The optimisation problem with two constraint variables and their Lagrangians is given by:

$$\frac{\partial EE_{CD}}{\partial P_C} + \delta_{CCD} \frac{\partial (P_{Cmax} - P_C)}{\partial P_C} + \delta_{DCD} \frac{\partial (P_{Dmax} - P_D)}{\partial P_C} = 0$$

$$\frac{\partial EE_{CD}}{\partial P_D} + \delta_{CCD} \frac{\partial (P_{Cmax} - P_C)}{\partial P_D} + \delta_{DCD} \frac{\partial (P_{Dmax} - P_D)}{\partial P_D} = 0$$

$$\frac{\partial DR_{CD}}{\partial P_C} + \Omega_{CCD} \frac{\partial (P_{Cmax} - P_C)}{\partial P_D} + \Omega_{DCD} \frac{\partial (P_{Dmax} - P_D)}{\partial P_C} = 0$$

$$\frac{\partial DR_{CD}}{\partial P_D} + \Omega_{CCD} \frac{\partial (P_{Cmax} - P_C)}{\partial P_D} + \Omega_{DCD} \frac{\partial (P_{Dmax} - P_D)}{\partial P_D} = 0$$
The optimum $EE_{CD}$ and $DR_{CD}$ can be obtained by solving Equations (41), (43) and (44), and by solving Equations (42), (45) and (46), respectively, with respect to the transmit power $P_C$ and $P_D$.

4 NUMERICAL RESULTS AND DISCUSSION

In this section, the system performance of the three transmission modes, presented in Section 3 and Figure 1, is evaluated and simulated in terms of EE, achievable DR, system outage probability and bit error rate under various environmental and transmission conditions in a cellular network using computer simulation. Then, we show how by using an adaptive way a proper transmission scheme can be chosen to optimise the system performance. The simulation parameters for the proposed models are listed in Table 1. For a given network topology, we assume that CUE-BS link and D2D pairs are randomly chosen and then for comparison purposes we apply different transmission schemes.

Two different scenarios are considered to evaluate and examine the EE performance of the three proposed modes. In the first scenario, we assume that the distance between the transmitted CUE and BS is fixed at 300 m and the distance between any two D2D links varies from 5 to 100 m as shown in Figure 2(a). As we can observe, the traditional CM, which is based on the communication through BS, has lower performance in terms of EE than D2D mode and coop-D2D, while when the distance between D2D link exceeds 55 m the non-cooperative transmission (DM) has lower EE than the cooperative transmission (coop-D2D). On the other hand, when the transmission distance is beyond 55 m, D2D mode becomes inefficient; this prove the concept presented in different previous studies [7, 12, 24] that the maximum transmission distance between any D2D links is between 10–50 m. So that the coop-D2D communication using one branch with two relays ($K = 1, n = 2$) per branch is superior to the direct D2D transmission scheme, using the relay nodes between D2D links decrease the distance between sender and receiver and increase the link reliability. In the second scenario, we assume that the distance between any D2D links is fixed at 80 m and the transmission distance between CUE-BS varies from 10 to 500 m as depicted in Figure 2(b). This scenario shows the effect of using D2D and coop-D2D communications on the cellular networks. As mentioned in Figure 2(b), D2D mode and coop-D2D outperform the CM in terms of EE. Furthermore, when the distance of the D2D link is short, the required transmit power of DTx proportionally decreases, then the interferences at the BS due to DTx and the transmitting relay decrease as well.

Moreover, the EE increases due the reduction of the overall required transmit power from CUE. Additionally, it can be mentioned that coop-D2D is even preferable, specially when the distance between CUE-BS exceeds 100 m as it helps decrease
the interference at BS which increases the cellular networks performance.

Similar performance trends to those demonstrated in Figure 2 can be observed for the achievable DR among the three different proposed modes in Figure 3. As displayed in Figure 3(a) the coop-D2D outperforms the two other transmission modes (DM or CM) in terms of achievable DR when the distance between any D2D links is less than 35 m. Based on these results, we can conclude that when deciding which transmission mode should be used, EE and the achievable DR should be evaluated together to reach the required desirable trade-off between the two-performance metrics under different conditions.

Additionally, it can be observed that the achievable DR of DM and coop-D2D transmissions is higher than the traditional CM, since CUE is normally farther away from the BS than the distance between two devices. On the other hand, the DR of the coop-D2D mode is also higher than that of the D2D mode as long as the distance between any D2D links is not short enough (<35).
Figure 4 shows the outage probability of three transmission modes. As we can see from Figure 4(a), D2D mode and coop-D2D are both superior to CM in terms of the outage probability, whereas coop-D2D mode outperforms the D2D mode (non-cooperative transmission) as well. Additionally, we notice that coop-D2D using $K=2$ branches with $n=1$ relay per branch has better performance than coop-D2D using $K=1$ branch with $n=2$ relays due to the diversity gain obtained from the $K=2$ branches which experience less link failure. In Figure 4(b), the distance between any D2D link is fixed at 80 m while the distance between CUE and BS varies from 10 to 500 m. Once again we can see that D2D mode and coop-D2D have better performance than through CM, and coop-D2D is even better than DM. Therefore, when deciding which mode to use at different end-to-end distances, the previous three metrics which are the EE, the achievable DR and the outage probability should be evaluated together to achieve a desirable trade-off between them in order to maintain the QoS required.

In terms of the bit error rate, the similar performance trend is observed as shown in Figure 5. As we can see, coop-D2D using $K=1$ branch with $n=2$ relays per branch performs better than the coop-D2D using $K=2$ branches with $n=1$ relay. This is mainly because the distance between a DTx-DRx pair decreases when increasing the number of intermediate node, resulting in the decreased overall system bit error rate.

Results in Figure 6 show the effect of using multiple branches and multiple relays scenarios on the performance of EE and DR. In this scenario, we assume that the transmission distance between CUE and BS and the transmission distance between D2D links are 300 and 80 m, respectively. In Figure 6(a), EE is evaluated once again but against the number of branches $K$ and with different numbers of relays per branch $n=1, 2, 3$ and 4. Clearly, the optimal transmission scheme is when
$K = 1$ (for all possible $n$), and the one with $K = 1$ branch and $n = 2$ relays is the most energy efficient transmission scheme. When $K$ increases, the best performed scheme shifts from $n = 2$ to $n = 1$ starting from $K = 3$. In Figure 6(b), the highest DR can be achieved by using one branch with four relays in D2D link and with the distance range specified. In practical systems, for deciding the required numbers of branches and relays, both achievable DR and EE can be jointly considered in order to attain the required trade-off between the two performances.

Figure 7 depicts EE against the numbers of D2D pairs in Figure 7(a) and CUEs in Figure 7(b), which are uniformly distributed in a cellular cell for both simulation and analytical model. Substantial performance gaps in EE between the direct transmission scheme in D2D or CUE-BS links and the optimal (cooperative) transmission schemes are demonstrated in Figure 7. Additionally, the performance gap expands with the increase of the number of D2D pairs as shown in Figure 7(a). We also notice that both simulation and analytical model have the same performance when comparing between the direct transmission scheme in D2D or CUE-BS links and the optimal (cooperative) transmission schemes. Similar performance trends and gaps are also found in Figure 8, the achievable DR for simulation and analytical mode against the numbers of D2D pairs shown in Figure 8(a) and CUEs in Figure 8(b).

The superiority of cooperative transmission schemes over the DM and the traditional CM is also demonstrated in the usage of their transmit power. In Figure 9, we allow the transmit power (Pc) of CUE to vary, based on which the power of the D2D transmitter $P_D$ will be set to overcome the interference caused by DTx. In Figure 10, the power of the D2D transmitter is the variable that will be used to determine the transmit power of CUE in order to overcome the interference from the CUE transmitter. Assuming that, the transmission distance between CUE and BS link is 300 m and the transmission distance between D2D links is 80 m, we can deduce from the results in Figures 9 and 10 that cooperative transmission is more efficient than non-cooperative transmission in terms of
power usage as it needs less power for the same end-to-end transmission distance. This will decrease the interference at the BS and DRx and increase the overall EE and achievable DR.

In cellular networks, EE, achievable, outage probability and bit error rate can be affected by various numbers of factors. By comparing direct transmission with cooperative transmission, it can be observed that cooperative transmission exploits additional transmission paths which cost more energy for creating diversity and utilise other devices as relays for support to each other. On the other hand, the diversity it creates reduces the packet loss rate resulting in the reduction of the retransmission time which can save energy. Furthermore, the total distance of each transmission hop can be reduced by using multiple relays in each branch, resulting in lower required transmit power for relays. However, if too many branches and relays are used the total energy consumption will increase due to the total circuitry power, as the total circuitry power affected by the total number of relays or the total number of transmitting devices but it is not affected by the transmission distance between any source and destination pairs.

5 | CONCLUSION

We have investigated the system performance of three different transmission and resource sharing modes involving D2D and coop-D2D communications underlaying a cellular network in terms of EE, DR, BER and $P_{\text{out}}$ under different environmental conditions. Based on the proposed optimisation models derived for EE and DR, we have shown that in different scenarios EE and DR of D2D and coop-D2D modes have better performance than CM. We have also demonstrated that based on the environmental conditions such as channel quality, path loss, transmission distance between CUE-BS and the transmission distance between D2D pairs, D2D and coop-D2D transmission schemes can be used collectively to achieve the best possible EE and DR. Based on the results presented in this study, an adaptive transmission strategy can therefore be derived to optimise the transmission scheme, leading to enhanced QoS in such a network.

REFERENCES

1. Arash, A., et al.: A survey on device-to-device communication in cellular networks. IEEE Commun. Surv. Tutorials. 16, 1801–1819 (2014)
2. Lin, X., et al.: An overview of 3GPP D2D proximity services. IEEE Commun. Mag. 52, (4), 40–48 (2014)
3. Fodor, G., et al.: Design aspects of network assisted device-to-device communications. IEEE Commun. Mag. 50, 170–177 (2012)
4. Anbiyaei, M., et al.: Energy-Efficient resource allocation for device-to-device underlay communications in cellular networks. IET Signal Proc. 13(6), 633–639 (2019)
5. Poornima, S., Babu, A.V.: Optimal power allocation for energy-efficient full-duplex cognitive relay networks under primary interference. IET Commun. 13(19), 3317–3325 (2019)
6. Lee, N., et al.: Power control for D2D underlaid cellular networks: Modeling, algorithms, and analysis. IEEE J. Sel. Areas Commun. 33(1), 1–13 (2015)
7. Mumtaz, S., et al.: Energy-efficient interference management in LTE-D2D communication. IET Signal Proc. 10(3), 197–202 (2016)
8. Li, B., et al.: Performance analysis and optimization for energy-efficient cooperative transmission in random wireless sensor network. IEEE Trans. Wireless Commun. 12, 4647–4657 (2013)
9. Ni, Y., et al.: Outage probability of device-to-device communication assisted by one-way amplify-and-forward relaying. IET Commun. 9(2), 271–282 (2015)
10. Chen, G., et al.: Outage probability analysis for a cognitive amplify-and-forward relay network with single and multi-relay selection. IET Commun. 7, 1974–1981 (2013)
11. Osman, R.A., et al.: Energy efficiency and achievable data rate of device-to-device communications in cellular networks. In: Proceedings of IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), pp. 53–59, Exeter, UK, June 2017
12. Maher, E.A., El-Mahdy, A.: Interference management for D2D-enabled HetNets with imperfect channel estimation. IET Commun. 1–10 (2019)
13. Guo, J., et al.: Device-to-device communication underlaying a finite cellular network region. IEEE Trans. Wireless Commun. 16, 332–347 (2017).
14. Wang, L., et al.: Hypergraph-based wireless distributed storage optimization for cellular d2d underlays. IEEE J. Sel. Area Commun. 34, 2650-2666 (2016)
15. Hoang, T.D., et al.: Energy-efficient resource allocation for D2D communications in cellular networks. IEEE Trans. Veh. Technol. 65, 6972-6986 (2016)
16. Li, C., et al.: Efficient antenna allocation algorithms in millimetre wave wireless communications. IET Commun. 12(5), 543–551 (2018)
17. Huang, S., et al.: Robust artificial noise-aided transmit optimisation for MISO wiretap channel with device-to-device underlay communication. IET Commun. 12(8), 1019–1027 (2018)
18. Lee, J., Lee, J.H.: Performance analysis and resource allocation for cooperative D2D communication in cellular networks with multiple D2D pairs. IEEE Commun. Lett. 23, 909–912 (2019)
19. Alibeigi, M., Taherpour, A.: Optimisation of secrecy rate in cooperative device to device communications underlaying cellular networks. IET Commun. 13(5), 512–519 (2019)
20. Zuo, J., Yang, L.: Energy efficient power allocation for D2D communications in fading channels. Electron. Lett. 54(3), 177–179 (2018)
21. Ding, J., et al.: Energy-efficient power control for underlaying d2d communication with channel uncertainty: User-centric versus network-centric. IEEE J. Commun. Networks 18, 589–599 (2016)
22. Dai, H., et al.: Energy-efficient resource allocation for device-to-device communication with WPT. IET Commun. 11(3), 326–334 (2017)
23. Morattab, A., et al.: Mode selection map-based vertical handover in D2D enabled 5G networks. IET Commun. 13(14), 2173–2185 (2019)
24. Sharma, S., Singh, B.: Weighted cooperative reinforcement learning-based energy-efficient autonomous resource selection strategy for underlay D2D communication. IET Commun. 13(14), 2078–2087 (2019)
25. Sultana, A., et al.: Energy-efficient power allocation in underlay and overlay cognitive device-to-device communications. IET Commun. 13(2), 162–170 (2019)
26. Cao, Y., et al.: Cooperative device-to-device communications in cellular networks. IEEE Wireless Commun. 22, 124−129 (2015)
27. Wei, L., et al.: Energy efficiency and spectrum efficiency of multihop device-to-device communications underlaying cellular networks. IEEE Trans. Veh. Technol. 65, 367–380 (2016)
28. Lee, J., Lee, J.H.: Performance analysis and resource allocation for cooperative D2D communication in cellular networks with multiple D2D pairs. IEEE Commun. Lett. 23, 909–912 (2019)
29. Min, H., et al.: Reliability improvement using receive mode selection in device-to-device uplink period underlaying cellular networks. IEEE Trans. Wireless Commun. 10, 413–418 (2011)

How to cite this article: Osman RA, Peng X-H, Omar MA, Gao Q. Quality of service optimisation of device-to-device communications underlaying cellular networks. IET Commun 2021;15:179–190, https://doi.org/10.1049/cmu2.12040